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FUTURE PROSPECTS FOR COMPRESSION IGNITION FUEL IN CALIFORNIA: FUEL-RELATED IMPLICATIONS OF POSSIBLE PATHWAYS TO MITIGATION OF PUBLIC HEALTH THREATS

Christopher L. Saricks, Donald M. Rote, and Frank Stodolsky
Argonne National Laboratory
and James J. Eberhardt
United States Department of Energy
Address for correspondence:
Center for Transportation Research, ES-362
9700 South Cass Avenue
Argonne, IL 60439
E-mail: csaricks@anl.gov

ABSTRACT

This paper documents methods and results of an investigation of the options for and year 2010 consequences of possible new limitations on the use of diesel fuel in California, USA. California's Air Resources Board will undertake a risk management process to determine steps necessary to protect the health and safety of the public from carcinogenic species resident on diesel combustion exhaust particles. Environmental activist groups continue to call for the elimination of diesel fuel in California and other populous states. It is the declared intention of CARB *not* to ban or restrict diesel fuel, *per se*, at this time. Thus, two "mid-course" strategies now appear feasible.

1. Increased penetration of natural gas, LPG, and possibly lower alcohols into the transportation fuels market, to the extent that some CI applications would 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.

Each of these alternatives results in some degree of (conventional) diesel displacement. In the first case, diesel pilot fuel is assumed admissible for NG-powered heavy-duty vehicles, and gasoline demand in California increases by 32.2 million liters per day overall, about 21 percent above projected 2010 baseline demand. It may be possible to meet this gasoline

demand without severe disruption in 2010. Natural gas demand increases by 13.6 million diesel liter equivalents per day, about 7 percent above projected (total) consumption level. In the second case, compression-ignition engines utilize diesel substitutes. Although causing the least disruption to California, this case introduces new costs to the U. S. domestic economy in fuel distribution logistics, replacement fuel production capacity and investment, and total energy productivity. For each case we show air emission, greenhouse gas and energy changes. Economic implications of vehicle and engine replacement were not evaluated.

Key words: transport fuel, carcinogen, air regulation, diesel combustion, synthetic diesel

1. BACKGROUND OF THE ISSUES

On August 27, 1998, the California Air Resources Board 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, 1998). This declaration was more limited and certainly more tractable 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 compression-ignition using interests, 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 the likely effects on energy and emissions, and speculates on the economic impact, of full implementation of two of these initiatives by 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

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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. However, at present, only (largely voluntary) good will efforts are underway to accelerate transition from diesel to more benign substitute heavy vehicle fuels. Also, 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. Two "mid-course" actions appear feasible at present.

1. CARB will continue to pursue penetration of natural gas (more likely in liquefied form), LPG, and possibly lower alcohols into the transportation fuels market, to the extent that some heavy-duty applications would operate on spark-ignition (SI) engines.
2. CARB will issue new specifications requiring diesel fuel reformulation based on more detailed investigation of exhaust products of individual diesel fuel constituents. This could increase the penetration of Fischer-Tropsch synthetic diesel fuel from natural gas and, eventually, di-methyl ether (DME) and possibly bio-diesel as compression-ignition (CI) fuels into the marketplace, albeit at premium cost and lower full-fuel-cycle efficiency

Each of these alternatives results in some degree of (conventional) diesel displacement. 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 we examine 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 impact on atmospheric loading of primary and secondary particulate matter that massive shifts to gasoline- and (potentially) CNG-fueled SI engines could produce.

Replacement Fuel Case. In a somewhat less stringent case, the compression ignition engine not only survives, but also thrives on diesel substitutes such as Fischer-Tropsch or DME that, though expensive to produce and use per feedstock joule, 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.) Although this scenario logically would cause the least overall disruption to the California economy, associated costs accrue to the U. S. domestic economy owing to fuel distribution logistics, replacement fuel production capacity and investment, and total energy productivity.

2. RESULTS IN BRIEF

In the Advanced CI Displacement Case, diesel pilot fuel is admissible for NG-powered heavy-duty vehicles, and gasoline demand in California increases by 32.2 million liters per day overall. Natural gas demand increases by 13.6 million diesel-liter equivalents (lower heating value) per day; of this total, the compressed natural gas (CNG) demand represents an incremental 5.4 million standard cubic meters. End-use energy consumption and air emissions changes for this scenario are shown in Figures 1 and 2. Greenhouse gas emission changes incorporate the greenhouse warming increased methane potential (GWP) indices developed by the International Panel on Climate Change; thus, emissions due to greater NG consumption increase GWP-weighted emissions disproportionately. SOx and PM_{10} are reduced relative to the base case, but NOx reduction is less dramatic. The Replacement Fuel Case with Fischer-Tropsch synthetic diesel from natural gas results in an almost 76-million liter daily demand for that synthetic, including its use as a replacement process fuel. This represents an increase of 26.5 million diesel-liter equivalents over the quantity of diesel displaced. Overall emissions comparisons with base case results are shown in Figure 3a.

Using DME in this case requires somewhat less diesel-equivalent energy for replacement fuel (64 million liters). Associated emission changes shown in Figure 3b.

3. SCENARIO ASSUMPTIONS AND METHODOLOGY

Two sets of strategies cover the scenarios described in Section 1. 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 Case*: replaces all diesel fuel in CI engines on a 100-percent basis with either (a) Fischer-Tropsch process (FT) diesel made from NG or (b) dimethyl ether (DME) made from NG.* In this case, 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.

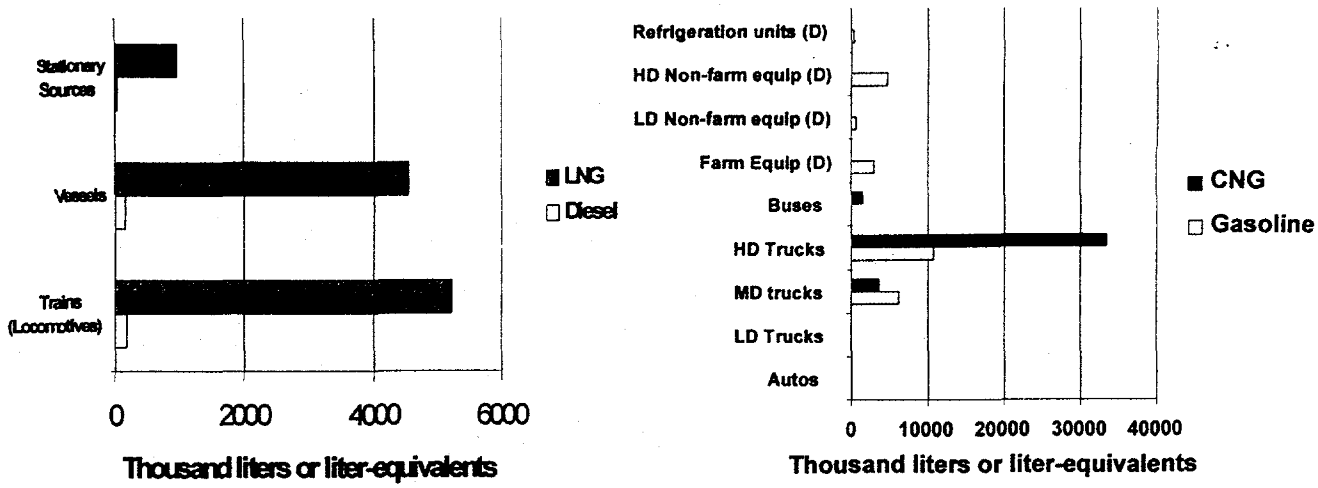

Figure 1. Increased Daily Fuel Use: Advanced CI Displacement Case

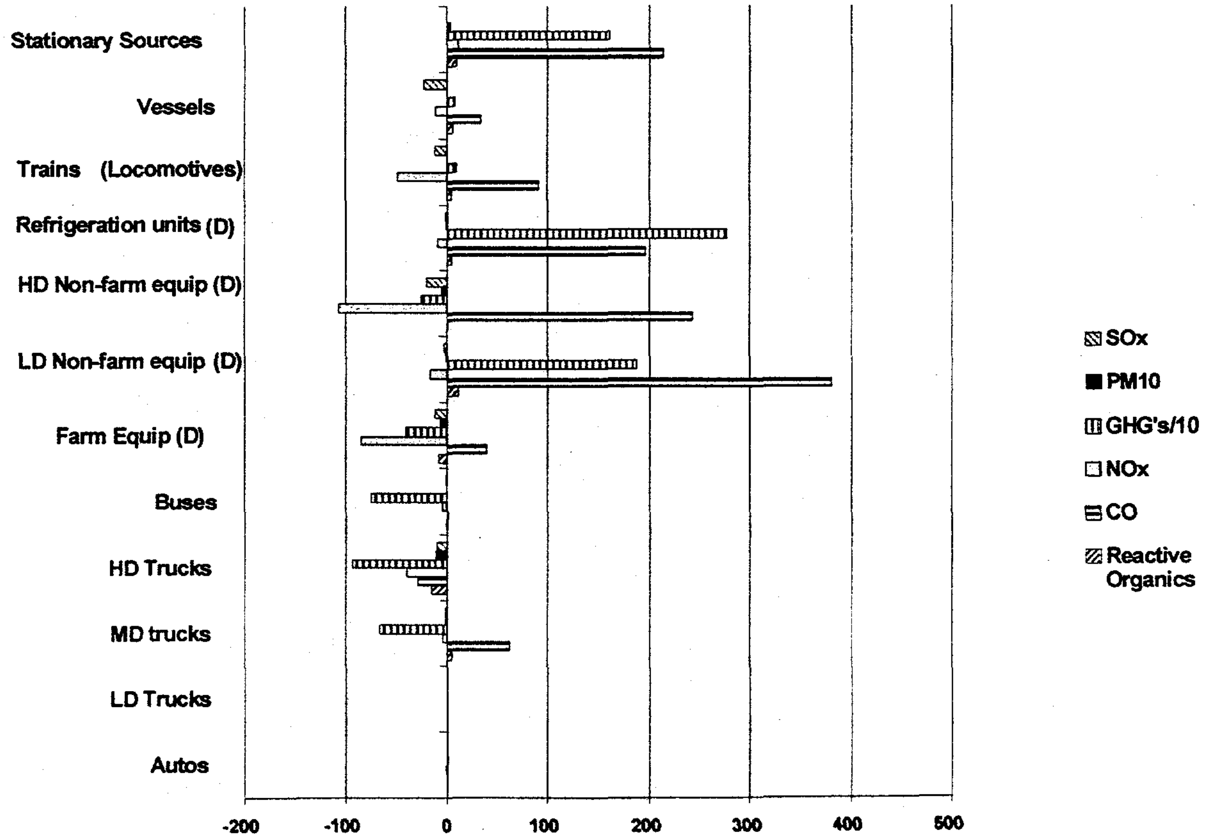

Figure 2. Change from Baseline in Daily Metric Tons of Emissions: CI Displacement Case

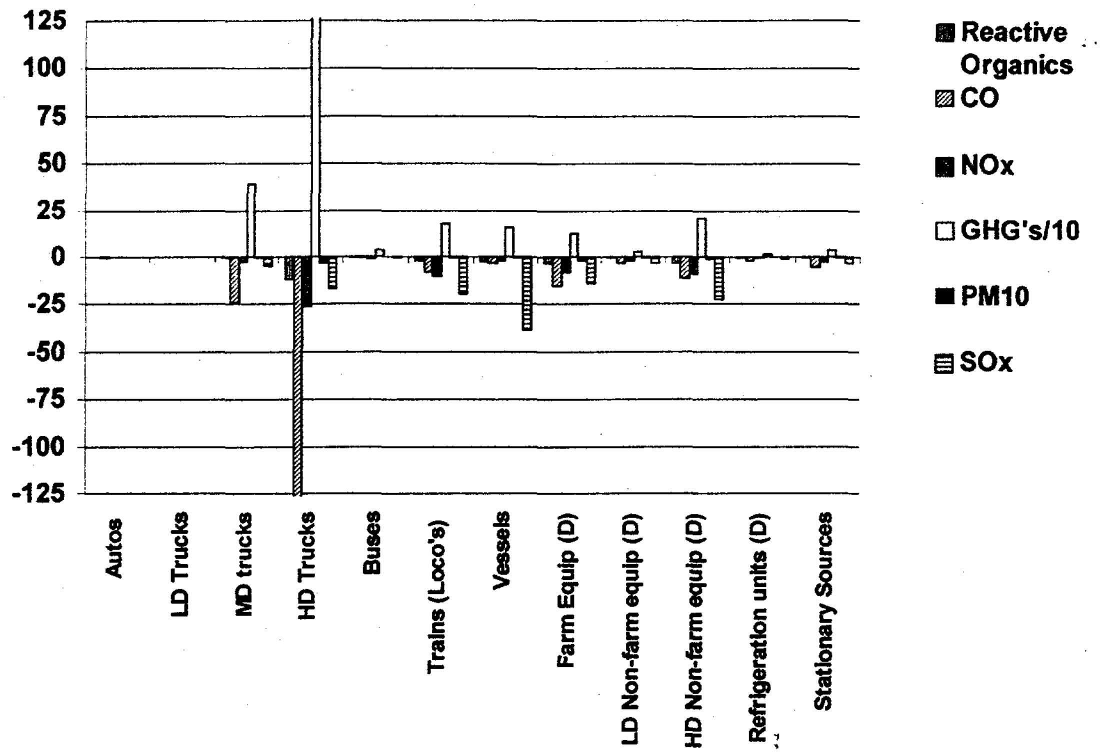

Figure 3a. Change from Baseline in Daily Metric Tons of Emissions: F-T Replacement Case

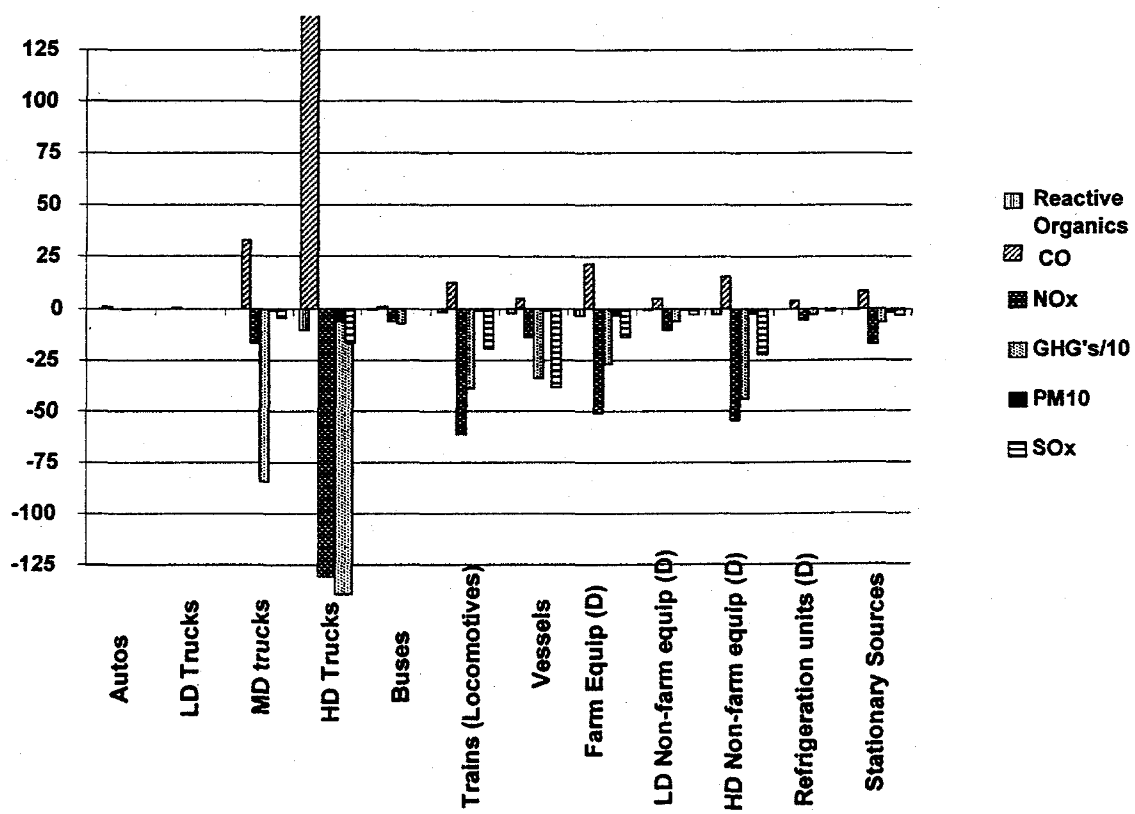

Figure 3b. Change from Baseline in Daily Metric Tons of Emissions: DME Replacement Case

3.1. 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). 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.

3.1.1 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 (California, 1997), 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 was assumed to be independent of 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 reference cited above.

- 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 (1995) 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 been the result of biases in the data base created by failing to take account of the differences in loads and driving cycles between gasoline and diesel trucks.

3.1.2 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. 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).

3.1.3 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 2500 hp to the newest 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 in 1995 to 3.00 x 10^6 liters 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 were adopted from ARB (1998) for 1995 values. Emissions for 2010 were estimated from a linear projection of ARB's 1990 & 1995 data in ARB.

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/day. The corresponding fuel sales figure from DOE/EIA (1996) was 1,590,000 liters/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 (1998), 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. Fuel use was estimated from the sulfur emissions assuming that the sulfur content of the diesel fuel was the same as that used by other off-road sources--namely, farm and light duty industrial and commercial equipment.

3.2. Advanced CI Displacement Case

3.2.1 On Road Vehicles

LD Diesel Powered Highway Vehicles. Catalytically controlled gasoline-powered vehicles replace these units.

MD & HD Trucks and Buses. 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. 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.

3.2.2 Off-Road Sources

3.2.2.1 *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.

3.2.2.2 *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 in Section 3.1.2.

3.2.2.3 *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 3.2.2.1 were assumed here.

3.3. Fuel Replacement Case

There are three alternative fuels that can be relatively easily used in conventional CI engines: biodiesel, Fischer-Tropsch (FT), and dimethyl ether (DME). All three offer some emission benefits. Both FT 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. Of the three, FT is most compatible with existing 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 FT process yields middle distillates that are very low in aromatics and sulfur compounds. Only FT and DME are considered as feasible near-term substitutes in our analysis. The change in fuel use and emissions from replacing diesel with FT fuel was estimated with the following equations:

$$F_{FT} = F_D * LHV_D / LHV_{FT} \quad (1)$$

$$\Delta\varepsilon = (\text{emission factor for FT})/(\text{emission factor for D}[=\varepsilon_D]) * \varepsilon_D \quad (2)$$

The use of FT fuel results in a net reduction of all emissions except CO_2.

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 there exists an infrastructure for propane distribution that might be adaptable to DME, its scale would require substantial expansion if it were to be used as a substitute for diesel. The fuel use and change in emission from replacing diesel with DME fuel was estimated as in equations 1 and 2 for FT. With the exception of CH_4 & CO, all emissions are reduced by the substitution of DME for diesel. The reduction of ROG is similar to that for FT, but the NO_x is substantially greater. The CO_2 emissions are lower, consistent with the lower carbon weight fraction of DME.

4. 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. We have examined two possible outcomes of an 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. (We have also computed the effects of these outcomes over the total energy cycle—extraction + production + combustion--but do not report them in this paper.)

Our engine displacement case scenario has mixed effects. With diesel pilot fuel admissible for NG-powered heavy-duty vehicles, gasoline demand only increases by 32 million liters per day overall. This is *possibly* feasible to meet without severe disruption in 2010 if only a modest increase in such capacity worldwide by that time may be assumed. Natural gas demand increases by 13.6 million diesel gallon equivalents per day; of this total, the CNG demand represents an incremental 5.4 million standard cubic meters. It is not likely that this increase in daily flow could be supplied 100 percent by domestic pipelines, and thus NG importation would probably be necessary, initially from Canada and Mexico but then from abroad. CO and GWP-weighted greenhouse gases are reduced from baseline, although methane emissions increase due to greater NG consumption. SOx and PM_{10} are substantially reduced, although NOx reduction is less dramatic.

Each of the "replacement case" alternatives has unique characteristics. The Fischer-Tropsch case results in an almost 76-million liter demand for that synthetic, including its use as process fuel. This represents an increase of 26.5 million diesel-liter equivalents over the quantity of diesel displaced. There is no indication that inherently safe production capacity to meet that level of demand can be on line by 2010. If we assume it can, 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 requires somewhat less diesel-equivalent energy for replacement fuel (64 million liters) and results in a lower GHG increase and greater PM10 and NOx decreases than Fischer-Tropsch, but actually increases CO relative to baseline due to the presence of oxygen in the ether. 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.

5. ACKNOWLEDGEMENTS AND DISCLAIMER

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