**Session No. 703**

# Risk Assessment of Alternative Fuels[1]

**Judy Freeman**
**Serap Erdal**
**Sally Higgins**

## Abstract

The purpose of this paper is to identify and assess risks related to alternative fuels, and relate those risks to public health and life cycle questions. Using the school bus fleet of the Chicago Public Schools as a model, this paper compares the environmental health and safety impact of current diesel fuel usage with that of increased use of alternative technologies and fuels.

Four alternative fuels have been studied: Low sulfur diesel (baseline), biodiesel (BD20), ethanol-diesel blends (ED10), and compressed natural gas (CNG) from renewable feedstocks. Impact was assessed utilizing the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) 1.7 Well to Wheel model.

## Introduction

Using the school bus fleet of the Chicago Public Schools as a model, this paper compares the environmental health and safety (EHS) impact of diesel fuel usage expected as new baseline low sulfur rules are fully implemented after 2009, and with increased use of alternative technologies and fuels. Four fuels have been studied: Low sulfur diesel (baseline), biodiesel (BD20), ethanol-diesel blends (ED10), and compressed natural gas (CNG) from renewable feedstocks. The year modeled is 2010 in order to capture the most stringent requirements currently being targeted.

Impact was assessed utilizing the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) 1.7 Well to Wheel model. GREET performs life cycle analysis of fuels, accounting for extraction of fossil fuels or farming activities of renewable fuels which produce the feedstock, through processing of feedstock into a usable fuel, distribution of feedstocks and fuels, to fuel consumption. Default settings in GREET were used for each of these fuels with some exceptions to consider technologies not currently included in GREET, and to account for

[1] The author would also like to acknowledge the following: M. Wang, Argonne National Labs, Mr. Arnaldo Cruz, Operations Manager, Chicago Public Schools; Mr. Steve Rosenblatt, Director, USA EPA Region 5 Air and Radiation Division (deceased), John Ingersoll, EcoCorp, and John Madole, Green SEED Energy.

specific emissions factors for school bus diesel operations in Chicago. Since the GREET model is open source code, estimates were able to be manually inserted so that data analysis was carried out within the GREET structure. The conclusions from this analysis were then compared with the literature and, where possible, previous modeling efforts.

## Background and Context

The management of energy consumption and investigation into new energy sources are receiving increased attention in the United States. Such a paradigm shift as may be developing in energy management carries with it substantial risks in terms of management of change. Change is happening in many layers of the energy production industry and with energy consumers (individuals and companies) as well. What will emerge will challenge our current EHS knowledge and experience.

How we adapt and adopt standards for protecting workers and the public in these new industries (and new operations in old industries) will require the most rigorous use of the old tools, quick learning, adaptation and invention of new tools, and the wisdom to know which to use and when.

All of the hazardous air pollutants which make up the mobile toxics list are known carcinogens. Other vehicle exhaust constituents such as particulate matter, cause asthma, particularly in children who make up the primary exposed population from school bus emissions. There is no greater environmental health concern than energy and emissions from transportation fuel.

In 1993, EPA estimated that 42% of all air toxics emitted were from mobile sources.[2] In 1995, EPA estimated air toxics account for half of all cancers attributed to outdoor sources.[3] Still, little change occurred in adoption of alternative fuels for many years. Even with the current focus, alternative fuel accounts for only small percentage of all fuel used in the U.S. However, these trends are shifting, and there are new incentives to use alternative fuels in school buses. This represents a significant opportunity to have an impact on mobile air toxics sources. As data on alternative fuels and corresponding emissions is gathered and analyzed it can inform the choices of engine/vehicle choices being made as school bus fleets are replaced and retrofitted.

Thus, it is particularly important at this time to “get it right”. But issues in this area are complex. Complexity is compounded when volumes of literature are available, but offer data reflecting different fuels, in different formulations, from a variety of chemical analysis protocols and reporting criteria, operating different vehicles, studying different constituents of concern, impacting multi-media, different population centers, different weather patterns and so on.

EHS professionals are particularly sensitive to avoid plunging into a course of action that results in unintended consequences as happened when Methyl Tertiary Butyl Ether (MTBE) was mandated by name in the Clean Air Act to reduce carbon monoxide emissions, only to trade impacted media as MTBE made its way into the public water supply.

---

[2] US EPA, Technical Support Branch, Emission Planning and Strategies Division, Office of Mobile Sources, Office of Air and Radiation, “Motor Vehicle-Related Air Toxics Study”, April, 1993.

[3] US EPA, Office of Mobile Sources, “Air Toxics from Motor Vehicles” Fact Sheet OMS-2, EPA4000-F-92-004, February, 1995.

Yet, little consistent, reliable, end-of-pipe data exists for alternative fuels. This considered one of the weaknesses of this study and its one of its primary recommendations for near term research.

## Fuel Choices

Fuel choices in this study are considered near term technology options for school buses. By modeling energy use and emissions for current operations and each alternative and comparing against the literature, solid recommendations can be made to guide which technologies offer the greatest potential to reduce the energy and environmental impact.

## Regulatory Framework

Constituents of concern for school buses air pollution are generally covered in two areas of the Clean Air Act's regulatory framework: Criteria Pollutants and Hazardous Air Pollutants (HAPS).

Clean Air Act (CAA)
The Clean Air Act provides the regulatory structure for much of the consideration of air emissions. Title II of the CAA covers Emissions Standard for Moving Sources.[4] It allows the EPA administrator to "set standards applicable to the emission of any air pollutant from any class or classes of new motor vehicles or new motor vehicle engines, which…cause, or contribute to, air pollution which may… endanger public health or welfare."[5]

National Ambient Air Quality Standards (NAAQS) (Criteria Pollutants)
CAA (Title I) requires EPA to set National Ambient Air Quality Standards (NAAQS)[6] for pollutants considered harmful to public health and the environment: Primary Standards to protect public health, including the health of sensitive populations such as asthmatics and children and Secondary Standards to protect against decreased visibility, damage to animals, crops, vegetation, and buildings. NAAQSs are set for six criteria pollutants.

Where cities, counties and states are deficient in their control of any of these criteria pollutants, USEPA can, and does impose stricter enforcement on that area until compliance can be assured. A non-attainment designation given an area in violation of the most stringent standards for each of these six pollutants, means restrictions on permits for new sources and monitoring of those industries which have been in operation for some time.

Cook County, which includes Chicago and suburbs, is "non-attainment" for 8-Hr Ozone and PM-2.5 and has had trouble meeting the requirements for PM-10 and VOCs.

4 Clean Air Act
5 Clean Air Act, Title II, 202(a)(1)
6 Clean Air Act, 40CFR50

| | Primary Standards | | Secondary Standards | |
|---|---|---|---|---|
| **Pollutant** | **Level** | **Averaging Time** | **Level** | **Averaging Time** |
| Carbon Monoxide | 9 ppm (10 mg/$m^3$) | 8-hour | None | |
| | 35 ppm (40 mg/$m^3$) | 1-hour | | |
| Lead | 1.5 µg/$m^3$ | Quarterly Average | Same as Primary | |
| Nitrogen Dioxide | 0.053 ppm (100 µg/$m^3$) | Annual (Arithmetic Mean) | Same as Primary | |
| Particulate Matter ($PM_{10}$) | 150 µg/$m^3$ | 24-hour | Same as Primary | |
| Particulate Matter ($PM_{2.5}$) | 15.0 µg/$m^3$ | Annual (Arithmetic Mean) | Same as Primary | |
| | 35 µg/$m^3$ | 24-hour | Same as Primary | |
| Ozone | 0.075 ppm (2008 std) | 8-hour | Same as Primary | |
| | 0.08 ppm (1997 std) | 8-hour | Same as Primary | |
| | 0.12 ppm | 1-hour (Applies only in limited areas) | Same as Primary | |
| Sulfur Dioxide | 0.03 ppm | Annual (Arithmetic Mean) | 0.5 ppm (1300 µg/$m^3$) | 3-hour |
| | 0.14 ppm | 24-hour | | |

**Table 1. National Ambient Air Quality Standards**

## National Emissions Standards for Hazardous Air Pollutants (HAPS)

Section 112 of the CAA Amendments (CAAA) of 1990 regulates 188 hazardous air pollutants (HAPS) that are considered a risk to human health.[7, 8] EPA identified those which pose the greatest potential threat to public health in urban areas in "Draft Integrated Urban Air Toxics Strategy" which listed 33 air toxics of concern.[9, 10]

---

7 Clean Air Act Amendments, Section 112, 1990

8 US EPA, "The original list of hazardous air pollutants as follows:", Technology Transfer Network Air Toxics Web Site, http://www.epa.gov/ttn/atw/188polls.html

9 US EPA, "Draft Integrated Urban Air Toxics Strategy" xxx

10 J Winebrake, D He, M Wang, Center for Transportation Research, Argonne National Laboratory, "Fuel-Cycle Emissions for Conventional and Alternative Fuel Vehicles: An Assessment of Air Toxics", August, 2000.

| | | |
|---|---|---|
| Acetaldehyde *<br>Acrolein<br>Acrylonitrile<br>Arsenic<br>Benzene *<br>Bis(2-ethylhexyl)phthalate<br>1,3-Butadiene *<br>Cadmium compounds<br>Carbon tetrachloride<br>Chloroform<br>Chromium compounds | Coke oven emissions<br>1,4-dichlorobenzene<br>1,3-dichloropropene<br>2,3,7,8-tetrachlorodibeno-p-dioxin<br>Ethylene dibromide<br>Ethylene dichloride<br>Ethylene oxide<br>Formaldehyde *<br>Hydrazine<br>Lead<br>Manganese | Mercury<br>Methyl Chloride<br>Methylene diphenyl disocynate<br>Methylene chloride<br>Nickel<br>Polycyclic organic matter<br>Propylene dichloride<br>Quinoline<br>Tetrachloroethylene<br>Trichloroethylene<br>Vinyl chloride |

* Indicates the 4 air toxics identified by EPA as generated primarily by mobile sources.

**Table 2. Air Toxics Identified by EPA**

In its 1993 "Mobile Vehicle-Related Air Toxics Study"[11], EPA estimated that 42% of all air toxics were from mobile sources. The four identified as the primary sources included:

- Acetaldehyde – 39% from mobile sources
- Benzene – 60% from mobile sources
- 1,3-Butadiene – 56% from mobile sources
- Formaldehyde – 33% from mobile sources

## Highway Diesel Rules

In the beginning of the CAA, diesel emissions were not regulated to the same standards as were gasoline emissions. However, USEPA is currently phasing in requirements for more stringent standards for new diesel engines and fuels. The rules mandate the use of lower sulfur fuels in diesel engines beginning in 2006 for highway diesel fuel. These new standards require that sulfur content not exceed 15 ppm (by weight) in 100% of diesel supply for on-road vehicles by 2009.[12] Compliance with this new standard is assumed in the GREET calculations in this report.

## Clean Water Act, Resource Conservation and Recovery Act

In a multi-media approach, it is also necessary to examine the contribution of pollutants from transportation fuels to water and soils. This is of particular concern since MTBE was used to oxygenate fuels to reduce CO air emissions, only to have it release to the groundwater. [13]

Gas stations are prime sources of groundwater contamination, where all drips, spills, overfills and leaking underground storage tanks contribute to contamination of the soil and eventually the

[11] U.S. EPA, Technical Support Branch, Emission Planning and Strategies Division, Office of Mobile Sources, Office of Air and Radiation, "Motor Vehicle-Related Air Toxics Study", April, 1993.

[12] U.S. EPA. Nonroad and Highway Diesel Fuel Regulations, http://www.epa.gov/fedrgstr/EPA-AIR/2006/May/Day-01/a3930.htm

[13] US EPA, www.epa.gov/mtbe/

groundwater.[14] Leaking underground storage tanks containing transportation and heating fuels have a history of contaminating soils and groundwater in every state and there are active programs in each state to address the issue.[15]

Further water pollution concerns arise when fertilizer run off occurs from biomass crops and results in increases in nitrates downstream. This nitrate loading of surface waters is considered one of the causes of the hypoxia, or "dead zone" in the Gulf of Mexico.[16]

## Chicago as a Model

Recently, Chicago has been lauded as America's "Green City" and indeed has taken many steps in that direction. Mayor Richard Daley, along with 810 other mayors, has committed to the reduction of greenhouse gas (GHG) emissions as outlined in the US Mayor's and Manager's Climate Protection Agreement.[17]

Under this Agreement, participating cities commit to:

- Strive to meet or beat the Kyoto Protocol targets in their own communities
- Urge state and federal government to enact policies and programs to reach GHG emission reduction targets for the US in the Kyoto Protocol - 7% reduction from 1990 levels by 2012;
- Urge Congress to pass bipartisan GHG reduction legislation and establish a national emission trading system.

The GREET model can help to assess what fuel technology choices could help the City of Chicago meet this greenhouse reduction goal.

### ERMS Trading Program

Chicago operates under a "cap and trade" program designed to reduce emissions of volatile organic compounds (VOCs) in the Chicago metropolitan ground-level ozone nonattainment area by 12%. The program is mandatory for major VOC sources in the Chicago area and each source has a VOC emissions cap. Where VOC sources fall below the caps, they may trade emission allowances with firms which are less successful, or new sources whose potential emissions were not included in the original cap. This program is administered by the Illinois EPA and is an important element of the state's implementation plan (SIP) for meeting the ozone standard in the Chicago metropolitan area.[18] Chicago currently does not meet the national ambient air quality standard for ground-level ozone (smog) and is classified by USEPA as a "severe" nonattainment area.

---

[14] US. EPA, "Cleaning Up Underground Storage Tank Releases", http://www.epa.gov/OUST/cat/index.htm

[15] US EPA, www.epa.gov/OUST/

[16] National Ocean Service, National Centers for Coastal Ocean Science, Gulf of Mexico Hypoxia Assessment, National Oceanic and Atmospheric Administration, "Hypoxia in the Gulf of Mexico, rogress towards the completion of an Integrated Assessment", oceanservice.noaa.gov/products/pubs_hypox.html#Intro

[17] US Mayor's and Managers, Climate Protection Agreement, www.usmayors.org/climateprotection

[18] US EPA, "Approval and Promulgation of Implementation Plans; Illinois Trading Program", http://www.epa.gov/EPA-AIR/2000/December/Day-27/a32945.htm

## Environmental and Health Concerns

Shown in graph[19], Chicago's air usually falls between "good" and "moderate", although ozone is considered unhealthy" in the heat of summer. PM2.5 levels are also unhealthy for sensitive groups like school children.

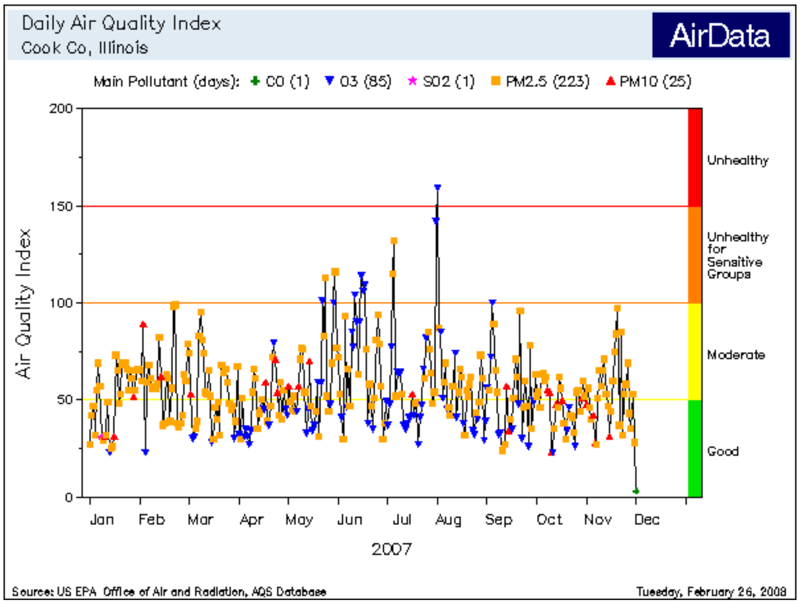


**Exhibit 1.**

In 1999, the US EPA Air and Radiation Division included Chicago in its study of "Estimation of Motor Vehicle Toxic Emissions and Exposure in Selected Urban Areas" [20] which reported air toxics estimates for 1990, 1996, 2007 and 2020 for benzene, acetaldehyde, formaldehyde, 1,3-butadiene, MTBE, and diesel particulates.

In this study, the agency compared emissions from four scenarios, with implementation of the National Low-Emission Vehicle (NLEV)[21] program as baseline. To this, they added:

1. limiting sulfur levels to 40 ppm;
2. limiting sulfur levels to 40 ppm and tightening hydrocarbon emissions standards for light duty cars and trucks; and
3. limiting sulfur levels to 40 ppm and tightening hydrocarbon emissions standards for light duty cars and trucks and assuming 50% of total light duty truck duty truck sales in compliance in 5 years.

[19] US EPA Office of Air and Radiation, AQS Database, February 26, 2008

[20] U S EPA Air and Radiation Division, "Estimation of Motor Vehicle Toxic Emissions and Exposure in Selected Urban Areas, Volume 1, Draft, EPA 420D-99-002A, March, 1999.

[21] 40 CFR Part 86 Subpart R

They concluded that “significant reductions in fleet-average toxics emissions are observed between 1990 and 2020 with no further vehicle or fuel controls” from current regulations. For Chicago, the 40 ppm sulfur limit had the greatest impact on benzene and 1,3-butadiene emissions. Aldehyde emissions were less affected by this measure. Authors assumed that MTBE would be taken off the market in Chicago and either ETBE or ethanol replaced as an oxygenator.

The authors projected that tightening hydrocarbon emissions standards for light duty trucks would have a moderate impact on air toxics by 2007. However, by implementing new standards in new light duty trucks, the expected fleet turnover that would occur by 2020 would result in 15% - 25% reductions. Reductions could be expected in benzene, acetaldehyde, 1,3-butadiene, and MTBE. Formaldehyde emissions show a slight increase and diesel particulate emissions increase substantially. Exposure to workers and children against the total population and determined that the exposure to workers was 20% greater and the exposure to children was slightly less than the total population. The report is silent as to any difference between children who ride to school in buses compared with those who might use other means of travel.

In 2000, Argonne published “Fuel-Cycle Emissions for Conventional and Alternative Fuel Vehicles: An Assessment of Air Toxics”[22] which projected that every alternative fuel technology studied would show dramatic reduction in all air toxics with few exceptions for some parameters. Only the electric vehicle showed improvement in air toxics in every category. Benzene emissions were reduced with every fuel option.

| |
|---|
| HEV3: Acetaldehyde (slight), Butadiene |
| HEV2: Formaldehyde |
| HEV1: Acetaldehyde, |
| E85: VOCs, Acetaldehyde (1431% - 1946%), Formaldehyde (>200%) |
| M85: Formaldehyde (424%, urban) |
| CNG: Formaldehyde |
| Bi-CNG: Formaldehyde |
| CD: Butadiene |
| CARFG3b: Acetaldehyde, Formaldehyde |
| CARFG3a: Formaldehyde |
| FRFG2b: Acetaldehyde, Butadiene (slight), Formaldehyde |
| FRFG2a: Formaldehyde |

**Table 3. Alternative Fuels with Potential Air Toxics Increases**

[22] J Winebrake, D He, M Wang, Center for Transportation Research, Argonne National Laboratory, “Fuel-Cycle Emissions for Conventional and Alternative Fuel Vehicles: An Assessment of Air Toxics”, August, 2000

| | | MSHA PELs* | | |
|---|---|---|---|---|
| **Component** | **OSHA PEL** | **Underground coal mines** | **Metal and nonmetal mines** | **niosh REL** |
| Carbon dioxide ($CO_2$) | 5,000 ppm (9,000 mg/m$^3$), 8-hr TWA† | 5,000 ppm (9,000 mg/m$^3$), 8-hr TWA; 30,000 ppm (54,000 mg/m$^3$), STEL§ | 5,000 ppm (9,000 mg/m$^3$), 8-hr TWA; 15,000 ppm (27,000 mg/m$^3$), STEL | 10,000 ppm (18,000 mg/m$^3$), 8-hr TWA; 30,000 ppm (54,000 mg/m$^3$), 10-min ceiling |
| Carbon monoxide (CO) | 50 ppm (55 mg/m$^3$), 8-hr TWA | 50 ppm (55 mg/m$^3$), 8-hr TWA; 400 ppm (440 mg/m$^3$), STEL | 50 ppm (55 mg/m$^3$), 8-hr TWA; 400 ppm (440 mg/m$^3$), STEL | 35 ppm (40 mg/m$^3$), 8-hr TWA; 200 ppm (230 mg/m$^3$), ceiling (no minimum time) |
| Formaldehyde | 1 ppm, 8-hr TWA; 2 ppm, 15-minute STEL | 1 ppm (1.5 mg/m$^3$), 8-hr TWA; 2 ppm (3 mg/m$^3$), STEL | 2 ppm (3 mg/m$^3$), ceiling | 0.016 ppm (0.020 mg/m$^3$), 8-hr TWA; 0.1 ppm (0.12 mg/m$^3$), 15-min ceiling |
| Nitrogen dioxide ($NO_2$) | 5 ppm (9 mg/m$^3$), ceiling | 3 ppm (6 mg/m$^3$), 8-hr TWA; 5 ppm (10 mg/m$^3$), STEL | 5 ppm (9mg/m$^3$), ceiling | 1 ppm (1.8 mg/m$^3$), 15-min ceiling |
| Nitric oxide (NO) | 25 ppm (30 mg/m$^3$), 8-hr TWA | 25 ppm (30 mg/m$^3$), 8-hr TWA | 25 ppm (30 mg/m$^3$), 8-hr TWA; 37.5 ppm (46 mg/m$^3$), STEL | 25 ppm (30 mg/m$^3$), 10-hr TWA |
| Sulfur dioxide ($SO_2$) | 5 ppm (13 mg/m$^3$), 8-hr TWA | 2 ppm (5 mg/m$^3$), 8-hr TWA; 5 ppm (10 mg/m$^3$), STEL | 5 ppm (13 mg/m$^3$), 8-hr TWA; 20 ppm (52 mg/m$^3$), STEL (5 min) | 0.5 ppm (1.3 mg/m$^3$), 10-hr TWA |

*MSHA limits are based on threshold limit values (TLV®s) of the American Conference of Governmental Industrial Hygienists (ACGIH). 1973 TLV®s are used for metal and nonmetal mines. Current TLVs are used for underground coal mines.
†-weighted average.
§-term exposure limit.

**Table 4. Constituents of Concern in Diesel[23]**

---

[23] National Institute for Occupational Safety and Health, Division of Standards Development and Technology Transfer, "Current Intelligence Bulletin 50" "Carcinogenic Effects of Exposure to Diesel Exhaust", August, 1988

Chicago Public Schools

The children of the Chicago Public Schools (CPS) are served by a fleet of approximately 2000 buses.[24] A school bus in Chicago will travel an average of 20,000 miles in a typical school year.[25] Diesel buses average 6.2 miles per gallon (MPG).[26] The State of Illinois estimates that at least 70 percent of the 18,500 school buses in service today are powered by diesel fuel.[27]

The fleet of the CPS and its private bus company vendors already operate some alternative fuel vehicles. However, numbers are shifting as some old vehicles are retrofitted, new vehicles are added and previous orders are fulfilled. Therefore, current operations reflect a "Low Sulfur Diesel" baseline, although the fleet is currently in a transitional phase. However, by 2010 all conventional diesel buses should be retrofitted or replaced.

Asthma Rates in Chicago

The rate of hospitalization for asthma in Chicago in 1996 was 42.8 per 10,000 population which is more than twice the rate for suburban Chicago or the rest of the U.S.[28] Children are particularly vulnerable to asthma.

Methodology

The complexity of the calculation of EHS concerns of multiple technologies producing multiple fuels from multiple feedstocks, and the energy and environmental inputs and outputs of each, would have been impossible in the time frame of this study but for the 20-year effort by the Center for Transportation Research at Argonne National Laboratory and the GREET model.

GREET

GREET varies from many other models of its type in that it captures not only values for efficiency and emissions factors for the fuel as it is consumed, but also the energy use and emissions factors for the production and distribution of the feedstocks and conversion of feedstock into product. Fuel choices are subjected to a series of "pathways" that are meant to provide detail in the assessment of each choice as to a true sum of the energy and emissions consequences of that choice. It is the choices of fuel production feedstocks, energy sources, and production and distribution methods that create the pathways that apply values to the environmental and energy use impact of transportation fuels cradle to grave. Detailed assumptions underlay each choice, and are applied to the results. Where assumptions are known to vary, they can be manually altered in the open source Excel spreadsheet GREET structure.[29] GREET includes more than 100 fuel production pathways and 70 vehicle/fuel systems. [30] GREET calculates the following parameters for specific fuels, operating in specific vehicle:

---

[24] Mr. Arnaldo Cruz, Operations Manager, Chicago Public Schools, Telephone conversation, February 26, 2008.

[25] Mr. Steve Rothblatt, Director, US EPA Region 5 Air and Radiation Division from Press Release, "Chicago Department of Environment and Chicago Public Schools Reduce School Bus Emissions", April, 2007 .

[26] Mobile6.2

[27] State of Illinois brochure

[28] SD Thomas, S Whitman, "Asthma Hospitalization and Mortality in Chicago", Chest 116:135S – 141S, American College of Chest Physicians, 1999

[29] M. Wang, Argonne National Labs, GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation), Version 1.7 Well to Wheel model, 2007.

[30] Ibid

- "Consumption of total energy (energy in non-renewable and renewable sources), fossil fuels (petroleum, natural gas, and coal together), petroleum, coal and natural gas.
- Emissions of CO2-equivalent GHGes - primarily carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O).
- Emissions of six criteria pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxide (NOx), particulate matter <10 micron (PM10), particulate matter < 2.5 micron (PM2.5),and sulfur oxides (SOx)."

## GREET Pathways

GREET is structured in modules that relate to each of the parameters chosen. Some critical pathway items in terms of energy use and emissions include:

- Feedstock
- Fuel
- Distribution
- Fuel Use

Where possible, with few exceptions, default settings were selected in each module for the four alternative fuel types. This is intended to focus the study only on the basic fuel choices made.

Simulations have been conducted which include the following scenarios:

- Baseline conditions: 100% phasing in of low sulfur diesel
- Biodiesel (BD20)
- Ethanol-diesel blends (ED10)
- Compressed natural gas (CNG) from renewable feedstocks.

| FUEL | FEEDSTOCK | PROCESS |
|---|---|---|
| Baseline: Conventional Diesel/ | Petroleum | Refine |
| Low Sulfur Diesel | | |
| Biodiesel | Soy Beans | Soy Bean Extraction, Refine |
| Diesel/Ethanol Blend | Petroleum/ Corn & Corn Stover | Refine |
| CNG | Organic Waste | Digest |

**Table 5. Pathway Choices**

There are two ways in which the GREET model did not serve as a perfect fit for this study:

- Factors have been included in the model for Light Duty Trucks #1 and #2, but not for school buses. The outcome of using Light Duty Truck #2 as a surrogate would underestimate exposures. Therefore, emissions factors for diesel school buses, operating in Chicago were manually entered into the model using emission Factors from the EPA Mobile6.2 model were used to replace data assumptions in the GREET model that were less specific as to place.[31]

| Emission factors from EPA MOBILE6.2 model | | | | | | |
|---|---|---|---|---|---|---|
| **CAL_YEAR** | **Season** | **POL** | **VTYPE** | **g/mi** | **g/day** | **MPG** |
| 2010 | Summer | CO2 | Diesel School Bus | 1635.2 | 44527.6 | 6.2 |
| 2010 | Summer | SO4 | Diesel School Bus | 0.0011 | 0.029 | 6.2 |
| 2010 | Summer | Gas PM2.5 | Diesel School Bus | 0 | 0 | 6.2 |
| 2010 | Summer | Brake PM2.5 | Diesel School Bus | 0.0053 | 0.145 | 6.2 |
| 2010 | Summer | Tire PM2.5 | Diesel School Bus | 0.003 | 0.082 | 6.2 |
| 2010 | Summer | HC | Diesel School Bus | 0.5726 | 15.593 | 6.2 |
| 2010 | Summer | CO2 | Diesel School Bus | 1.8696 | 50.91 | 6.2 |
| 2010 | Summer | NOx | Diesel School Bus | 8.1553 | 222.071 | 6.2 |
| **CAL_YEAR** | **Season** | **POL** | **VTYPE** | **g/mi** | **g/day** | **MPG** |
| 2010 | Winter | CO2 | Diesel School Bus | 1634.8 | 44517 | 6.2 |
| 2010 | Winter | SO4 | Diesel School Bus | 0.0011 | 0.029 | 6.2 |
| 2010 | Winter | Gas PM2.5 | Diesel School Bus | 0 | 0 | 6.2 |
| 2010 | Winter | Brake PM2.5 | Diesel School Bus | 0.0053 | 0.145 | 6.2 |
| 2010 | Winter | Tire PM2.5 | Diesel School Bus | 0.003 | 0.082 | 6.2 |
| 2010 | Winter | HC | Diesel School Bus | 0.5846 | 15.918 | 6.2 |
| 2010 | Winter | CO2 | Diesel School Bus | 1.9331 | 52.639 | 6.2 |
| 2010 | Winter | NOx | Diesel School Bus | 8.4812 | 230.943 | 6.2 |

**Table 6. Emission factors from EPA MOBILE 6.2 model**

- Current iterations of the GREET model do not contain modules for calculating energy efficiency and emissions factors for CNG from renewable sources. CNG modules are extant, but these represent only natural gas from under ground sources. Near term plans are to add additional modules to the CNG section of GREET, but this may be limited to capture and conversion of landfill gas.[32] Such options would come closer to reflecting our model fuel source, but would not capture it entirely. Surrogates were found for the "feedstock" portion of the model, but not for "fuels".

[31] US EPA, MOBILE6 Vehicle Emission Modeling Software, www.epa.gov/otaq/m6.htm
[32] Conversation with Michael Wang, Argonne National Labs, February 7, 2008

# Discussion

## Low Sulfur Diesel[33]

Diesel is traditionally a major sources of particulate, it's primary emissions: carbon dioxide, carbon monoxide, nitric oxide, nitrogen dioxide, sulfur oxides, hydrocarbons, including polycyclic aromatic hydrocarbons (PAHs) and particulates. Particulates are composed of elemental carbon, organic matter (including PAHs) and metallic compounds. PAHs are found in both the gaseous and particulate fractions of diesel exhaust. Particulate emissions from diesel are significantly greater than from gasoline. Diesel exposures are highest where diesel traffic is heaviest – along highways and in cities. Children riding in school buses, a more vulnerable segment of the population, experience elevated exposure to diesel.[34]

**CIDI Vehicle: Conventional and LS Diesel**

| | Btu/mile or grams/mile | | | | Percentage of each stage | | |
|---|---|---|---|---|---|---|---|
| Item | Feedstock | Fuel | Vehicle Operation | Total | Feedstock | Fuel | Vehicle Operation |
| Total Energy | 597 | 2,690 | 15,603 | 18,890 | 3.2% | 14.2% | 82.6% |
| Fossil Fuels | 575 | 2,655 | 15,603 | 18,833 | 3.1% | 14.1% | 82.8% |
| Coal | 111 | 473 | 0 | 583 | 19.0% | 81.0% | 0.0% |
| Natural Gas | 274 | 833 | 0 | 1,107 | 24.8% | 75.2% | 0.0% |
| Petroleum | 189 | 1,350 | 15,603 | 17,143 | 1.1% | 7.9% | 91.0% |
| CO2 | 60 | 200 | 1,234 | 1,493 | 4.0% | 13.4% | 82.6% |
| CH4 | 1.422 | 0.224 | 0.003 | 1.648 | 86.2% | 13.6% | 0.2% |
| N2O | 0.001 | 0.003 | 0.012 | 0.016 | 7.1% | 19.2% | 73.7% |
| GHGs | 93 | 206 | 1,237 | 1,536 | 6.0% | 13.4% | 80.6% |
| VOC: Total | 0.054 | 0.069 | 0.175 | 0.297 | 18.0% | 23.1% | 58.8% |
| CO: Total | 0.101 | 0.109 | 0.285 | 0.496 | 20.5% | 22.0% | 57.5% |
| NOx: Total | 0.381 | 0.329 | 8.155 | 8.865 | 4.3% | 3.7% | 92.0% |
| PM10: Total | 0.030 | 0.126 | 0.039 | 0.195 | 15.2% | 64.7% | 20.1% |
| PM2.5: Total | 0.013 | 0.048 | 0.013 | 0.074 | 18.2% | 64.7% | 17.1% |
| Sox: Total | 0.130 | 0.223 | 0.008 | 0.362 | 36.0% | 61.6% | 2.4% |
| VOC: Urban | 0.009 | 0.038 | 0.109 | 0.156 | 5.8% | 24.5% | 69.7% |
| CO: Urban | 0.004 | 0.057 | 0.177 | 0.239 | 1.8% | 24.0% | 74.2% |
| NOx: Urban | 0.017 | 0.152 | 5.073 | 5.242 | 0.3% | 2.9% | 96.8% |
| PM10: Urban | 0.001 | 0.029 | 0.024 | 0.055 | 1.3% | 54.0% | 44.8% |
| PM2.5: Urban | 0.000 | 0.017 | 0.008 | 0.025 | 1.9% | 67.2% | 30.8% |
| Sox: Urban | 0.012 | 0.105 | 0.005 | 0.122 | 9.5% | 86.2% | 4.3% |

**Table 7. Low Sulfur Diesel—Baseline**

[33] H Frumkin, MJ Thun, "Diesel Exhaust", CA: A Cancer Journal for Clinicians, 2001:51:193-198, www.caonline.amcancersoc.org/cgi/content/full/51/3/193.

[34] GM Solomon, TR Campbell, GR Feuer, J Masters, A Samkian, KA Paul, "No Breathing in the Aisles/ Diesel Exhaust Inside School Buses", National Resources Defense Council, Coalition for Clean Air, January, 2001.

Biodiesel – BD20[35,36]

Biodiesel is of particular interest to the US petroleum industry because its physical and chemical properties, similar to conventional petroleum-based fuels, mean it can be delivered and used in existing systems with little or no modifications. Biodiesel may be produced from seed oils (soy, corn, canola, or palm oil) and waste fats oils and grease, however, soy oil currently holds the predominant market share of feedstock used in production of biodiesel in the U.S.

Biodiesel is produced by transesterifying triglycerides from soybeans with methanol. It is this process which is currently modeled pathway in GREET. BD-20 is a blend of 80% low sulfur diesel and 20% biodiesel. The basic formula used to calculate methanol production is:

100 lbs of oil + 10 lbs of methanol → 100 lbs of biodiesel + 10 lbs of glycerol.[37]

**CIDI Vehicle: BD20**

| | Btu/mile or grams/mile | | | | Percentage of each stage | | |
|---|---|---|---|---|---|---|---|
| Item | Feedstock | Fuel | Vehicle Operation | Total | Feedstock | Fuel | Vehicle Operation |
| Total Energy | 953 | 3,278 | 15,603 | 19,834 | 4.8% | 16.5% | 78.7% |
| Fossil Fuels | 925 | 3,230 | 12,677 | 16,832 | 5.5% | 19.2% | 75.3% |
| Coal | 144 | 482 | 0 | 625 | 23.0% | 77.0% | 0.0% |
| Natural Gas | 331 | 1,575 | 0 | 1,906 | 17.4% | 82.6% | 0.0% |
| Petroleum | 449 | 1,174 | 12,677 | 14,301 | 3.1% | 8.2% | 88.6% |
| CO2 | -150 | 221 | 1,236 | 1,308 | -11.5% | 16.9% | 94.6% |
| CH4 | 1.207 | 0.345 | 0.003 | 1.556 | 77.6% | 22.2% | 0.2% |
| N2O | 0.051 | 0.004 | 0.012 | 0.066 | 76.5% | 5.3% | 18.1% |
| GHGs | -107 | 230 | 1,240 | 1,363 | -7.9% | 16.9% | 91.0% |
| VOC: Total | 0.066 | 0.518 | 0.175 | 0.758 | 8.7% | 68.3% | 23.1% |
| CO: Total | 0.172 | 0.118 | 0.285 | 0.575 | 29.9% | 20.5% | 49.6% |
| NOx: Total | 0.502 | 0.352 | 8.155 | 9.010 | 5.6% | 3.9% | 90.5% |
| PM10: Total | 0.048 | 0.124 | 0.039 | 0.212 | 22.8% | 58.6% | 18.5% |
| PM2.5: Total | 0.026 | 0.048 | 0.013 | 0.086 | 30.2% | 55.2% | 14.6% |
| SOx: Total | 0.238 | 0.223 | 0.007 | 0.468 | 50.9% | 47.6% | 1.5% |
| VOC: Urban | 0.009 | 0.033 | 0.109 | 0.151 | 5.8% | 22.1% | 72.1% |
| CO: Urban | 0.005 | 0.049 | 0.177 | 0.231 | 2.2% | 21.0% | 76.8% |
| NOx: Urban | 0.019 | 0.130 | 5.073 | 5.222 | 0.4% | 2.5% | 97.1% |
| PM10: Urban | 0.001 | 0.024 | 0.024 | 0.050 | 2.2% | 48.7% | 49.1% |
| PM2.5: Urban | 0.001 | 0.014 | 0.008 | 0.023 | 3.2% | 62.2% | 34.6% |
| SOx: Urban | 0.014 | 0.091 | 0.004 | 0.109 | 12.8% | 83.3% | 3.9% |

**Table 8. Biodiesel**

[35] H. Huo, M. Wang, C. Bloyd, V. Putsche. Argonne National Laboratory, Center for Transportation Technologies and Systems, National Renewable Energy Laboratory, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, "Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels", March 12, 2008

[36] D. Clements, G. Knothe, National Renewable Energy Laboratory, "Biodiesel Production Technology", August 2002–January 2004, www.nrel.gov

Ethanol – ED10 (E-Diesel)
The use of 10% ethanol in diesel is far less common than the addition of ethanol to gasoline. Argonne's Center for Transportation Research has included calculations of the energy and emission effects of E-diesel in its GREET model.[38,39,40]
In the research that yielded the GREET baseline assumptions, Argonne concluded that "there is very little information about consistent, controlled tests of buses using E-diesel." They cite two studies showing "no net fuel efficiency loss for an E-diesel blend relative to premium diesel".

Argonne cited "limited testing on ED15 by the Chicago Transit Authority, in conjunction with SwRI which showed no statistically identifiable net fuel efficiency difference for an E-diesel blend relative to premium diesel", although Argonne found the report statistically flawed and used more conservative estimates as a result. They noted that "test results for tractors and buses using diesel and E-diesel are very limited. In fact, there were no controlled tests that assured that diesel and E-diesel would be tested in typical operating conditions for tractors or buses."

Ethanol yields a slight, but not significant advantage in terms of Fine-PM emissions for buses fueled by E-diesel over petroleum diesel buses while both urban and rural fine-PM emissions are greater with the E-fuels because of their greater reliance on coal as a power and process fuel.

The Argonne study found that, "Although use of E-diesel can achieve reductions in petroleum use, … energy- and GHG-related net changes … of low-sulfur diesel buses do not establish a conclusive case for the superiority of E-diesel fuels. Within the range of our assumptions, as modeled within the 10% and 90% extreme values, … ED10 and ED15 could produce greater overall emissions and consume more total energy and fossil fuels per unit of activity than neat diesel. … E-diesel fuels are likely to require more total energy input per unit of output heating value than either conventional or low-sulfur diesel.

"…, despite a relatively weak overall performance on total criteria pollutant emissions, buses fueled by E-diesel do show a net reduction in important pollutants (PM10 and CO) in urban areas. They are essentially neutral on VOCs as well as on NOx and Sox. (VOC emission rates per unit of travel by diesels are so small to begin with that percentage changes less than 100% or so are inconsequential). Thus, the combined net benefit of petroleum displacement and reduction in urban fine particulate loading is possibly an attractive environmental and energy policy-oriented feature of E-diesel fuels."

---

[38] M Wu, M Wang, H Huo, Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, "Fuel-Cycle Assessment of Selected Bioethanol Production Pathways in the United States", November 7, 2006.
[39] M Wang, D Santini, "Corn-Based Ethanol Does Indeed Achieve Energy Benefits", Notes to be published in ECO: Ethanol, Climate Change, Oil Reduction, A Public Forum Newsletter by the Environmental and Energy Study Institute, February 15, 2000
[40] M Wang, C Saricks, H Lee, Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, "Fuel-Cycle Energy and Emission Impacts of Ethanol-Diesel Blends in Urban Buses and Farming Tractors", July, 2003

Other results noted:

- "Total energy use" includes energy consumption for both ethanol and petroleum diesel, but "Fossil fuel and petroleum use" only includes petroleum diesel since ethanol is 100% renewable. Non-renewable energy use at other pathway points (delivery, etc.) limits this benefit.

- While an ethanol-gasoline blend exhibits superior GHG emission benefits over conventional gasoline, the E-diesel blend offers less dramatic results.

Argonne concluded that "the most noteworthy benefits of E-diesel use lie with petroleum reductions and reductions in urban PM10 and CO emissions by urban bus operations. … with respect to pollution abatement, E-diesel could be a non-trivial asset of fuel portfolios for urban buses needing to reduce their PM10 emissions."

## Estimating Net Energy Value

Much has been made of energy and emissions imbalances in the production of ethanol, with critics of ethanol citing:

- Use of agricultural land for fuel production instead of food crops;
- Use of energy- and emissions-intense fertilizers and other agricultural chemicals to boost production. Nitrogen-based fertilizers also create nitrate run-off which further degrades vase areas of the Gulf of Mexico.
- Depending upon farming operations and methods of calculation, the net energy value (NEV) of ethanol is low or even negative.

In response, the paper points to significant increases in recent years in farm production efficiencies and advances in ethanol production technology which have led to greater energy efficiency related to ethanol. They set the input:output ratio at 1:34.

Argonne concludes that "producing ethanol from domestic corn stocks achieves a net gain in a more desirable form of energy. Ethanol production uses abundant domestic supplies of coal and natural gas to convert corn into a premium liquid fuel that can displace petroleum imports."

**CIDI Vehicle: E-Diesel**

| Item | Btu/mile or grams/mile | | | | Percentage of each stage | | |
|---|---|---|---|---|---|---|---|
| | Feedstock | Fuel | Vehicle Operation | Total | Feedstock | Fuel | Vehicle Operation |
| Total Energy | 773 | 3,689 | 15,603 | 20,066 | 3.9% | 18.4% | 77.8% |
| Fossil Fuels | 745 | 2,913 | 14,643 | 18,301 | 4.1% | 15.9% | 80.0% |
| Coal | 141 | 568 | 0 | 708 | 19.9% | 80.1% | 0.0% |
| Natural Gas | 361 | 1,070 | 0 | 1,430 | 25.2% | 74.8% | 0.0% |
| Petroleum | 243 | 1,275 | 14,643 | 16,162 | 1.5% | 7.9% | 90.6% |
| CO2 | 1 | 219 | 1,226 | 1,447 | 0.1% | 15.2% | 84.8% |
| CH4 | 1.348 | 0.280 | 0.003 | 1.632 | 82.6% | 17.2% | 0.2% |
| N2O | 0.032 | 0.005 | 0.012 | 0.049 | 65.1% | 10.3% | 24.5% |
| GHGs | 41 | 227 | 1,230 | 1,499 | 2.8% | 15.2% | 82.1% |
| VOC: Total | 0.043 | 0.113 | 0.175 | 0.332 | 13.1% | 34.2% | 52.8% |
| CO: Total | 0.123 | 0.131 | 0.285 | 0.540 | 22.8% | 24.4% | 52.8% |
| NOx: Total | 0.434 | 0.376 | 8.155 | 8.965 | 4.8% | 4.2% | 91.0% |
| PM10: Total | 0.038 | 0.162 | 0.039 | 0.239 | 15.7% | 67.8% | 16.5% |
| PM2.5: Total | 0.017 | 0.058 | 0.013 | 0.088 | 19.5% | 66.1% | 14.4% |
| SOx: Total | 0.160 | 0.244 | 0.008 | 0.412 | 38.8% | 59.3% | 2.0% |
| VOC: Urban | 0.009 | 0.048 | 0.109 | 0.166 | 5.3% | 29.2% | 65.5% |
| CO: Urban | 0.005 | 0.054 | 0.177 | 0.236 | 2.1% | 22.9% | 75.0% |
| NOx: Urban | 0.019 | 0.145 | 5.073 | 5.236 | 0.4% | 2.8% | 96.9% |
| PM10: Urban | 0.001 | 0.028 | 0.024 | 0.053 | 1.7% | 52.1% | 46.3% |
| PM2.5: Urban | 0.001 | 0.016 | 0.008 | 0.024 | 2.5% | 65.4% | 32.1% |
| SOx: Urban | 0.013 | 0.100 | 0.005 | 0.119 | 11.2% | 84.6% | 4.2% |

**Table 9. Ethanol.**

## Compressed Natural Gas (CNG)

The consumption of natural gas for transportation, while growing, is a very small part of the US market share for fuels. Several US cities currently fuel buses with CNG, including parking lot shuttles at O'Hare and Midway Airports in Chicago.

Natural gas consists typically of 93% methane, 3% ethane and 2% propane, with the remainder being nitrogen and carbon dioxide.[41]

However, there are currently no sources of CNG derived from renewable sources in the US. There are also currently no US installations of the technology which would process the waste organics to produce methane. There are many such installations in Europe and elsewhere and several cities which fuel their buses with CNG from organic wastes.

[41] Dr. John Ingersoll, conversation September, 2007.

| | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|---|
| **Total Consumption** | 23,007,017 | 22,276,502 | 22,388,975 | 22,010,596 | 21,653,086 | 23,005,305 |
| Vehicle Fuel | 14,950 | 18,271 | 20,514 | 22,884 | 24,919 | 26,280 |
| % of Total | 0.0006498 | 0.0008202 | 0.0009163 | 0.0010397 | 0.0011508 | 0.0011423 |

**Table 10. Natural Gas Consumption by End Use (Million Cubic Feet)[42]**

The technology identified is a form of anaerobic digestion (AD) which is thermophillic (TAD) (operating at temperatures of 104°F – 159°F.) By initiating the process with small amounts of heat, natural decomposition of organic wastes is accelerated. Residence times are shortened, and compost by-products are pathogen-free and of high quality. $CH_4$ and $CO_2$, which are emitted naturally as organic matter decomposes, are captured and put to beneficial reuse.

AD is a known technology in the US on farms where hog manure is digested, or in waste or wastewater treatment systems. Typically, these are mesophillic systems operating in the range of 77°F – 104°F.

TAD operations in Europe and elsewhere report that any organic material, including the organic fraction of municipal solid waste, may be appropriate for TAD although it is most efficient on a steady diet of feedstock with a steady N:C ratio. Algae and agricultural wastes not appropriate for biodiesel or ethanol may do well, and the glycerin by-product from biodiesel is considered highly efficient.

## Adapting GREET to add CNG

Extraction of natural gas and acquisition of biomass are very different, and thus energy use and emissions factors are also quite different. It has been assumed that the feedstock module for GREET's "Methanol from Biomass" pathway will adequately estimate those values. This module is likely the closest to reflecting the true energy and environmental expenditures of renewable biomass in a CNG operation, and may even be conservative. While feedstock modules in GREET for methanol work quite well, the fuel production modules do not. Thermophillic anaerobic digestion does not resemble methanol production.

Except for a small amount of the natural gas produced from the system and fed back into the system, no energy is used in the production of methane from TAD. Organic matter decomposes in the presence of anaerobic bacteria that convert the waste products into methane, carbon dioxide, water and compost. Compost is then screened and the non-compostable fraction landfilled. Thermophillic anaerobic digesters produce 30 – 50% more methane than mesophillic.

[42] Energy Information Administration, "Natural Gas Navigator", tonto.eia.doe.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm

While no values exist in the GREET model for TAD, or any process that could be said to be an appropriate surrogate, it is assumed that the values for energy usage in the production of CNG from TAD would be no more than those for extracted gas. Thus, the values that exist in GREET for CNG from extracted natural gas have been allowed to remain as a place holder until better values can be obtained.

## CNG

**Bi-Fuel CNGV on CNG** **Extracted Natural Gas**

| | Btu/mile or grams/mile | | | | Percentage of each stage | | |
|---|---|---|---|---|---|---|---|
| **Item** | **Feedstock** | **Fuel** | **Vehicle Operation** | **Total** | **Feedstock** | **Fuel** | **Vehicle Operation** |
| Total Energy | 1,571 | 1,675 | 20,576 | 23,823 | 6.60% | 7.00% | 86.40% |
| Fossil Fuels | 1,561 | 1,463 | 20,576 | 23,600 | 6.60% | 6.20% | 87.20% |
| Coal | 54 | 1,038 | 0 | 1,091 | 4.90% | 95.10% | 0.00% |
| Natural Gas | 1,418 | 352 | 20,576 | 22,346 | 6.30% | 1.60% | 92.10% |
| Petroleum | 89 | 73 | 0 | 162 | 54.80% | 45.20% | 0.00% |
| CO2 | 111 | 140 | 1,222 | 1,473 | 7.60% | 9.50% | 82.90% |
| CH4 | 4.908 | 0.188 | 0.25 | 5.346 | 91.80% | 3.50% | 4.70% |
| N2O | 0.002 | 0.002 | 0.012 | 0.016 | 11.70% | 12.50% | 75.80% |
| GHGs | 225 | 145 | 1,231 | 1,601 | 14.00% | 9.00% | 76.90% |
| VOC: Total | 0.123 | 0.013 | 0.23 | 0.365 | 33.60% | 3.40% | 63.00% |
| CO: Total | 0.171 | 0.037 | 3.852 | 4.06 | 4.20% | 0.90% | 94.90% |
| NOx: Total | 0.486 | 0.152 | 0.442 | 1.081 | 45.00% | 14.10% | 40.90% |
| PM10: Total | 0.019 | 0.184 | 0.036 | 0.239 | 8.00% | 77.10% | 15.00% |
| PM2.5: Total | 0.011 | 0.049 | 0.021 | 0.081 | 13.80% | 59.90% | 26.30% |
| SOx: Total | 0.241 | 0.336 | 0.006 | 0.582 | 41.40% | 57.70% | 0.90% |
| VOC: Urban | 0.002 | 0.001 | 0.143 | 0.146 | 1.70% | 0.60% | 97.70% |
| CO: Urban | 0.004 | 0.007 | 2.396 | 2.408 | 0.20% | 0.30% | 99.50% |
| NOx: Urban | 0.012 | 0.026 | 0.275 | 0.314 | 3.90% | 8.40% | 87.70% |
| PM10: Urban | 0 | 0.002 | 0.022 | 0.024 | 1.70% | 6.60% | 91.70% |
| PM2.5: Urban | 0 | 0.001 | 0.013 | 0.015 | 2.20% | 6.60% | 91.20% |
| SOx: Urban | 0.005 | 0.059 | 0.003 | 0.068 | 7.90% | 87.00% | 5.00% |

## CNG

**Bi-Fuel CNGV on CNG** **Renewable Natural Gas**

| | Btu/mile or grams/mile | | | | Percentage of each stage | | |
|---|---|---|---|---|---|---|---|
| **Item** | **Feedstock** | **Fuel** | **Vehicle Operation** | **Total** | **Feedstock** | **Fuel** | **Vehicle Operation** |
| Total Energy | 375 | 1,675 | 20,576 | 22,626 | 1.66% | 7.40% | 90.94% |
| Fossil Fuels | 371 | 1,463 | 20,576 | 22,410 | 1.66% | 6.53% | 91.82% |
| Coal | 28 | 1,038 | 0 | 1,066 | 2.63% | 97.37% | 0.00% |
| Natural Gas | 45 | 352 | 20,576 | 20,973 | 0.21% | 1.68% | 98.11% |
| Petroleum | 298 | 73 | 0 | 371 | 80.32% | 19.68% | 0.00% |
| CO2 | -2,143 | 140 | 1,222 | -781 | 274.39% | -17.93% | -156.47% |
| CH4 | 0.033 | 0.188 | 0.25 | 0.471 | 7.01% | 39.92% | 53.08% |
| N2O | 0.012 | 0.002 | 0.012 | 0.026 | 46.15% | 7.69% | 46.15% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| GHGs | -2,139 | 145 | 1,231 | -763 | 280.34% | -19.00% | -161.34% |
| VOC: Total | 0.02 | 0.013 | 0.23 | 0.263 | 7.60% | 4.94% | 87.45% |
| CO: Total | 0.081 | 0.037 | 3.852 | 3.970 | 2.04% | 0.93% | 97.03% |
| NOx: Total | 0.183 | 0.152 | 0.442 | 0.777 | 23.55% | 19.56% | 56.89% |
| PM10: Total | 0.017 | 0.184 | 0.036 | 0.237 | 7.17% | 77.64% | 15.19% |
| PM2.5: Total | 0.012 | 0.049 | 0.021 | 0.082 | 14.63% | 59.76% | 25.61% |
| SOx: Total | 0.023 | 0.336 | 0.006 | 0.365 | 6.30% | 92.05% | 1.64% |
| VOC: Urban | 0.001 | 0.001 | 0.143 | 0.145 | 0.69% | 0.69% | 98.62% |
| CO: Urban | 0.002 | 0.007 | 2.396 | 2.405 | 0.08% | 0.29% | 99.63% |
| NOx: Urban | 0.006 | 0.026 | 0.275 | 0.307 | 1.95% | 8.47% | 89.58% |
| PM10: Urban | 0.001 | 0.002 | 0.022 | 0.025 | 4.00% | 8.00% | 88.00% |
| PM2.5: Urban | 0 | 0.001 | 0.013 | 0.014 | 0.00% | 7.14% | 92.86% |
| SOx: Urban | 0.003 | 0.059 | 0.003 | 0.065 | 4.62% | 90.77% | 4.62% |

**Table 11.**

The first charts shows the energy and emissions values for CNG when using extracted natural gas feedstock, the second renewable feedstock.

With heat, carbon dioxide and compost as natural by-products, the technology lends itself well to co-locating with greenhouse operations with the potential for a closed loop system which would produce algae as a feedstock for the TAD process which is a part of this panel. Such a system could provide a demonstration of best practices in this regard. Further, it could power a co-located industrial park which will utilize the heat and feedstocks created in a synergistic balance.

CNG is also linked to future hydrogen fuel cells development, since the energy source for producing hydrogen is natural gas and methane carries four hydrogen atoms.

## Results

| Item | Btu/mile or grams/mile | | | | |
|---|---|---|---|---|---|
| | Low Sulfur Diesel | Biodiesel BD20 | Ethanol diesel ED10 | Extracted CNG | Renewable CNG |
| Total Energy | 18,890 | 19,834 | 20,066 | 23,823 | 22,626 |
| Fossil Fuels | 18,833 | 16,832 | 18,301 | 23,600 | 22,410 |
| Coal | 583 | 625 | 708 | 1,091 | 1,066 |
| Natural Gas | 1,107 | 1,906 | 1,430 | 22,346 | 20,973 |
| Petroleum | 17,143 | 14,301 | 16,162 | 162 | 371 |
| CO2 | 1,493 | 1,308 | 1,447 | 1,473 | -781 |
| CH4 | 1.648 | 1.556 | 1.632 | 5.346 | 0.471 |
| N2O | 0.016 | 0.066 | 0.049 | 0.016 | 0.026 |
| GHGs | 1,536 | 1,363 | 1,499 | 1,601 | -763 |
| VOC: Total | 0.297 | 0.758 | 0.332 | 0.365 | 0.263 |
| CO: Total | 0.496 | 0.575 | 0.54 | 4.06 | 3.970 |
| NOx: Total | 8.865 | 9.01 | 8.965 | 1.081 | 0.777 |
| PM10: Total | 0.195 | 0.212 | 0.239 | 0.239 | 0.237 |
| PM2.5: Total | 0.074 | 0.086 | 0.088 | 0.081 | 0.082 |
| Sox: Total | 0.362 | 0.468 | 0.412 | 0.582 | 0.365 |
| VOC: Urban | 0.156 | 0.151 | 0.166 | 0.146 | 0.145 |
| CO: Urban | 0.239 | 0.231 | 0.236 | 2.408 | 2.405 |
| NOx: Urban | 5.242 | 5.222 | 5.236 | 0.314 | 0.307 |
| PM10: Urban | 0.055 | 0.05 | 0.053 | 0.024 | 0.025 |
| PM2.5: Urban | 0.025 | 0.023 | 0.024 | 0.015 | 0.014 |
| Sox: Urban | 0.122 | 0.109 | 0.119 | 0.068 | 0.065 |

**Table 12.**

## Findings

In all but one air pollution emissions category including criteria pollutants, air toxics, and greenhouse gases, CNG exhibited superior and sometimes dramatically superior reductions. CO emissions, both urban and total were greater for CNG. As would be expected, natural gas and methane values were higher, since this is the fuel source from TAD. Better values are needed for production contributions from TAD for these findings to be validated. In general, biodiesel and ethanol showed higher concentrations of emissions and higher energy use than low sulfur diesel.

## Conclusions and Recommendations

- There is considerable material available on energy use and emissions for alternative fuels, but there is difficulty in synthesizing the literature into a coherent picture of the risks associated with each. While there is considerable literature on the subject, there is no consistent standard in reporting the data and difficulty in comparing one study to another because of the wide variations in study parameters related to: region, climate and weather patterns, constituents of concern, health effects, populations, vehicle miles traveled, and equipment and many other factors.

- There appears to be no consistent reporting mechanisms for studying energy and emissions from alternative fuels and no consistent methodology for aggregating data for risks with multiple variables. While gaps still exist in GREET, it offers a good structure for developing such standards.

- There is a strong need for reliable, recent tail pipe emissions data.

- The addition of CNG from renewable feedstock should be considered for future iterations of GREET.

- While gaps in the model prevented the level of confidence in the projections for CNG from renewable resources as with the other fuels, the preliminary data appears to indicate that thermophillic anaerobic digestion is an important technology to investigate for its beneficial energy and emissions profile.

- Future research should be considered as to optimal sizing of a greenhouse facility for an urban area such as Chicago to capture maximum greenhouse gas emissions in conjunction with TAD operations.

.

- Early data on hydrogen indicates that this might also be an important area of research. This technology is likely also compatible with TAD

- The GREET model lends itself well to a benchmarking regimen. As the quality of the data becomes more refined, it can provide direction for improvements in energy and emissions control in the fuels industry. On-going research into new feedstocks, new processing technologies and new approaches can be tested against this standard.

- There is great promise in new technologies. Serious investigation of how to maximize energy efficiency and reduce risk in bringing them on line will answer the challenge of how to continually find ways to improve the model and reduce EHS risks of transportation fuels from cradle to grave.

## Bibliography

M Melendez, J Taylor, J Zuboy, WS Wayne, D Smith, "Emission Testing of Washington Metropolitan Area Transit Authority (WMATA) Natural Gas and Diesel Transit Buses, National Renewable Energy Laboratory, NREL/TP-540-36355, December, 2005

# Addendum to Risk Assessment in Alternative Energy: Is Pond Scum the Answer?

**Sally M. Higgins, CSP CFPS**
**Judy Freeman**

<u>Historical Perspective of Algae as Fuel Source</u>

Consider that 42% of the current US energy market is liquid fuels, 38% is imported (Brown - 237), 25% is used for production of electricity, and 60% of oil is for ground transportation. (Riesling) One is consistently bombarded by news reports expressing our governments concern for national security due to our dependence on oil. Many remember similar concerns during the 1970's. Recent rapid increase in oil prices renewed national interest in algae as a biofuel.

Algae as a fuel source is not a new concept. When one looks at the history of the discussion, algae appears to be an answer we can't seem to believe. Consider that the Mayan and Aztec cultures used algae as a human fuel source. Moving closer to modern day, in the 1950s, NASA began discussions on the concept of algae for fuel. In 1960, concepts emerged on large scale systems of growth ponds for harvesting algae for biomass. In 1976, the Department of Energy's (DOE) predecessor organization was working algae technology to evaluate wastewater treatment/fuel production based on microalgae.(Sheehan -17) The first, federal laboratory dedicated to solar energy development was established in 1978 – Solar Energy Research Institute (SERI), located in Golden, CO. The facility's research focus expanded over the years to encompass the use of plant life for transportation fuels. In the 1980s, DOE initiated the Aquatic Species Program (ASP) to support production of hydrogen. The ASP initially focused on algae growth and use of carbon dioxide from coal power plants.

1982 ASP focused exclusively on high oil algae for biodiesel. In 1987, SERI , now the National Renewable Energy Laboratory (NREL), developed cost estimates for a pilot-scale facility on the Salton Sea in southern California, continuing its work on algal oils for transportation fuels. (Weissman) NREL's researchers were the first to demonstrate the existence of carboxylic acetylcoenzyme A (ACCase), an enzyme key to the synthesis of the molecules desired for production of the lipids (Daniels-3). The NREL project was closed with the much referenced "A Look Back at the US Department of Energy's Aquatic Species Program: Biodiesel from Algae" in 1998, and the belief that the economics of algae as a biodiesel fuel source was not viable (Sheehan-19) Important is to recognize that the report was based on 1998 technologies and the cost of oil at that time. Europe, already paying the higher price for oil, acknowledged the need for biodiesel fuels and now has a substantial commercial enterprise in biodiesel from rapeseed. (Sheehan - 6) Fortunately, the research arena continued the momentum in the US as studies focused on optimizing algal growth and neighboring algae beds to coal burning power plants for carbon dioxide capture.

Today, the desire for biodiesel is its ability to be used in existing diesel engines with minimal to no modifications and that it can be blended at any ratio with diesel fuel. Though initial growth studies focused on open pond algae farms, current work is to use photo bioreactors. GreenFuel Technologies Corp in Cambridge Mass is focused on improving algae that can produce both biodiesel and ethanol using a photo bioreactor. This technology gains control of the variables that can decrease algae production but incurs an increased cost due to capital.

Sandia National Labs has researchers working on algae for biodiesel. Boeing partnered, in 2006, with Virgin Atlantic and GE Aviation to test biofuels from different sources in a joint goal to fly a biofuel propelled 747 (Gonzalez). The ASP closeout report indicated the open race-track pond system was the only economically feasible growth methodology when balanced against the price of oil in 1996. The increase in the price of oil changed this perspective and NREL is looking to return to algae in the coming year.

## Concepts of Algae as Fuel Source

To understand what algae brings to the biodiesel arena, one should consider the concept of plant as fuel. Biomass is plant matter that can be used as solid fuel. It can also be converted to liquid or gaseous form to be used as a fuel.

Microalgae require carbon dioxide to produce the oil-rich biomass. The water environment provides better access to growth resources of water, carbon dioxide and minerals. Algae growth rate is five times that of existing biomass fuel sources (rapeseed, soy and corn) (Brown). Algae grows in less desirable environment – saline, brackish, waste ponds – with the desert southwest as an ideal location due to high salinity of groundwater. Through photosynthesis, algae uses carbon dioxide, water and sunlight to create carbohydrates, oils and proteins.

Algae as a fuel can range from its natural oil being captured for biodiesel fuel, its carbohydrates being processed into ethanol, its protein can be used as animal feed, and its solid mass can become a burning fuel.

## Benefits of Algae as Fuel Source

Algae is one of the most efficient plants at photosynthesis and can achieve growth rates that double volume over night. Added to that is the fact that algae can be harvested day after day as opposed to traditional fuel crops. Technology is advancing to convert form open ponds to tubes that increase surface area limitations of ponds and increase turbulence of algal media.

Already in place is the technology using algae to reduce carbon dioxide emissions from fossil fuels generating plants. The algae beds have the waste carbon dioxide redirected from power plants thereby reducing emissions and increasing algal growth. Forced carbon dioxide on some species can increase bed growth to three doublings per day (Brown-236). GreenFuel bioreactors estimate the cost savings of the algae beds would be 20-40% less than pollutant scrubbers installed for the same facility (Riesling-1) Always seeking a new source, researchers are using carbon dioxide from another carbon dioxide producer – microbrewery in Fort Collins, Colorado to study algae growth.

The algae itself produces oil lipids that can be converted to biodiesel fuel. Researchers estimate that fifty percent of algae's body weight is oil versus twenty percent for present day palm oil (Haag). Brown and Jarvis predicted that we could extract thirty times more oil per unit of growth area compared to existing fuel sources (Brown-237). Researchers measure energy in quads. A quad is equal to that generated by 7.5 gallons of biodiesel fuel and scientists estimate that 500,000 acres of algae would produce 1 quad (Briggs-3). Michael Briggs calculated the current national biodiesel fuel requirements at 19 quads. The corresponding algae farm real estate footprint to meet that quantity is estimated at 15,000 square miles (1/7$^{th}$ the area of Colorado) compared to that of 450 million acres using cropland sources (Briggs-2). Algae is versatile, being able to recycle carbon dioxide to secondary fuel – biodiesel or biomass product. Michael Briggs, professor at UNH, discusses concerns that biodiesel is 5-8% less energy dense than petroleum. But, he adds that algae oil's greater lubricity and more efficient combustion offset this loss to just 2% less energy dense (Briggs-3).

Adding to the reduced footprint required for the algae production farm, the selected land can be those not desired for traditional croplands- alkaline, high salinity, waste contamination. The algae farm does not compete for land presently used for human or animal food consumption. Algae can grow in both human and animal waste streams. Nutrients can be extracted from algae utilizing agricultural runoff waste streams to "re-produce" fertilizer constituents such as nitrogen and phosphorus, essentially recycling the nitrogen and phosphorus waste stream.

Other considerations for algae as a biodiesel source include:

- No net carbon dioxide emissions, no sulfur emissions, it is non-toxic, and highly biodegradable;
- Flashpoint of biodiesel is over 300F;
- Biodiesel studies show better range in vehicle fuel mileage (20 gallons for 1000 miles) (UNH Biodiesel - 1); and
- Algae biomass can then be converted to ethanol for vehicles. A German bioreactor in Bremen is drying the algae brew into cakes which can be processed into biodiesel or ethanol.

## Challenges of Algae as Fuel Source

With all of these positive factors driving the research on algae, the challenges that must be overcome still keep the fuel source as an idea on the horizon. The untreated lipids have high oxygen content and can be too viscous for standard engines. Success was achieved in the 1980's through chemical modifications of the natural oils. (Sheehan-7) What will these modifications bring to the algae resource as potential concern?

With all the options from algae, which energy form will be the primary goal – versus easiest or quickest to obtain? How can we best convert most of algae to biodiesel and rest to biomass fuel or other fuel source options?

How can we grow on large scale? To be successful, we must grow sufficient algae crop to replace petroleum as the transportation fuel. What are the costs of growing the algae in a controlled environment versus in the open pond, besides capital investment? What impact will open ponds have with unwanted strains of algae that can reduce growth or survival of the select high lipid producing algae? Researchers have narrowed the best algae to 300 species labeled ideal for oil source (Sheehan-11). What are the ramifications of genetically engineering algae growth for oil production, since no one species meets all the needs of the technology (Sheehan-14).

Will it be important to controlling sulfur dioxide from coal fired plant emissions from increasing algae pond acidity? Research indicates algae will grow in these undesirable environments. We can extract 70% of the algae oil by simple pressing the algae. How critical is the other 30% if we must add hexane solvent to complete the final removal? What does the solvent bring to the waste streams we want to reduce? Another waste stream to manage is that NOx emissions can be higher in biodiesel engines (Sheehan-19).

The ASP stated "When the time is right, we fully expect to see renewed interest in algae as a source of fuels .."(Sheehan-1) In 1998, DOE expected petroleum costs to remain relatively flat over the 20 year future (Sheehan-21). With the significant increase in the price of oil over the past eighteen months, one may find that the time is right.

## Bibliography


Briggs, Michael. *Widescale biodiesel Production from Algae:* University of New Hampshire, Physics Department, revised August 2004. http://www.unh.edu/p2/biodiesel/article_alge.html.

Brown, Lewis M and Javis, Eric E. *Oil Production by Microalgae in Outdoor Mass Culture*: Biofuels Information Center (B02456), January 1, 1992.

Daniels, Olivier. *An algae-based fuel:* Biofuture No 255, May 2005.

Gonzalez, Angela. *To go green in jetfuel, Boeing looks at algae:* The Seattle Times, August 30, 2007. http://archives.seattletimes.nwsource.com/cgi-bin/texis.cgi/web/vortex/display?slug=boeingenergy30&date=20070829&query=To+go+green+in+jet+fuel

Haag, Amanda Leigh *Pond-Powered Biofuels*: *Turning Algae into America's New Energy:* Popular Mechanics, March 29, 2007.

Riesling, Thomas F. *Cultivating Algae for Liquid Fuel Production:* Permaculture Activists, No. 59 October, 2006. http://oakhavenpc.org/cultivating_algae.htm.

Sheehan, John, Dunahay, Terri, Benemann, John and Roesler, Paul. *A Look Back at the US Department of Energy's Aquatic Species Program – Bio-diesel from Algae Closeout Report*: NREL/TP-580-24-190, July 1998. http://www.nrel.gov/docs/legosti/fy98/24190.pdf.

UNH Biodiesol Group. *Biodiesel vv. Hydrogen*: University of New Hampshire, Physics Department, August 2004. http://www.unh.edu/p2/biodiesel/article_biodiesel_vs_hydrogen.html

Weissman, J.C. and Goebel, R.P. *Desing and Analysis of Pond Systems for the Purpose of Producing Fuels:* Final Report to the US Department of Energy, 1987.