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Alternatives to Diesel Fuel in California—Fuel Cycle Energy and Emission Effects of Possible Replacements Due to the TAC Diesel Particulate Decision

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ABSTRACT

Limitations on petroleum-based diesel fuel in California could occur pursuant to the 1998 declaration by California's Air Resources Board (CARB) that the particulate matter component of diesel exhaust is a carcinogen, therefore a toxic air contaminant (TAC) subject to the state's Proposition 65. It is the declared intention of CARB *not* to ban or restrict diesel fuel, *per se*, at this time. Assuming no total ban, Argonne National Laboratory (ANL) explored two feasible "mid-course" strategies, each of which results in some degree of (conventional) diesel displacement. In the first case, with substantial displacement of compression-ignition by spark-ignition engines, diesel fuel is assumed admissible for ignition assistance as a pilot fuel in natural gas (NG)-powered heavy-duty vehicles. Gasoline demand in California increases by 32.2 million liters (8.5 million gallons) per day overall, about 21 percent above projected 2010 baseline demand. Natural gas demand increases by 13.6 million diesel liter (3.6 million gallon) equivalents per day, about 7 percent above projected (total) consumption level. In the second case, compression-ignition engines utilize substitutes for petroleum-based diesel having similar ignition and performance properties. For each case we estimated localized air emission plus generalized greenhouse gas and energy changes. Fuel replacement by di-methyl ether yields the greatest overall reduction in NOx emissions, though all scenarios bring about PM_{10} reductions relative to the 2010 baseline, with greatest reductions from the first case described above and the least from fuel replacement by Fischer-Tropsch synthetic diesel. Economic implications of vehicle and engine replacement were not formally evaluated.

Key words: air quality regulation, diesel fuel alternatives, internal combustion, regulated emissions, greenhouse gases

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BACKGROUND OF THE ISSUES

On August 27, 1998, the California Air Resources Board (CARB) officially declared the fine particulate matter component of diesel exhaust a human carcinogen (at any concentration) and therefore subject to measures designed to reduce or eliminate its potential threat to public health as a toxic air contaminant (ARB, 1998b). This declaration was more limited than an earlier proposal in California to declare whole diesel exhaust as a toxic substance, irrespective of the constituent properties of the fuel itself. The flexibility afforded by the actual declaration enables the state to advance initiatives, in conjunction with trucking and other users of diesel fuel, both to clean up the harmful constituents of diesel fuel and to explore its modest to vigorous substitution by alternative fuels considered more benign. This paper examines two candidate strategies to realize this initiative with respect to the full fuel cycle energy and emissions effects they would have if fully implemented by the year 2010.

In its resolution of 8/27/98, CARB declares that a risk management process will be undertaken to determine exactly what steps *are* necessary to protect the health and safety of the public from diesel particulate as a toxic air contaminant. These steps may include, but are not necessarily limited to, full implementation of all existing regulations controlling diesel particulate exhaust (from any combustion source) plus selective incremental limitations on source categories found to be more detrimental to public health. It is the declared intention of CARB *not* to ban or restrict diesel fuel, *per se*, at this time. Task forces have been organized to evaluate and prepare recommendations on various mitigating technology and fuel options. However, at present, only (largely voluntary) good-will efforts are underway to accelerate transition from diesel to more benign substitute heavy vehicle fuels, and environmental activist groups continue to seek an outright ban on diesel fuel use in California and other populous states, such as New York. More proactive pursuit of amelioration of diesel particulate generation and exposure is probably needed. At the request of the U.S. Department of Energy, researchers at Argonne National Laboratory (ANL) identified two "mid-course" strategies that, among others, may be considered feasible. (Because ongoing discussions at the time that the work was undertaken emphasized *replacements* for conventional diesel, strategies selected for analysis explicitly excluded changes to conventional diesel fuel itself--e.g., total removal of sulfur and/or aromatics--that might directly respond to California's health concerns.) They are:

1. Increased penetration of natural gas and greater gasoline use in the transportation fuels market, to the extent that key compression-ignition (CI) applications revert to spark-ignition (SI) engines.
2. New specifications requiring diesel fuel reformulation based on more detailed investigation of exhaust products of individual diesel fuel constituents. This could increase the penetration into the marketplace of Fischer-Tropsch (F–T) synthetic diesel fuel from natural gas and, eventually, di-methyl ether (DME) and possibly bio-diesel as CI fuels, albeit at premium cost and lower full-fuel-cycle efficiency.

Each of these alternatives seeks to eliminate the aromatic (mono- and polycyclic) component of organic particulate emissions because part of the information driving CARB's decision was that diesel exhaust particulate is known to transport carcinogenic organic species such as benzene. Thus, each case results in some degree of (conventional) diesel displacement by straight-chain alternatives. We define these cases based on the size and composition of each affected California fleet.

Advanced Displacement Case. For the case in which diesel fuel reformulation or replacement proves an unsuitable option for many key applications, natural gas and propane make inroads in

CI heavy-duty truck and locomotive propulsion. Otherwise, the fleet (especially the lighter end) switches to SI engines. Here ANL examines the magnitude of changeover in vehicle populations to the year 2010 and the resulting change in petroleum energy consumption and emissions. Although the state of knowledge in the area is rapidly evolving, we look at the expected changes in emissions of primary and secondary particulate matter that massive shifts to gasoline- and (potentially) CNG-fueled SI engines could produce. These projections take into account in all cases, including the two below, the present and future emission standards already legislated (as of 8/1/99) for application in California.

Replacement Fuel Cases. Under somewhat less stringent cases, the compression ignition engine utilizes diesel substitutes such as Fischer-Tropsch or DME that, though expensive to produce and use per feedstock joule (or Btu), may be deemed acceptable fuels under California regulation. (However, at present, neither the characteristics nor carcinogenicity of particle emissions from combustion of F-T diesel or DME is well understood). Replacement Case A assumes 100% substitution of conventional diesel by F-T, while Case b assumes this replacement to be by DME. Although a replacement case assuming significant penetration of bio-diesel was considered, it was not evaluated for this study because of high distribution and purchase cost penalties and its likelihood of increasing secondary fine particulate formation as well as primary ozone precursor production due to its increased NOx emissions.

SCENARIO ASSUMPTIONS AND METHODOLOGY

Two sets of strategies cover the cases introduced in the preceding section. In each case, the strategy's outcomes must be indexed to a base case energy use and emissions forecast to the year 2010 for California that sets the output requirements for all alternative futures departing from this baseline. Thus, the three cases examined in this study are defined as follows:

Base Cases 1995 & 2010 - Energy & emissions data projected from data for 1990 – 1995 on the basis that forecasted activity levels and requirements do *not* change.

Advanced CI Displacement Case*: restricts the use of diesel fuel to "pilot" applications that allow continued but limited operation of CI engines.* The following changes occur.

a) All medium-duty (MD) and heavy-duty (HD) trucks, and buses equal to or greater than 8.4 m (27.5 ft.) in length, use compressed natural gas (CNG) as a fuel in spark ignition (SI) engines on a 1 for 1 bus replacement basis; buses less than 8.4 m operate with gasoline engines. Representative converted or production truck tractor and bus engines operating on appropriate test cycles were used to compute the effects of this change. Locomotives and vessels employ a dual fuel propulsion system using liquefied natural gas (LNG) with ignition pilot diesel, operating under California duty cycle conditions. Again, a representative engine for this application was used for computation.

b) All other mobile applications use gasoline engines.

Replacement Fuel Cases A and B*: replaces all diesel fuel in CI engines on a 100-percent basis with either (A) Fischer-Tropsch process (F-T) diesel made from NG or (B) di-methyl ether (DME) made from NG.* In these cases, diesel vehicles and engines are not replaced except through natural turnover (as in the base case), but may need to be modified to accommodate some properties of the respective replacement fuel.

Base Case Energy Use and Emissions Estimates for the Years 1995 and 2010

The sources of diesel exhaust emissions discussed in this paper include all diesel source classes categorized in emissions inventories prepared by the California Air Resources Board's (ARB, 1997a, 1997b). After collection of emissions and energy use data from ARB inventories as well as supplementary sources, our complete menu of diesel-fueled source types for the 1995 and 2010 base years was as follows.

- Mobile Sources (diesel & gasoline vehicles listed separately)
  - On-Road Vehicles: Light-duty passenger cars; Light-duty (LD) trucks; Medium-duty (MD) trucks; Heavy-duty (HD) trucks; Urban buses
  - Off-Road Vehicles: Ships; Trains; Mobile equipment; Farm equipment; LD non-farm equipment; HD non-farm equipment; Refrigeration equipment
- Stationary Area Sources (diesel only)
- Stationary Point Sources (diesel only)

Each of these source classes is briefly discussed in turn below. It should be noted that the data used in this study become increasingly uncertain as the discussion progresses through the list of source classes. In all cases, California-specific emission factors for these sources, incorporating the effect of present and future California-specific emission controls by source category, were employed in emissions calculations for regulated pollutants (CO, ROG, NO_x). Energy use and emissions for the prototype large engines discussed are based on measurement data from testing of those units. The projected inventory for the affected source categories in year 2010 is shown in Table 1.

On-Road Mobile Sources--Cars and Trucks

The base case data for this source category came directly from the statewide totals for the California Vehicle Emissions Ozone Planning Inventory (ARB, 1997a, 1997b), except:

- The breakdown by engine displacement is based on data from the 1992 Truck Inventory and Use Survey (TIUS) database for the State of California (TIUS, 1992). The separation by displacement (percent in each category) was assumed to be applicable in any projection year.
- Carbon dioxide (CO_2) emissions were calculated using molecular weight percent carbon by fuel and backing out the carbon monoxide, reactive organic gas, and soot components. (CO_2 results were consistent with the limited data given in the California Vehicle Emissions Ozone Planning Inventory.)
- The sulfur dioxide (SO_2) emissions were calculated by applying fuel weight percent sulfur. The resulting SO_2 values were also consistent with the limited inventory data.
- N_2O and CH_4 emissions were calculated using emission factors estimated by Delucchi (1997) and U. S. EPA (1998).
- The fuel economies for the HD gasoline with catalysts and diesel for 1995 and the MD and HD gasoline with catalysts and diesel trucks for 2010 were derived from the TIUS inventory data. All other fuel economy values were calculated as the ratio of distance traveled to fuel consumed.

Fuel economy values generally did not show the diesels to be more efficient than the gasoline-powered MD and HD trucks. This may have resulted from the TIUS' not explicitly accounting for the differences in loads and driving cycles between gasoline and diesel trucks.

On-Road Mobile Sources--Urban Buses

The base case data for this source category are also directly from the statewide totals for the California Vehicle Emissions Ozone Planning Inventory (1997b). We estimated from available data (FTA, 1997; APTA, 1996) that 28% of the total population of the present bus fleet is less than or equal to 8.4 m (27.5 ft) in length (mostly demand-response, para-transit vehicles), with the remainder greater than 8.4 m (mostly standard transit buses). The smaller buses are assumed powered 50% by gasoline and 50% by diesel, with large buses assumed to be all diesel-powered (this ignores the fact that some buses are already powered by CNG, LNG, or LPG in dedicated- or dual-fuel mode).

Mobile Sources - Off-Road

Locomotives

The vast majority of locomotives in the United States are of the diesel-electric type. They range in power rating from about 1864 kW (2500 hp) to the newest 4474 kW (6000-hp) units. Typical duty cycles have been defined for different types of locomotive service. Our analysis assumed a California locomotive fleet composition developed for ARB by Engines, Fuels, and Environmental Engineering, Inc. (EF&EE, 1993). Daily locomotive fuel use rises from 2.26 x 10^6 liters (5.97 x 10^5 gallons) in 1995 to 3.00 x 10^6 liters (7.93 x 10^6 gallons) in 2010, in accordance with recent data and projections on diesel fuel sales to railroads (DOE/EIA, 1996). Emissions remain at mid-1990s levels, as reported in the EF&EE study, as changes in emission control technology compensate for growth in locomotive populations and fuel use.

Vessels

Information on marine vessel fuel use, emissions and vehicle population for California is extremely limited. Estimates of diesel fuel use were based on diesel sales to "vessel bunkering" (which includes sales to commercial and private boats but excludes sales to the military) and "military" in California (DOE/EIA, 1996). Our 2010 fuel use estimate is based on a linear projection of fuel sales for the years 1992 & 1996, with emission data adopted from ARB (1998a) for 1995 values. Emissions for 2010 were estimated from a linear projection of ARB's 1990 & 1995 data in the 1998 ARB report.

Mobile Farm Equipment

Fuel use and emission data for this source class were available for gasoline and diesel-powered units from ARB (1995b), with growth factors for the diesel sources available from the same reference for the years 1990 to 2010.

Mobile Industrial/Commercial Equipment (non-farm equipment)

Fuel use and emission data for gasoline and diesel-powered units in this source class were also available from ARB (1995b). Growth factors for the diesel sources were available from the same reference for the years 1990 to 2010. ARB divides this source category into light duty (LD) & heavy duty (HD) equipment, setting the dividing line at 130 kW (175 hp). Consistency checks indicated that data for this source category from this reference were highly suspect. For example, diesel fuel use by the Mobile Industrial/Commercial Equipment category was 31,530,000 liters (8,330,000 gallons)/ day. The corresponding fuel sales figure from DOE/EIA (1996) was 1,590,000 liters (420,000 gallons)/day—one-twentieth the ARB estimate. If the ARB reference were correct, this source category would consume more diesel fuel than all the on-road vehicles. It was decided to reduce the ARB diesel fuel use figures for both LD and HD equipment by a factor of ten. Consistency checks on emissions taking into account fuel use ratios indicated that, while HD emissions appeared to be consistent with other source categories, the LD equipment emissions appeared to be a factor of ten to twenty too high relative to the HD equipment and the farm equipment category. It was decided that the latter emissions should also be reduced by a factor of ten. These reductions in fuel use for the LD equipment and in fuel use for the HD equipment category are intended to bring these source data into concurrence with the other source data *for the purposes of this study only.*

Mobile Refrigeration Equipment

This equipment category consists mostly of diesel-fueled engines, according to ARB (1995b). ARB's fuel use and emission data for this source class and growth factors for the years 1990 to 2010 were available for both gasoline and diesel-powered units. No adjustments of the data for this category were deemed necessary.

Stationary Point & Area Sources

These two source categories were the least well delineated in the literature. Emission data for both source categories for the years 1990 and 1995 were taken from ARB (1998a), and linearly projected to the year 2010. Diesel fuel use at point sources was estimated from DOE/EIA fuel sales data, assuming that point sources and power plants were approximately synonymous. Since detailed information about area source populations and types of fuel used was not available, an alternative estimation scheme had to be devised. Base year fuel use was estimated from the inventory's sulfur emission totals as if these emissions had been generated from combustion of legal California off-road ("red") diesel fuel, the fuel used by other off-road sources such as farm and light duty industrial and commercial equipment.

Advanced CI Displacement Case

On Road Vehicles

Catalytically controlled gasoline-powered vehicles replace light-duty diesel powered highway vehicles. MD and HD trucks with diesel engine displacements < 8 L were replaced with gasoline engines, while those with displacements ≥ 8 L were replaced by SI engines burning CNG. Fuel use comparison of our representative CNG-fueled engines with a control vehicle on appropriate speed and load emission test cycles indicated a 30% reduction in fuel economy after accounting for the difference in lower heating value. (It is acknowledged that this is a very conservative assumption with respect to projections of the state of CNG propulsion technology in 2010. CNG has been successfully demonstrated in compression ignition engines, and its use in this application rather than SI would help close the fuel economy gap although, if currently available engines are a reliable indicator, with negligible benefit for reduction of fine particle emissions.) The larger engines tend to be used on longer-haul trips, and test results have shown a higher average fuel economy drop for these duty cycles (NREL, 1996). Diesel buses ≤ 8.4 m in length were replaced with gasoline-powered units. Buses > 8.4 m in length were assumed to be all diesel-powered and were replaced with SI engines burning CNG, and emissions from a low-speed emissions test cycle were employed in this case.

Off-Road Sources

Locomotives & Vessels

Engines for these applications are dual-fueled (LNG + pilot diesel) and assumed to operate on the California duty cycle. Such engines were field-tested by Burlington Northern Railroad in freight service (Burlington Northern Railroad, 1998). It was assumed that pilot diesel was used 6% of the time and the ratio of efficiencies was 1.0459 (avg. of 1.032 and 1.06, from Olsen, 1997). The change in emissions from both locomotives and vessels were estimated by taking a simple ratio of duty-cycle weighted emission factors times the base case emissions.

Mobile Equipment

Units in this category that use diesel fuel in CI engines were replaced by gasoline engines burning gasoline. The estimation procedures used here are identical to those described for the base case.

Stationary Diesel Engines

As no details were available on these engine populations, it was assumed that dual fuel engines operating at full load could replace these engines. The same representative engines used in the base case were assumed here.

These categories represent the full slate of diesel combustion activities that are assumed to be displaced. Thus, any portion of the California area source emission inventory attributable to diesel combustion in, for example, small residential and commercial space heating applications was excluded from our analysis.

Fuel Replacement Case A

There are three alternative fuels that can be relatively easily used in conventional CI engines: biodiesel, Fischer-Tropsch (F-T), and di-methyl ether (DME). All three offer some emission benefits. Both F-T and DME can be manufactured from natural gas and are therefore not limited by feedstock availability. Biodiesel, on the other hand, is produced from vegetable (and some waste animal) oils whose supply for non-nutritional uses is presently quite limited, cost per gallon very high, and increased NOx emission relative to conventional diesel documented. (We did not include bio-diesel in our replacement analysis due to its associated distribution and cost penalties and its likelihood of increasing secondary fine particulate formation as well as primary ozone precursor emissions). Of these candidates, F-T is most compatible with existing distribution and fueling infrastructure for conventional diesel, and only minimal adjustments are required to obtain optimal performance from existing CI engines. Its physical properties are very similar to number 2 diesel fuel, and its chemical properties are superior in that the F-T process yields middle distillates that, if correctly processed (as through a cobalt-based catalyst), contain no aromatics or sulfur compounds. Thus, only F-T and DME were considered feasible near-term substitutes in our analysis.

For Case A, F-T replaces conventional diesel 100 percent. The net effect at the tailpipe is that all criteria pollutants are reduced relative to the 2010 baseline. GHGs are slightly increased due primarily to test results measuring higher (+4 g/bhp-h) CO_2 emissions from a typical HDD engine (DDC Series 60) operating on F-T compared to results for the same engine operating on California reformulated diesel.

Fuel Replacement Case B

DME is a light fuel, similar to propane. It is a gas at temperatures above -25°C and can be stored in the liquid state under modest pressure (its vapor pressure at 20°C is about 5 atm.). It has an auto-ignition temperature slightly lower than that of diesel (allowing compression ignition at nearly the same compression ratio) and a slightly higher cetane number (permitting good startability), making it a good candidate for diesel substitution. However, currently available fuel injection systems are not suitable for DME. Although infrastructure exists for propane distribution that might be adaptable to DME, substantial expansion of scale would be necessary to achieve adequate substitution for diesel.

For Case B, DME replaces conventional diesel 100 percent. With the exception of CH_4 & CO, all end-use emissions are reduced by the substitution of DME for diesel. The reduction of ROG is similar to that for F-T, but NOx reduction is substantially greater. The CO_2 emissions are lower, consistent with the lower carbon weight fraction of DME.

FULL CYCLE IMPACTS: FUEL PRODUCTION, DISTRIBUTION, AND END USE

Over the life of a given quantity of transportation fuel, energy is consumed and emissions generated during upstream (pre-end use) activities, as well as during vehicular (end use) activities. Also associated with these activities is the production of the so-called greenhouse gases (GHGs), implicated as agents of global warming. A fuel-cycle model, called the Greenhouse gas, Regulated Emissions and Energy use in Transportation (GREET) model, has been developed at Argonne National Laboratory to estimate fuel-cycle energy use and emissions of various transportation fuels (Wang, 1999). For a given transportation fuel, a fuel cycle includes these stages: primary energy recovery; primary energy transportation and storage; fuel production; fuel transportation, storage, and distribution; and vehicular fuel combustion. The GREET model takes into consideration all emissions and energy-consuming sources along the pathway from feedstock recovery (say, as natural gas) through feedstock transport, production, distribution, and end use (combustion) of a given fuel.. The model calculates fuel-cycle grams-per-mile (g/mi.) emissions and Btu-per-mile (Btu/mi.) energy use for each fuel cycle. It includes emissions of five criteria pollutants (volatile organic compounds, carbon monoxide, nitrogen oxide, particulate matter with size smaller than 10 microns, and sulfur oxides) and three GHGs (methane [CH_4], nitrous oxide [N_2O], and carbon dioxide [CO_2]). The three GHGs are further combined with their global warming potentials (GWPs) as CO_2-equivalent GHG emissions (with values of 1.0, 21.0, and 310.0 for CO_2, CH_4, and N_2O, respectively, as adopted by the Intergovernmental Panel on Climate Change and the Kyoto Protocol).

Figure 1 shows the GREET-calculated changes in fuel use by fuel type in year 2010 (relative to the baseline environmentally-regulated "business-as-usual" projections shown in Table 1) attributable to the advanced CI displacement case. For the two replacement cases, all replacement fuel is a synthetic (either F-T or DME) and therefore does not represent competitive demand in the market for *existing* fuels. Figures 2 - 4 show respective changes in end use emissions due to the (one) displacement and (two) replacement cases, while Figures 5 - 6 compare the effects over the full fuel production and combustion cycle on, respectively, energy demand and total GHG emissions. Figure 5 shows that the respective energy requirements of F-T and DME production are quite substantial given current production plant factors. All cases result in net GHG emission increases relative to 2010 baseline, due primarily to fuel production processes for which it has been assumed that carbon sequestration practices are not included. The lowest net increases come from advanced CI displacement and the highest by F-T replacement.

It can be seen that fuel replacement by DME yields the greatest overall reduction in NOx emissions. F-T results in only modest net NOx reductions, due to its limited end use emission reduction potential for NOx and its high production emissions. Depending upon production plant location economics, these emissions may or may not occur in California. All cases bring about PM_{10} reductions relative to the 2010 baseline, the greatest from advanced CI displacement and the least from fuel replacement by F-T.

CONCLUSIONS AND DISCUSSION

It is anticipated that California will move forward to expedite substitution of (conventional) diesel fuel by formulations that can meet the challenge posed by the CARB's August, 1998 decision on diesel particulate toxicity—that is, fuel formulations characterized by implicitly lower particulate mass in the exhaust. (California has already lowered the maximum permitted sulfur weight fraction of on-road diesel fuel to 50 PPM, and is considering further cuts to both on- and off-road sulfur limits.) We have examined two possible outcomes of active pursuit of this strategy out to the year 2010, but by no means do these outcomes represent an exhaustive set of possible policy results.

Our advanced compression-ignition engine displacement case has mixed effects. With diesel pilot fuel admissible for NG-powered heavy-duty vehicles, gasoline demand only increases by 32 million liters (8.5 million gallons) per day overall, about 21 percent above projected 2010 baseline demand. Natural gas demand increases by 13.6 million diesel liter (3.6 million gallon) equivalents per day, about 7 percent above projected (total) consumption level. Of this total, the CNG demand represents an incremental 5.4 million standard cubic meters (192 million SCF). It was not analyzed whether this increase in daily flow could be supplied 100 percent by domestic pipelines, and thus NG importation may be necessary, initially from Canada and Mexico but then from abroad. End-use NO_x, SO_x and PM_{10} are all reduced, but GHGs (from combustion activity) increase.

Each of the replacement case alternatives has unique characteristics. The Fischer-Tropsch case (Case A) results in an almost 76-million liter (20-million gallon) demand for that synthetic, including its use as process fuel. This represents an increase of 26.5 million diesel-liter (7 million diesel-gallon) equivalents over the quantity of diesel displaced. There is no indication that production capacity to meet that level of demand can be on line by 2010, and safety concerns already exist about present capacity due to a 1997 explosion at the Bintulu plant in Malaysia. With the required capacity available, current indications are that all air emissions of priority pollutants will decline while GHG emission rises. Reduction in SOx is especially dramatic; fine particulate less so. The DME case (Case B) requires less diesel-equivalent energy for replacement fuel (64 million liters or 17 million gallons) and results in a lower GHG increase and greater PM_{10} and NO_x decreases than Fischer-Tropsch. However, it increases CO relative to baseline, especially from heavy-duty trucks (in which category there is currently a gap between actual and permissible CO emission rates). Again, the existence of DME production capacity to meet such a demand by 2010 is highly speculative and current and projected petroleum prices appear unlikely to create incentives sufficient to drive a rapid pace of capacity expansion.

Our evaluation did not quantify the economic effects of replacing or modifying diesel engines or the impact of new fuel costs. Recent estimates of the start-up and operating costs of new production capacity for both F-T and DME range between $40-$200 million, depending on demand and location (Hansen, 1995; Singleton, 1997). Although no consensus exists, there is belief in some quarters that the cost to refiners of removing sulfur and aromatics and controlling for carbonaceous combustion emissions from conventional diesel fuel, with no sacrifice in cetane number, will become prohibitive over the long term given the increasing share of crude petroleum that is proving to be high in carbon and/or relatively sour. In this case, investment in F-T production capacity could be more attractive economically than intensive refinery processing of conventional fuel. Optimism about a parallel future for DME has yet to be expressed because that alternative will require changes to engine, dispensing, and distribution infrastructure as well as an (initially) high cost of production (in which financing of added production capacity is subsumed). There may be a feasible demand/cost space within which a combination of the values of key variables relating to crude feedstock price and quality, product quality required for vehicle emission reductions, improvement in F-T process yields, and F-T production capacity on line makes a strong economic case for the gas-based synthetic as replacement. However, neither that space nor the variable values have yet been identified. Meanwhile, a near-term option for market acceptance of F-T that would utilize both existing and planned production capacity is its blending with conventional diesel as an agent to reduce sulfur and aromatics (with NOx and PM likely controlled by exhaust treatment).

In summary, ANL found that no single case yields the least combined impact for all of the important components of emissions and energy use. The advanced CI displacement case, which uses a substantial amount of NG, is perhaps the best choice if it is desired to minimize overall negative effects on energy and the environment.

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REFERENCES

American Public Transit Association--APTA (1996) 1996 Transit Fact Book.

Air Resources Board (California)—ARB (1995) Emission Inventory Procedural Manual, v. 3, Methods For Assessing Area Source Emissions. Sacramento, CA.

Air Resources Board (California)—ARB (1997a) Emissions by category, 1995 estimated emissions, statewide; emissions by category, 2010 forecasted emissions. Sacramento, CA. [URL http://www.arb.ca.gov/ceidars/emssumcat.query?F_DIV=O&F_YR=1995&F_AREA=CA]

Air Resources Board (California)—ARB (1997b) Predicted California vehicle emissions, ozone planning inventory, MVEI7G emission factors scenario: computer model run date: 5/27/97. Sacramento, CA [URL http://www.arb.ca.gov/msei/pubs/sw_scab.pdf].

Air Resources Board (California)—ARB (1998a) Proposed Identification of Diesel Exhaust as a Toxic Air Contaminant: Part A, Exposure Assessment. Sacramento, CA (23 Feb.).

Air Resources Board (California)—ARB (1998b) Resolution 98-35, August 27, 1998.

Burlington Northern Railroad (1998) The natural gas locomotive at Burlington Northern Railroad, Pacific Rim TransTech Conference, Seattle, WA (June).

Delucchi, M. A. (1997) Emissions of non-CO2 greenhouse gases from the production and use of transportation fuels and electricity, report no. UCD-ITS-RR-97-5, Institute of Transportation Studies, University of California at Davis.

Department of Energy, Energy Information Administration--DOE/EIA (1996) Fuel oil and kerosene sales, 1996 [URL http://www.eia.doe.gov/oil_gas/petroleum/pet_frame.html].

Engine, Fuel, and Emissions Engineering, Inc.--EF&EE (1993) Controlling locomotive emissions in California, prepared for California Air Resources Board, Oct. 13, 1993.

Environmental Protection Agency--EPA (1998) The draft 1998 inventory for U.S. greenhouse gas emissions and sinks (1990-1996). Washington, DC.

Federal Transit Administration--FTA (1997) New bus model testing program, 12 December 1997. [URL http://www.pti.psu.edu/open/fta/ftaopen.htm].

Hansen, J.B., et al.—Hansen (1995) Large scale manufacture of dimethyl ether—a new alternative diesel fuel from natural gas, SAE technical paper 950063, Society of Automotive Engineers International, Warrendale, PA (Feb.).

National Renewable Energy Laboratory—NREL (1996) Alternative-fueled truck demonstration natural gas program: Caterpillar G3406LE development and demonstration, Golden CO [URL http://www.afdc.nrel.gov/demoproj/hdv/hdvrpts/vonsec1.html].

Olsen, L.E. (1997) Personal comm. to L. Torres, EMPRESAS POLAR, 20 May 1997.

Singleton, A.H.—Singleton (1997) Advances make gas-to-liquids process competitive for remote locations, Oil and Gas Journal, Aug. 4, 68-72.

Truck Inventory and Use Survey (Bureau of the Census, U.S. Department of Commerce)--TIUS (1992) California truck registration and usage, summary of California based trucks by GVW class, fuel type, and engine displacement, 1992, CD-ROM issued June, 1995.

Wang, M.Q.—Wang (1999) GREET 1.5 – Transportation Fuel-Cycle Model, Vol. 1: Methodology, Development, Use, and Results, Argonne National Laboratory report no. ANL/ESD-39, Vol. 1 for U.S. Department of Energy, Argonne, IL (Aug.).

Table 1. Projected Baseline Fuel Use and Emissions Inventory for Affected Source Categories in California in Year 2010

Source Type	Number Registered (thousands)	Number with Displacement < 8L (thousands)	Number with Displacement >= 8L (thousands)	Daily VKT by Units w/Disp. < 8L (thousands)	Daily VKT by Units w/Disp. >= 8L (thousands)	Daily Fuel Use 10[illegible] liters (gals)	Fuel Economy km/l (mpg)	Daily Pollutants Emissions (Metric tons/day) in year 2010: ROG	CO	NOx	CO_2 (10[illegible] tons)	PM10	SOx	N2O	CH4
Autos/Motorcycles															
Gasol-Non Cat	30.22	30.22		1,601		70 (18.52)	22.87 (53.73)	8.98	65.01	3.44	0.03	0.01	0.03	0.03	0.19
Gasol-Cat	18,430.00	18,430.00		882,697		78,461 (20,757)	11.99 (28.16)	214.10	2519.52	276.53	177.20	14.35	38.46	37.46	28.09
Diesel	29.30	29.30		668		53.52 (14.16)	12.48 (29.31)	0.22	1.67	0.74	0.14	0.15	0.03	0.00	0.01
Auto Total	18,489.52										177.37				
LD Trucks < 6 klb															
Gasol-Non Cat	0	0		0		0		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gasol-Cat	8,596.00	8,596.00		446,337		47,325 (12,520)	9.43 (22.16)	81.07	1198.85	198.29	107.53	6.78	23.31	25.77	13.33
Diesel	6.24	6.24		142		12.44 (3.29)	11.39 (26.75)	0.05	0.31	0.15	0.03	0.04	0.01	0.003	0.001
LD Truck Total	8,602.24										107.57				
MD Trucks 6 to 14 klb															
Gasol-Non Cat	11.37	11.37		367		151.05 (39.96)	2.43 (5.71)	0.45	4.70	1.76	0.34	0.02	0.07	0.11	0.05
Gasol-Cat	2,043.00	2,043.00		122,461		26,982 (7,138)	5.58 (13.10)	28.66	469.74	112.24	61.70	3.10	13.34	40.48	6.40
Diesel	342.90	251.13	91.77	13,781	4,353	6,468 (1,711)	6.09 (14.30)	1.32	51.87	35.29	17.61	2.60	4.84	0.34	0.34
MD Truck Total	2,397.27										79.65				
HD Trucks >14 klb															
Gasol-Non Cat	3.53	3.53		124		51.64 (13.66)	2.40 (5.64)	0.21	2.09	0.93	0.12	0.01	0.03	0.07	0.02
Gasol-Cat	46.95	46.95		4,869		2,007 (531)	3.62 (8.50)	2.04	48.86	14.00	4.57	0.24	0.99	2.94	0.36
Diesel	427.40	223.17	204.23	24,357	40,871	23,190 (6,135)	2.60 (6.10)	33.15	312.08	318.95	62.85	13.20	17.12	0.61	0.97
HD Truck Total	477.88										67.53				
Diesel Buses	6.88			1,586		568.36 (150.36)	2.79 (6.56)	1.75	1.66	13.66	1.55	0.08	0.43	0.04	0.06
On-Road Diesel Tot.	*812.72*	*309.84*	*296.00*	*40,334*	*45,224*	*30,292.2 (8,013.8)*		*34.73*	*365.94*	*355.13*	*80.64*	*13.98*	*22.00*	*0.99*	*1.38*
Locomotives[8]	1,445.62					2,992.17 (791.58)		6.36	19.09	127.27	8.13	2.73	19.87	0.02	0.13
Line haul	775.76														
Local & switcher	669.86														
Vessels[7]						2,611.41 (690.85)		7.50	7.13	29.43	7.10	3.08	38.69	0.02	0.11
HD Farm Equip (G)[1]						340.28 (90.02)		8.00	234.68	4.43	0.40	0.16	0.16	0.00	0.00
HD Farm Equip (D)[1]						2,144.13 (567.23)		10.32	33.62	105.99	5.76	6.77	13.95	0.05	0.10
LD Non-farm equip (G) < 175 hp[1]						1,180.95 (312.42)		25.60	759.32	10.83	1.47	0.02	0.59	0.00	0.00
LD Non-farm equip (D) <175 hp[1,2,3]						492.23 (130.22)		2.34	7.69	22.88	1.32	1.49	3.21	0.04	0.03
HD Non-farm equip (G) =>175 hp[1]						460.78 (121.90)		0.92	26.02	0.56	1.02	0.01	0.23	0.00	0.00
HD Non-farm equip (D) =>175 hp[1,2]						3,389.07 (896.58)		8.70	24.05	112.96	9.20	5.29	22.37	0.08	0.15
Refrigeration units (D)[1,4]						254.62 (67.36)		1.51	5.36	12.15	0.68	0.93	1.65	0.18	0.03
Mobile off-road total (diesel only)						*11,883.7 (3,143.8)*		*36.74*	*96.95*	*410.68*	*32.20*	*20.28*	*99.73*	*0.39*	*0.55*
Stationary Equipment (diesel only)															
Point sources[5]						32.24 (8.53)		0.35	0.67	2.58	0.09	0.20	0.20		
Area sources[6]						519.86 (137.53)		1.72	11.73	33.72	1.39	3.49	3.26		
Stationary equipment total (diesel only)[9]						*552.11 (146.06)*		*2.06*	*12.40*	*36.30*	*1.47*	*3.69*	*3.47*		

[1]Data (from ARB,9/95) for year 1990 and growth factors (from ARB,9/95)for the years 1990 to 2010 for diesels only.

[2]To reconcile with state fuel use data (DOE/EIA, 1996), LD & HD fuel use values from ARB reduced by a factor of 10

[3]For consistency with the other sources in the mobile equipment category, the emissions were reduced by a factor of 10

[4]For convenience, refrigeration units grown at farm equip. rate.

[5]To estimate diesel fuel used, assumed point sources = electric utilities (fuel use data from DOE/EIA, 1996)

[6]Fuel use estimated from sulfur emissions, assuming area source fuel had same sulfur content as farm & LD non-farm equipment.

[7]Emissions from vessels projected using 1990 & 1995 data from ARB, 1/23/98. Fuel use estimated from sulfur emissions.

[8]Locomotive population & fuel use projected from fuel use data (DOE/EIA, 1996). Emissions unchanged from 1995, consistent with assumed emission factor reductions assumed by ARB, 11/16/97.

[9]Emissions from CARB 2-23-98

Figure 1. Advanced CI Displacement Case: Increase in End-Use Demand for Currently Available Fuels (Within California)—10^6 liters/day

Figure 2. Advanced CI Displacement Case: 2010 End-Use Emission Changes (Within California)—Metric tons/day

Figure 3. Fuel Replacement Case A: 2010 End-Use Emission Changes (Within California)—Metric tons/day

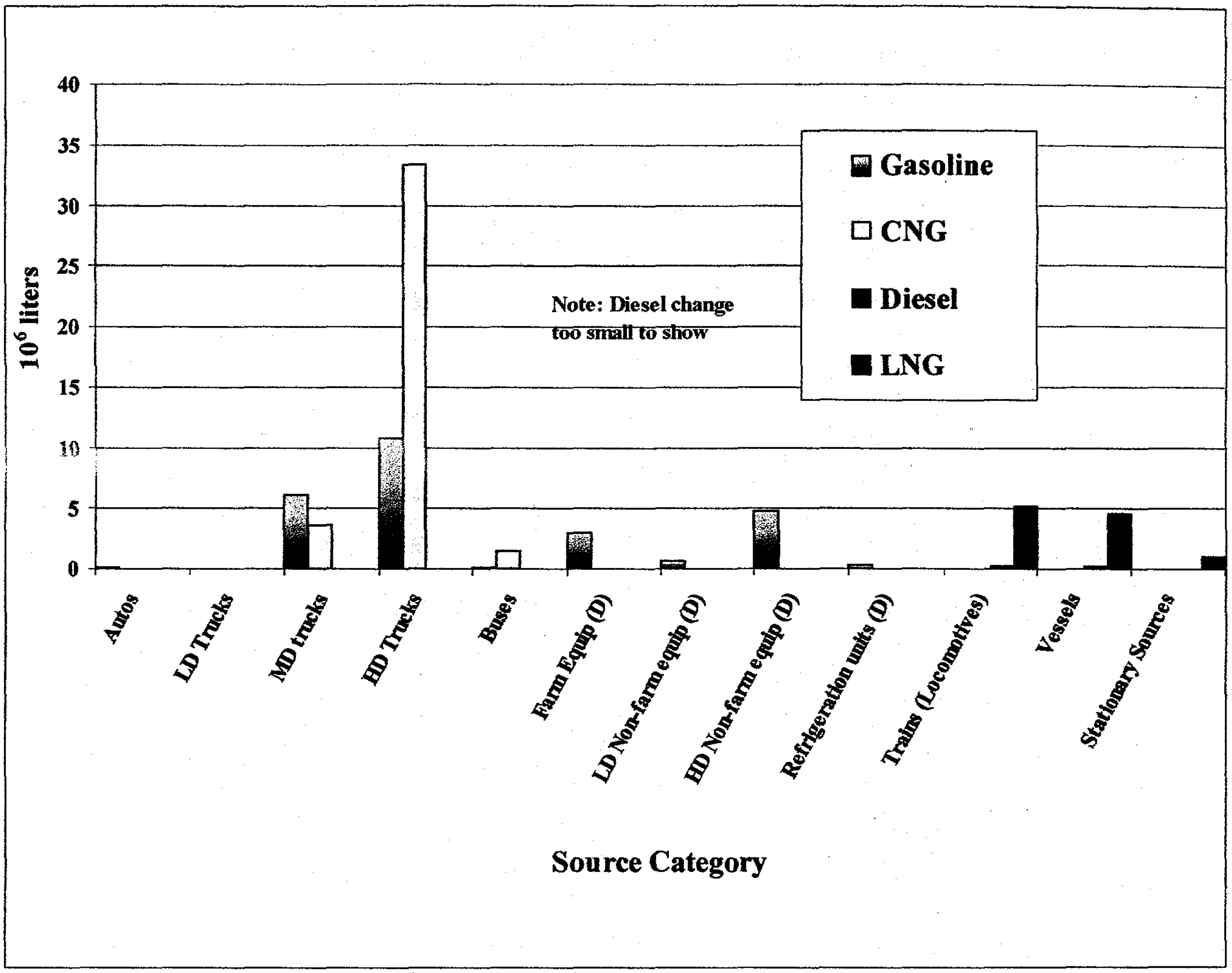
Figure 4. Fuel Replacement Case B: 2010 End-Use Emission Changes (Within California)—Metric tons/day

Figure 5. All Cases: Increase in Production Energy Use Relative to 2010 Baseline Forecast by ARB (1997a)—Terajoules (TJ)

(NOTE: 1 TJ = 9.48×10^8 Btu)

Figure 6. All Cases: Increase in Full Fuel Cycle GHG Emissions Relative to 2010 Baseline—Thousand Metric tons/day

Fig. 1


40
35
30
25
20
15
10
5
0
10^6 liters
Gasoline
CNG
Diesel
LNG
Note: Diesel change too small to show
Autos
LD Trucks
MD trucks
HD Trucks
Buses
Farm Equip (D)
LD Non-farm equip (D)
HD Non-farm equip (D)
Refrigeration units (D)
Trains (Locomotives)
Vessels
Stationary Sources
Source Category

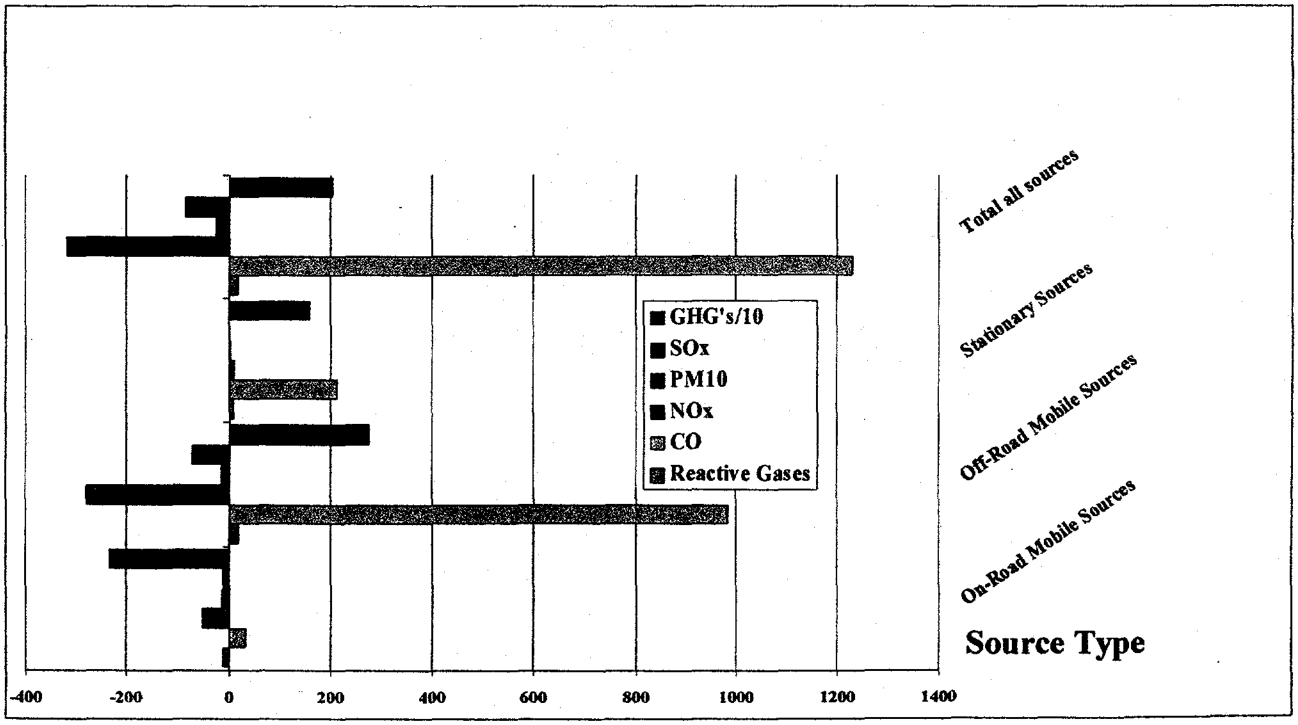
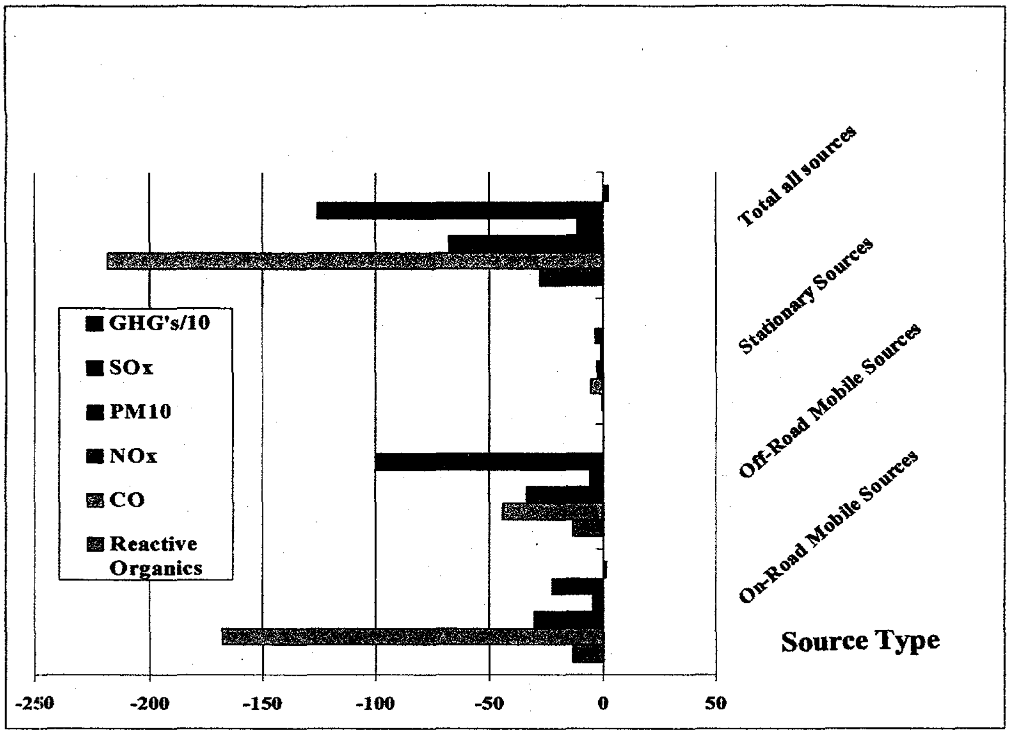
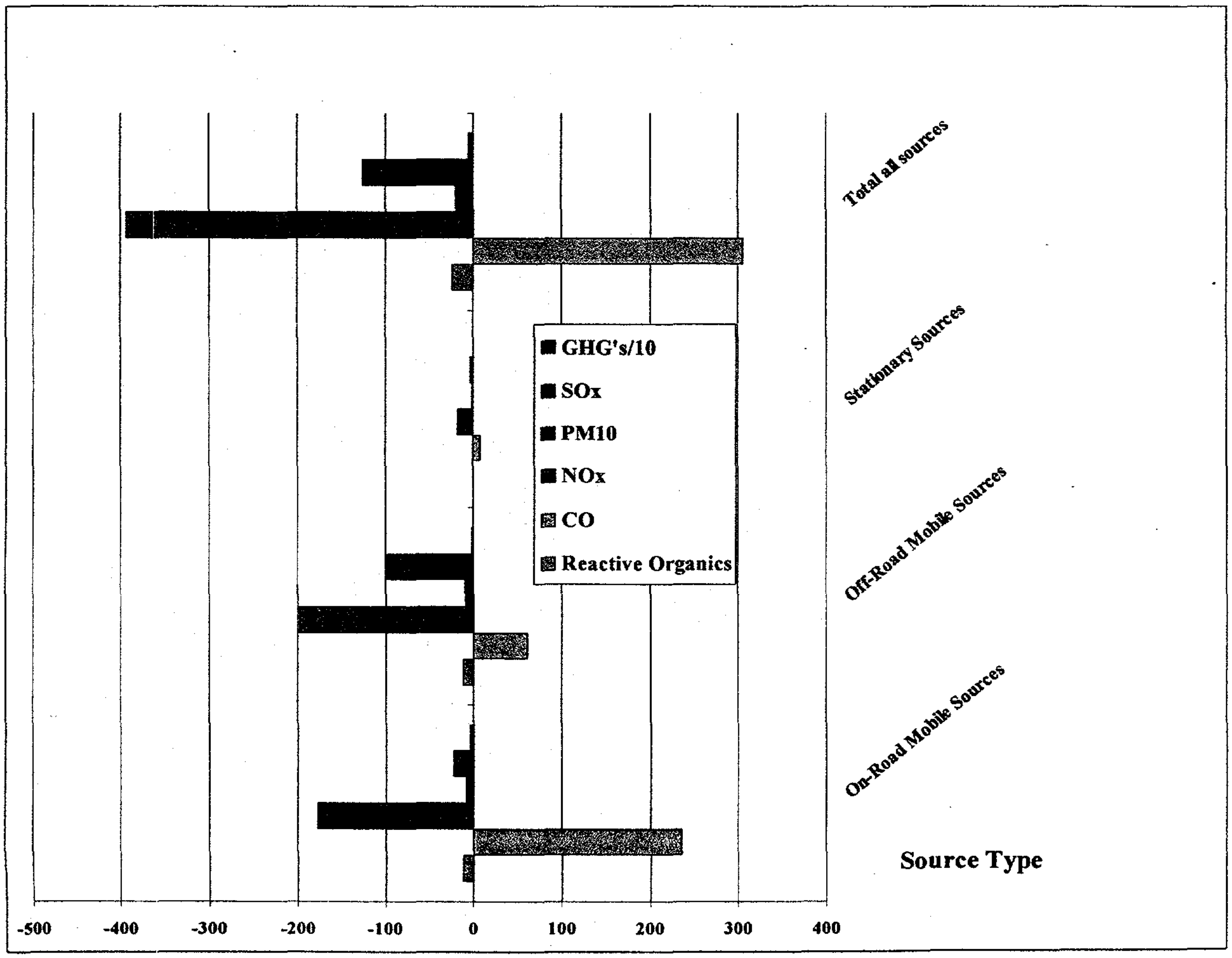

GHG's/10
SOx
PM10
NOx
CO
Reactive Gases
Total all sources
Stationary Sources
Off-Road Mobile Sources
On-Road Mobile Sources
Source Type
-400
-200
0
200
400
600
800
1000
1200
1400

Fig. 2

Fig. 3



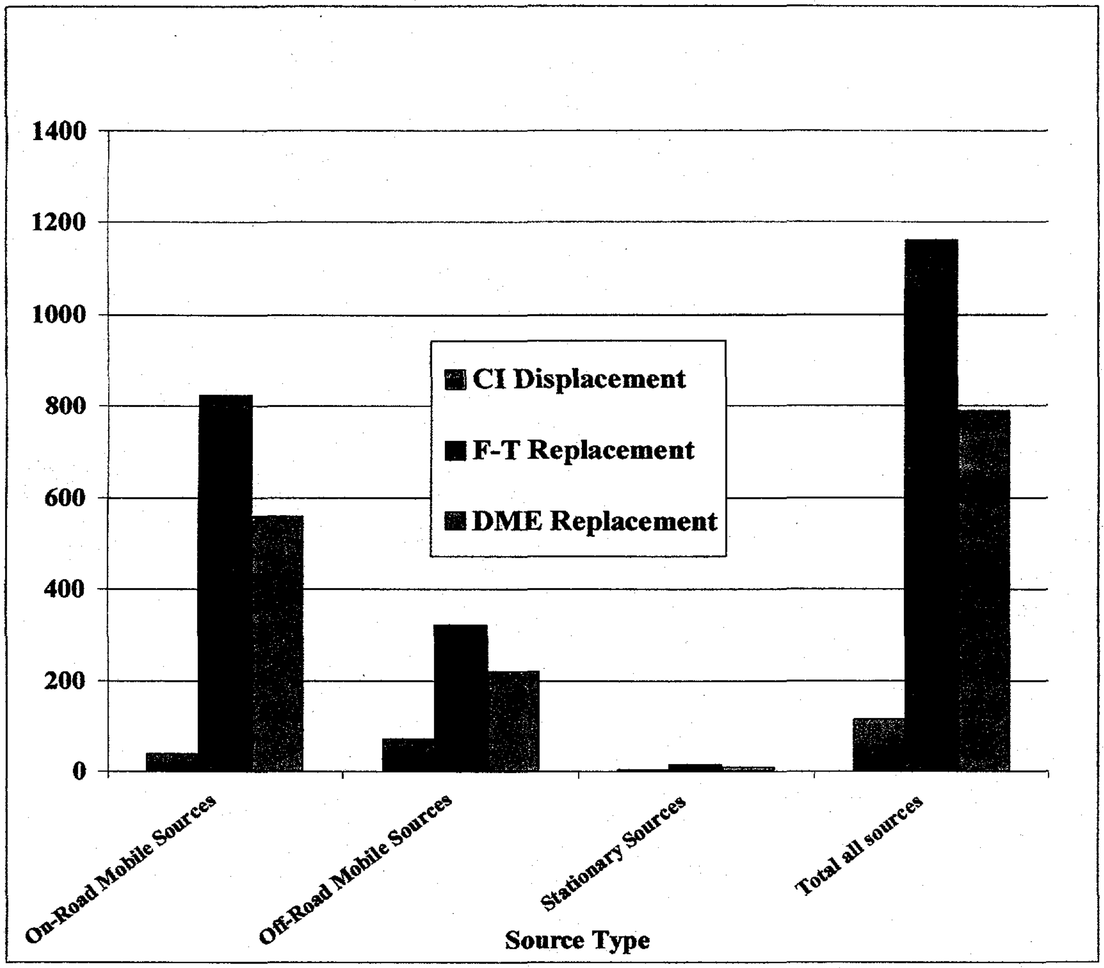
GHG's/10
SOx
PM10
NOx
CO
Reactive Organics
Total all sources
Stationary Sources
Off-Road Mobile Sources
On-Road Mobile Sources
Source Type
-250
-200
-150
-100
-50
0
50



GHG's/10
SOx
PM10
NOx
CO
Reactive Organics
Total all sources
Stationary Sources
Off-Road Mobile Sources
On-Road Mobile Sources
Source Type
-500
-400
-300
-200
-100
0
100
200
300
400

Fig. 4

Fig.5


1400
1200
1000
800
600
400
200
0
CI Displacement
F-T Replacement
DME Replacement
On-Road Mobile Sources
Off-Road Mobile Sources
Stationary Sources
Total all sources
Source Type

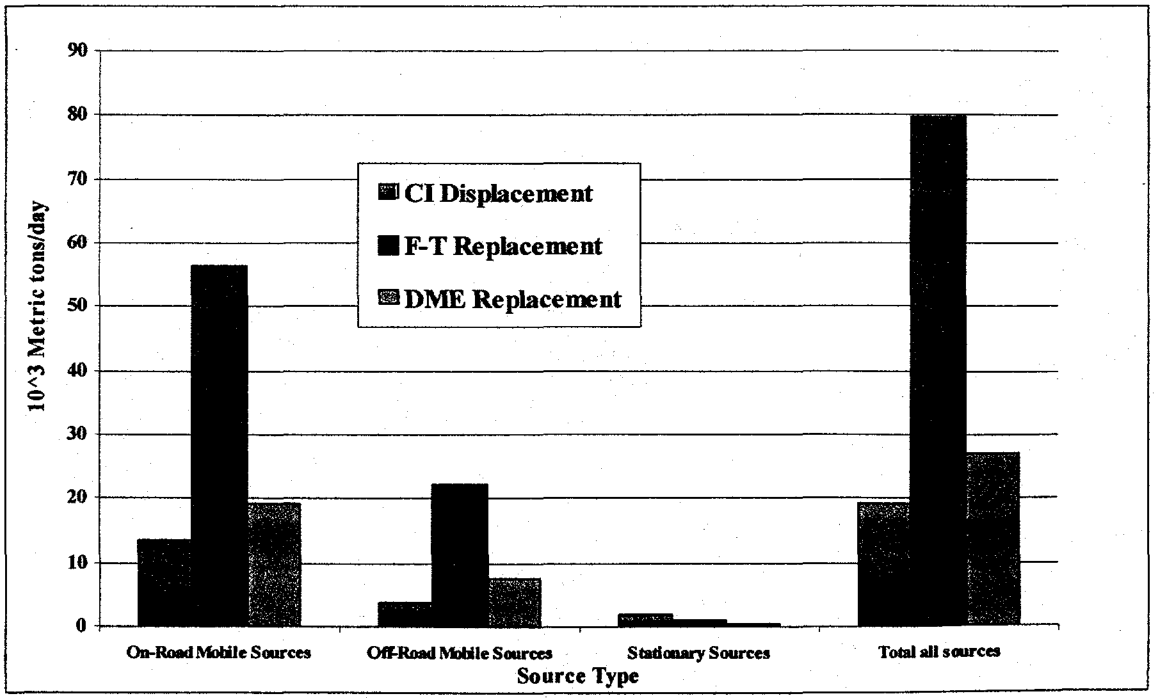

90
80
70
60
50
40
30
20
10
0
10^3 Metric tons/day
CI Displacement
F-T Replacement
DME Replacement
On-Road Mobile Sources
Off-Road Mobile Sources
Stationary Sources
Total all sources
Source Type

Fig.6