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LIFECYCLE-ANALYSIS FOR HEAVY VEHICLES

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ABSTRACT

Various alternative fuels and improved engine and vehicle systems have been proposed in order to reduce emissions and energy use associated with heavy vehicles (predominantly trucks). For example, oil companies have proposed improved methods for converting natural gas to zero-aromatics, zero-sulfur diesel fuel via the Fischer-Tropsch process. Major heavy-duty diesel engine companies are working on ways to simultaneously reduce particulate-matter and NO_x emissions. The trend in heavy vehicles is toward use of lightweight materials, tires with lower rolling resistance, and treatments to reduce aerodynamic drag. In this paper, we compare the lifecycle energy use and emissions from trucks using selected alternatives, such as Fisher-Tropsch diesel fuel and advanced fuel-efficient engines. We consider heavy-duty, Class 8 tractor-semitrailer combinations for this analysis. The total lifecycle includes production and recycling of the vehicle itself; extraction, processing, and transportation of the fuel itself; and vehicle operation and maintenance. Energy use is considered *in toto*, as well as those portions that are imported, domestic, and renewable. Emissions of interest include greenhouse gases and criteria pollutants. Argonne's *G*reenhouse Gases, *R*egulated *E*missions, and *E*nergy Use in *T*ransportation (GREET) model is used to generate per-vehicle fuel cycle impacts. Energy use and emissions for materials manufacturing and vehicle disposal are estimated by means of materials information from Argonne studies. We conclude that there are trade-offs among impacts. For example, the lowest fossil energy use does not necessarily result in lowest total energy use, and lower tailpipe emissions may not necessarily result in lower lifecycle emissions of all criteria pollutants.

INTRODUCTION

The overall objective of lifecycle analysis is to evaluate the energy and environmental implications of different technological and strategic alternatives so that society (or some subset of it, such as the United States) can satisfy its demands for various services with minimal impacts. In earlier work, we have discussed what these impacts are and how tradeoffs among impacts should be weighed (1). We have studied consumer goods packaging (2) and several options for reduced-impact automobiles, including lightweight vehicles, electric vehicles, and hybrids (3-5). These studies included all stages of products' lifecycles, from material extraction, through the production and use phases, to final disposition of the product by recycling or disposal.

In this paper, we examine the lifecycle energy use and emissions for heavy-duty trucks. This work is sponsored by the U.S. Department of Energy (DOE), Office of Transportation

Technologies, Office of Heavy Vehicle Technologies, and is performed by Argonne National Laboratory's (ANL's) Center for Transportation Research. Trucks are of interest for several reasons. They are highly visible on our highways and in our cities and make significant contributions to petroleum usage and deterioration of air quality in urban areas. Indeed, since the Arab oil embargo of 1973, essentially all of the increase in U.S. highway fuel consumption has been due to trucks (6). According to the Energy Information Administration (EIA), energy use by commercial trucks (greater than 10,000 lb gross vehicle weight), which account for the majority of ton-miles, has more than doubled since 1973, to nearly 2 million barrels per day in 1995. This trend is expected to continue so long as the robust U.S. economy continues to expand. Commercial trucks, the mainstay of trade and commerce, are essential for economic growth. As the gross domestic product, an indicator of economic activity, has grown, so has freight transport. Trucks will continue to play an essential role in meeting the increasing demand for movement of goods, crucial to economic growth. Trucks also make significant contributions to atmospheric emissions, especially particulate matter (PM) and oxides of nitrogen (NO_x). It is the objective of this paper to evaluate the potential for reductions in energy use (petroleum use in particular) and atmospheric emissions over the lifecycle of heavy trucks, possibly as the result of R&D on improved technology or alternative fuels. Although many aspects of truck use have been studied in detail, we do not believe that an overall lifecycle analysis has been performed. This work represents a scoping analysis, designed to illuminate the relative importance of the different factors contributing to energy use and emissions.

This study focuses on large, over-the-road tractor-semitrailer combinations (often called 18-wheelers), because of their large numbers and significant impacts. We first characterize these trucks, identify several types of potential improvements that could be made, and then estimate the energy and emissions implications of these changes by means of a spreadsheet model. Finally, we draw conclusions about tradeoffs among alternatives. Factors considered include energy use (total, petroleum-based, etc.), greenhouse gas (GHG) emissions, and criteria pollutant emissions. These are evaluated over the entire lifecycle of the truck, including vehicle production and recycling, maintenance, operation, and fuel production, transportation, and use.

CHARACTERIZATION OF TRUCKS TO BE STUDIED

Although the largest category of trucks ("heavy-heavy") includes all trucks over 26,000 lb gross vehicle weight (GVW), the greatest number are in the 60,000-80,000 lb range (7). These account for the majority of the mileage, and because they use more fuel per mile, the vast majority of diesel fuel use and emissions. On the basis of the most recent Truck Inventory and Use Survey (7), there are two million heavy-heavy trucks, of which 781,000 are in the 60,000-80,000 lb class (see Figure 1), the largest trucks permitted by regulations in most states. These are predominantly used in for-hire transport of goods over both long and short ranges, construction being the second-largest user. About half of the heavy-heavy trucks are tractor-semitrailer combinations. The vast majority have conventional cabs. Types of semitrailers include platforms, tankers, and enclosed vans, which may be refrigerated. Enclosed vans are the most populated category. There are many different variants of big trucks on the road; we have selected as the "typical" truck to examine an 80,000-lb GVW tractor-semitrailer combination with a conventional cab, sleeper compartment, and enclosed van. The results will be examined for sensitivity to this choice as appropriate. A typical example is shown in Figure 2.

The number of heavy trucks is much smaller than the number of light trucks and cars (totals: 47 million trucks and 146 million cars), but mileage and emissions for heavy trucks are high and fuel economy is low. Heavy trucks averaged 60,000 miles/y in 1993 (8). At a typical mileage of 5 mpg, the 781,000 trucks in the largest class allowed nationwide consume more than 9.4 billion gallons (223 million barrels) of diesel fuel per year. This is about 8% of total U.S. highway fuel use and over 40% of highway diesel use. Other sources indicate much higher annual mileages — up to 250,000 mi/y for some trucks in the chosen category — which would make their total fuel consumption much higher (9). Thus, this is an important class of vehicles to examine for possible reductions in fuel use and emissions.

CHANGES THAT WOULD AFFECT FUEL USE AND EMISSIONS

This section describes factors that could be changed in the design, construction, and operation of trucks, in order to reduce fuel use or emissions. These include material, design, engine and operation, and fuel. For each factor, the potential scope of changes is considered. Improvements are measured relative to typical new trucks currently on the road.

Changes in Truck Materials

Iron and steel are the predominant materials used in trucks, with rubber the next major contributor. Table 1 shows estimated material compositions for the tractor and the semitrailer. The most common changes, and those most likely to occur in the future, involve replacement of iron and steel in the engine, body, or other parts with lighter materials.

The most frequently used substitute is aluminum (Al), but magnesium (Mg) can also be used. Previous ANL work examined weight savings attainable by using Mg in automobiles (10). For applications not requiring high strength or high-temperature stability, plastics are an important alternative (11). The plastic parts are generally not lighter than the Al ones, but they are cheaper. One recent paper (12) cites a new line of trucks that uses about 450 lb of SMC per vehicle, for such parts as doors, hoods, fairings, and the grille opening. For some parts, the mass can be reduced by a factor of 2 (compared to iron and steel) by use of a lighter material. Table 2 (13) shows opportunities first identified in the early 1980s for weight reduction in tractors and semitrailers by using Al and Mg. The total mass reduction for a tractor-semitrailer combination with an enclosed van was about 3500 lb using Al and about 4400 lb using Mg (14-23% reduction). Much of this potential for mass reduction remains today. The substitution of Al for steel in the cab has taken place for perhaps two-thirds of new trucks sold (in some cases, fiber-reinforced plastic [FRP] has subsequently displaced the Al), fuel tanks are generally Al, and most new vans are Al. However, the rest of the substitutions are not standard; they are available as extra-cost options that are often not chosen. The potential remains for 1400 lb of weight reduction with Al and 2300 lb with Mg.

Another possible means of reducing weight would be replacement of conventional cabs with cab-over-engine (COE) designs. However, these designs, which are less comfortable for the trucker, lost market share when length restrictions were relaxed.

When the material composition of the truck is changed, there are several implications for energy use and emissions. First, the impacts of producing the truck materials are changed. Generally, a smaller mass of a more energy-intensive material is required, which often leads to only small changes in total energy use. The total may increase or decrease, depending on such factors as the type of part and the quantities of recycled materials used. But the mix of energy sources and the emissions profile can change significantly. Financial costs may be affected as well. In addition, because the truck is lighter, energy use for hauling is reduced (if the cargo is volume-limited), or additional cargo can be carried (if weight-limited). In either case, the energy use per ton-mile carried is reduced. If the mass of the vehicle were reduced by 2000 lb, fuel use per ton-mile would decrease by more than 3%.

Changes in Truck Design

The types of changes included here are such items as variations in the shape of the body. Examples include addition of roof fairings or skirts to reduce aerodynamic drag, new cab or trailer shapes for the same purpose, and use of different types of tires to reduce rolling resistance. These effects have been studied carefully in the past, and the easily achievable improvements have been made. The main effect of such changes is to reduce vehicle fuel consumption, for any fuel. Changes in this category can often be accomplished at little or no additional cost when equipment is replaced or with low retrofit costs. Details of possible design improvements will not be discussed; such improvements are only included here to compare potential for reduced impacts among the types of changes possible.

The components of the power requirements for a heavy truck traveling at 60 mph with a full load (80,000 lb GVW) and a partial load (65,000 lb GVW) are broken down in Table 3 to show their relative importance.

During the last 5-10 years, the aerodynamic coefficient has been reduced from ~0.76 for the first streamlined ("aero") trucks to ~0.6 for the best available today. Further decreases are possible, especially in the trailer. Another potential area for improvements is the "belly" and internal (engine compartment) aerodynamics. A target of 0.5 may be realistic; this would imply a 7.5-8% reduction in power required.

The rolling resistance of tires has also been reduced in the last decade or so, in a large step from conventional bias ply tires to the first generation of radials, and then in a smaller step to current radials, as indicated in Table 4. Additional improvement is likely to be small. Up to a 4% reduction in power required, compared to the best tires now in use, could be achieved with new tire designs. However, there is still much potential for improvement in trucks *on the road.* Additional reduction in friction losses (to 70% of standard radial losses) may entail a safety risk. Super-singles have long been used by the U.S. Army because of superior performance off-road and in Europe, where most trucks use different axle configurations than in the United States. Their use could further reduce rolling resistance, but they have not been widely accepted in the U.S. because of fears of reduced stability in the event of a blowout.

Drivetrain losses can be high (e.g., in tandem drive axles) and may also be amenable to significant improvement, perhaps leading to a 1-2% reduction in power requirements. Replacing the massive rear tandem axle of the tractor with a lighter single axle and a tag axle would yield an additional weight reduction of 300-400 lb. This would require addition of a traction-control system to maintain traction performance, but such a system would be relatively light.

On the basis of the above, we assume that a combined reduction in energy use from aerodynamic drag reduction, reduction in rolling resistance, and reduction in drivetrain losses would lower the truck energy requirement from 3.3 hp-hr/mi [note 1] to 2.79 hp-hr/mi (i.e., 15%).

Changes in Engine Design and Operation

We include here only sufficient information to estimate expected reductions in fuel usage and changes in emissions profiles for alternative engine types under development for use in heavy-duty trucks. One example is the advanced diesel engine being developed by the engine industry in partnership with the DOE's Office of Heavy Vehicle Technologies; the engine is targeted to achieve a thermal efficiency of 55%, compared to conventional best-in-class of 48% [note 2]. On-road brake-specific fuel consumption values used here are 0.336 lb/bhph for the conventional diesel and 0.275 lb/bhph for the advanced diesel running on liquid fuels (unchanged for liquefied natural gas, or LNG). Another example is the glow-plug-assisted compression-ignition natural gas engine, whose efficiency under certain operating conditions may approach that of a conventional diesel. Consideration of changes in operating practice, such as percent of time during operation that the vehicle spends idling, and variations due to terrain or length of trip are important. We assume the truck is traveling at highway speeds most of the time, but every truck spends a portion of its time at idle, which could significantly affect emissions and fuel consumption [note 3]. A separate Argonne study will investigate impacts of truck idling on fuel consumption and emissions.

Alternatives to Conventional Diesel Fuel

Changes in this category are expected to have the greatest potential for reducing both petroleum usage and environmental impacts from the use of large trucks. Total fuel cycle energy consumption and emissions from diesel fuel made from natural gas via the Fischer-Tropsch (F-T) process and natural gas (stored as LNG) were investigated in detail and compared against conventional petroleum diesel. F-T diesel fuel is an excellent fuel for compression-ignition engines because it contains essentially no sulfur and no aromatic compounds (sulfur and aromatic compounds contribute to particulate formation), and it has a high cetane number (the cetane number indicates the compression-ignitability of a fuel). The F-T process used in this analysis is proven commercial technology for syngas generation (noncatalytic partial oxidation in combination with steam reforming) (16). The conceptual F-T plant designed by Bechtel has a thermal efficiency of approximately 56.7% and a carbon conversion efficiency of 69.7% [note 4]. A review of the literature indicates that these efficiencies are conservative; state-of-the-art plants can achieve thermal efficiencies in the 61-69% range (and higher carbon conversion efficiencies) (17). A future analysis will investigate the full spectrum of F-T processes, including such advanced technologies as an autothermal reactor for the partial oxidation process step.

For natural gas combustion, the diesel engine is used as a platform for conversion to homogeneous combustion, ignition-assisted (through spark or pilot diesel fuel) operation (commonly called the Otto cycle). Relative to heterogeneous combustion, characteristic of current compression-ignition engines, homogeneous combustion leads to very low particulate emissions. Natural gas also produces low NO_x emissions relative to diesel fuel because of its lower combustion temperature. Two natural gas combustion strategies are being explored: stoichiometric combustion and lean-burn. While stoichiometric combustion has a clear advantage by allowing effective NO_x and CO reduction with a three-way catalyst, its thermal efficiency is only about 80% that of a conventional diesel engine (18). Lean-burn strategies promise to improve this to about 88%, but the technology needs to be improved. Misfire and combustion stability problems during part-load operation lead to higher hydrocarbon emissions, including methane. Further, an efficient three-way catalyst has not been developed for lean exhausts [note 5].

We did not investigate compressed natural gas (CNG), alcohols, biodiesel, and di-methyl ether (DME) because of their significant shortcomings relative to conventional diesel fuel. CNG has a very low energy density relative to diesel fuel, thereby severely restricting the range between fuelings, an important criterion for over-the-road tractor-semitrailer operators (however, combustion and emissions are the same as LNG operation; the only difference is the fuel system). We did not investigate alcohol fuel because of its poor compression-ignition characteristics and low feedstock-to-fuel conversion efficiency, based on the GREET 1.3 database. Although biodiesel is a promising compression-ignition fuel, supplies are currently limited relative to the fuel consumed by tractor-semitrailers. Future studies will include biodiesel, which has the potential to reduce petroleum usage and GHG emissions. DME is a relatively new compression-ignition fuel. Tests indicate that the California Ultra-Low Emissions Vehicle regulations can be met by DME-fueled medium-duty vehicles (20), but DME production, storage, distribution, and handling systems are not in place, and safety issues must be addressed.

We reviewed the literature to characterize engine thermal efficiency and emissions from F-T diesel and natural gas in heavy-duty applications. Emissions vary by engine design, operating conditions, and test procedures, making it difficult to accurately predict in-use emissions based on limited engine test data. Most of the literature contains tests from the old 13-mode U.S. Environmental Protection Agency (EPA) test procedure or the newer EPA Transient Test Procedure. The transient test procedure seeks to replicate urban driving conditions, so emissions of long-haul tractor-semitrailers may not be well represented by this test. However, given the uncertainty in emission rates even among tests of the same engine, we conclude that transient test data will suffice to arrive at reasonable first estimates of life-cycle emissions. A more complete study would consider emissions for each mode of operation (idle, transient, and steady state). For conventional diesel fuel and F-T diesel, we focus on NO_x and PM emissions, which are of particular interest. Emissions of air toxics are not included; however, these are expected to be very low for natural-gas-based fuels, which contain very small quantities (if any) of the materials of concern, and few are expected to be generated during vehicle operation. Exhaust measurements are needed to confirm this prediction.

For conventional (petroleum-derived) diesel fuel, we assume that the 1998 EPA heavy-duty engine emission standards are met for NO_x and PM (4 g/bhph and 0.1 g/bhph, respectively), that all particulate emissions are PM_{10}, and that the thermal efficiency for the conventional engine fueled with F-T diesel engine is the same as that for the conventional engine using petroleum diesel fuel. Emission assumptions are shown in Table 5. (There are indications that thermal efficiency could be improved with a high cetane fuel such as F-T diesel, but the findings are not conclusive.) We assume F-T diesel fuel reduces NO_x by 1 g/bhph in conventional diesel engines, compared to the use of petroleum diesel in such engines (from 4 g/bhph to 3 g/bhph). Southwest Research Institute found that F-T diesel produces only about 8% less NO_x and 33% less PM than does conventional fuel at standard fuel injection timing (21). However, the fuel injection system for the engine tested at Southwest Research Institute was not optimized for F-T diesel fuel. We assume engine operation on F-T diesel is optimized for low NO_x at the expense of thermal efficiency and PM [note 6]. (Figure 3 illustrates typical trade-offs.) We also consider the case of an advanced engine that is further optimized for F-T diesel fuel, yielding a NO_x emission of 2 g/bhph, corresponding to the goal outlined in the Statement of Principles (SOP), an agreement between EPA, the California Air Resources Board (CARB), and the leading manufacturers of heavy-duty engines (22). (A "clean" fuel, presumably with minimal aromatic content and minimal sulfur content, may be required to meet the emission goals outlined in the SOP.) For all cases, we assume PM emissions are 0.1 g/bhph.

For natural gas, we consider an optimized stoichiometric engine and an optimized lean-burn engine. Current stoichiometric natural gas engines emit moderately lower NO_x emissions (about 20% less) compared to conventional diesel engines (19, 23). However, these were diesel engines that were retrofitted for natural gas. We estimate that an optimized stoichiometric engine could achieve NO_x emissions of about one-half the current EPA standard, or 2 g/bhph [note 7]. Very low PM emissions, about 1/10th the PM emissions from diesel fuel (23), have been observed for natural gas. We assume PM emissions of 0.005 g/bhph, given that the engine is optimized and PM emissions are a result of combustion of lubricating oil. We assume an optimized lean-burn natural gas engine emits 1.5 g/bhph NO_x and 0.005 g/bhph PM. Hydrocarbon emissions are higher for natural gas engines than for conventional diesel engines; unburned methane is a particular problem. For both natural gas engines, we assume methane emissions are 0.54 g/bhph, and other HC emissions are 0.06 g/bhph, based on EPA estimates of an optimized natural gas engine (25). We assume the thermal efficiency of the stoichiometric engine is 80% that of a conventional diesel engine, and the thermal efficiency of the lean-burn engine is 88% that of a conventional diesel engine. The combinations of fuels, engines, and truck systems examined are indicated in Table 6.

ESTIMATION OF LIFECYCLE IMPACTS

GREET Model

The **G**reenhouse Gases, **R**egulated **E**missions, and **E**nergy Use in **T**ransportation (GREET) model was developed to calculate fuel-cycle energy use (Btu/mi) and emissions (g/mi) for various fuels (26). It calculates emissions of five criteria pollutants and three GHGs, as well as use of total energy, fossil energy, and petroleum. Emissions of air toxics are not modeled because data are unavailable. For each stage, energy consumed (in Btu per million Btu of energy throughput) is calculated and allocated to the different process fuels used. Fuel-specific energy use, together with emission factors of the combustion technology for a specific fuel, is then used to calculate combustion emissions. GREET includes a database of combustion emission factors for various combustion technologies, using different fuels and equipped with different emission control technologies. Combustion emission factors for VOC, CO, NO_x, PM_{10}, CH_4, and N_2O for different combustion technologies are derived primarily from the EPA's AP-42 document. SO_x emission factors for most fuels are calculated by assuming that all sulfur contained is converted into sulfur dioxide (SO_2). CO_2 emissions are calculated by assuming that all the carbon in the fuel, minus that in combustion emissions of VOC, CO, and CH_4, is converted to CO_2. Emissions of CH_4 and N_2O are estimated from several data sources.

On-road per-mile emissions of VOC, CO, and NO_x are calculated with EPA's Mobile5a model, and emissions of PM_{10} with EPA's Part5 model. Emissions from vehicle operations include tailpipe exhaust emissions, evaporative VOC emissions, and tirewear PM_{10} emissions, estimated by using EPA's Mobile5a and Part5 and the expanded GREET model. In GREET3.3 (in development), emissions from alternative-fueled vehicles (AFVs) are calculated using emission reduction rates relative to the benchmark of conventional diesel engines (CDS). Brake-specific engine emission estimates, engine thermal efficiency, and power requirements for the conventional truck (CD using diesel fuel) and alternative-fueled trucks were derived from the literature, as explained earlier.

The original version of GREET — GREET1.0 — includes fuel cycles but not vehicle cycles. It was extended (GREET2.3, which is still preliminary) to include energy use and emissions from production and recycling of vehicle materials, because of potentially significant contributions to the total energy cycle. The total vehicle weight is disaggregated into components and then further into different materials. For each material, the weights of the different components are summed; these steps, done by hand for this preliminary analysis, will become part of the model. Some vehicle components, such as batteries, tires, and fluids, are subject to regular replacements during the vehicle lifetime, and these additional materials were accounted for.

A submodel was added to GREET to calculate and sum energy use and emissions for each material, using unit process data on fuel use by type, material inputs, by-products, and process emissions. Emissions for material production are the sum of these process emissions, fuel combustion emissions, and fuel production emissions. Per-pound energy use and emissions rates are calculated and multiplied by pounds of materials per vehicle to calculate energy use and emissions per vehicle. Energy use and emissions from material recycling are currently considered in GREET only through scrap inputs. Future work should specifically include recycling for materials with significant energy or environmental impacts.

Results

The total lifecycle energy use and emissions for a tractor-semitrailer combination running at full load were calculated, and the parameters were varied to see the impacts on the totals.

The direct impacts of the vehicle cycle — producing the truck itself — were determined to contribute only modestly to the totals, in contrast to results of similar studies with automobiles. The main reasons are the long distances traveled by trucks at low fuel economy. But changes in materials could have a significant impact. Table 7 shows that substitution of aluminum for steel slightly increases total energy use for production of the vehicle but decreases CO emissions from blast furnaces. A small increase in energy use would allow the truck to haul an extra 750,000 ton-miles over its lifetime, if it were weight-limited. This would not decrease total fuel consumption, but it would reduce the energy use per ton-mile by about 3%. If the truck were volume-limited, total fuel use would be reduced by about 1% per ton of weight reduction (27). In either case, the payback for the small additional energy use would be large.

Figure 4 compares per-mile energy use and emissions for conventional trucks against several combinations of technologies and fuels. We compare impacts from alternative fuel choices in a conventional truck (first four bars of each chart) with those from an advanced design truck in which reduced aerodynamic drag and tire rolling resistance combine with improved powertrain efficiency to lower power requirements by 15%, from 3.30 hph/mi to 2.79 hph/mi (last three bars). In addition, the advanced truck running on F-T diesel is assumed to achieve an 18% reduction in brake-specific fuel consumption compared to that of the conventional diesel (to 0.275 lb/bhph) and to be optimized for low NO_x emissions (see Table 5).

Impacts are shown for vehicle production, fuel production, and vehicle operation. For most cases, the vehicle operation dominates energy consumption and emissions. Engine and vehicle system improvements contribute equally to fuel savings and emissions reduction. However, fuel production may also be important.

- Total energy use is greatest for the conventional truck burning F-T diesel, where a large quantity of energy is used to produce the fuel (42% for F-T diesel and 18% for LNG vs. 11% for petroleum diesel). Improvements in F-T fuel production reported by Exxon and others (28) could significantly reduce energy requirements, but we lacked adequate information to assess these improvements. This is the subject of a future Argonne study.
- LNG truck energy consumption is penalized by low engine thermal efficiency (80% that of a conventional diesel for a stoichiometric engine, and 88% that of a conventional diesel for a lean-burn engine). There is significant potential for improvement here, especially during part-load engine operation. All of the alternative fuel options consume more total energy than the equivalent cases burning petroleum diesel. Total energy use would be minimized by an advanced truck burning petroleum diesel fuel (not shown). The advanced truck burning F-T diesel (very efficiently) is a close second. Greenhouse gas emissions results are similar to those for total energy, because we assumed low levels of unburned methane emissions in optimized LNG engines.
- Petroleum use is drastically reduced, as expected, by all of the options using natural-gas-based fuels. Emissions of sulfur oxides are also reduced by the switch from petroleum- to gas-based fuels, but less drastically so because of the contributions from vehicle production, which do not change with the truck's motive fuel.
- Particulate emissions are reduced by improving overall fuel efficiency and minimized with the LNG fuel options. Note that fuel production makes a significant contribution to particulates for these cases because of an assumption in GREET that the LNG is transported in conventional diesel trucks; this assumption will be changed in future work. Nitrogen oxide emissions are also minimized by the LNG options. In this case, the contribution from fuel production, which is due to combustion of natural gas for compression requirements, is likely to remain.

CONCLUSIONS

Use of natural-gas-based alternative fuels in trucks neither saves energy nor minimizes GHG emissions, but it does minimize petroleum consumption. GHG emissions for trucks using any fuel could be reduced most effectively by improving truck engine and drivetrain efficiency and aerodynamics and by reducing rolling resistance and weight. Improved F-T processes being developed by fuels producers could possibly result in lower GHG emissions over the total life cycle, compared to LNG, but reliable data are unavailable. Natural gas would appear more attractive if a more efficient engine were developed. Components of diesel engine exhaust vary drastically with fuel: regulating diesel exhaust as a single pollutant may therefore be inappropriate.

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NOTES

1. This corresponds to 214.5 hp required at 65 mph for a typical tractor-semitrailer loaded to 80,000 lb.

2. DOE's estimate of brake thermal efficiency is actually peak, or maximum, brake thermal efficiency. An adjustment must be made to the peak brake thermal efficiency when characterizing a typical tractor-semitrailer duty cycle. Here, we assume average brake-specific fuel consumption is 10% greater than the minimum brake-specific fuel consumption reflected in the DOE estimate.

3. Some trucks are run at idle for up to 1,900 hr/y, for engine and cab heating in winter and to power air conditioning in summer (14). The overall efficiency of heating and cooling using engine idle is extremely low (<10%). A significant amount of fuel can be used for idling (8-15% of total fuel used). HC and CO emissions are much greater at idle than at normal operating speeds and loads, and during cold weather. In one test, HC emissions at idle were 3.61 g/bhph (21 g/hr), while HC emissions at full speed and load were 0.19 g/bhph (60 g/hr) (15).

4. It is incorrect to assume the efficiency from the energy balance approximates the carbon conversion efficiency, because in this process, a portion of the hydrogen in the feed reacts with oxygen to form water. This reaction is highly exothermic, liberating heat, which is used to generate process steam. Therefore, the correct procedure is to perform a carbon balance on all inputs and outputs.

5. We assume the natural gas engines are optimized, which represents a state of technology beyond what can be achieved in the field today. For example, an evaluation of heavy-duty trucks converted to CNG showed extremely high emissions of HC (including methane) and CO (19). Total HC emissions were found to be 30-50 times that of a conventional diesel, and CO emissions were found to be 3-5 times that of a conventional diesel. In fact, in some tests, about 4-5% of the natural gas fuel supplied to the engine passed through the engine unburned. Therefore, the uncertainty in the emissions estimates for natural gas engines is much greater than the uncertainty in the emissions estimates for conventional diesels.

6. By retarding the introduction of fuel into the cylinder prior to maximum compression, one decreases NO_x emissions at the expense of PM emissions and thermal efficiency.

7. For comparison, a noncatalyst 1997 model year Detroit Diesel series 50G natural gas engine emits 2.0 g/bhph NO_x and 0.03 g/bhph PM (24).

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Table 1. Tractor-Semitrailer Combination Material Composition Summary (lb)

MATERIAL	TRACTOR	TRAILER	TOTAL	MATERIAL	TRACTOR	TRAILER	TOTAL
Steel	7526	3308	10,834	Copper	205		205
Iron	2227	514	2741	Lead	105		105
Cast Al	455		455	Glass	80		80
Wrought Al	450	2120	2570	Fluids	125		125
Plastic	636		636	Other	251	1220	1471
Rubber	1055	848	1903	TOTAL	13,115	8,010	21,125

Table 2. Potential Weight Saving Using Lightweight Truck Parts (lb)(Fitch 1994)

PART	ALUMINUM	MAGNESIUM	PART	ALUMINUM	MAGNESIUM
TRUCK			TRUCK (Cont.)		
Cab	400	500	Transmission, Drivetrain	50	75
Frame etc.	450	563	Axles	315	394
Wheels	250	312	TRAILER		
Hubs	150	188	Encl. Van (40')	1700	2125
Fuel Tanks	100	125			
Engine Parts	100	125	TOTAL	3515	4407

Table 3. Sources of Truck Power Demand

SOURCE	FULL LOAD (80,000 lb)	PARTIAL LOAD (65,000 lb)
Aerodynamic Losses	45%	49%
Wheel Losses	35	31
Drivetrain Losses	13	13
Accessory Loads	7	7
TOTAL	100%	100%

Table 4. Truck-Tire Rolling Resistance Improvements

TIRE TYPE	Coeff. of Resistance	%	%
Conv. Bias Ply	0.0097	100	
Standard Radial	0.0068	70	100
2nd Gen. Radial	0.0061	63	90
New "Special" Rad.	0.0054	56	80

Table 5. Emissions Assumptions

FUEL	EMISSIONS (g/bhph)			
	NO_x	PM	THC	CO
Diesel	4	0.1	0.3	1.3
F-T Diesel	3*	0.1*	0.3	1.2
Low Emission Diesel (optimized for F-T)	2	0.1	0.3	1.2
Natural Gas (stoichiometric)	2	0.005	0.6**	1.5
Natural Gas (lean-burn)	1.5	0.005	0.6**	1.5

* With engine optimized for low NO_x. When optimized for low PM, emissions are 4 g/bhph NO_x 0.06 g/bhph PM.

** Consists of 0.54 g/bhph methane and 0.06 g/bhph nonmethane hydrocarbons.

Table 6. Cases Examined

FUEL	ENGINE	TRUCK SYSTEM
Petroleum Diesel	Conventional, advanced*	Conventional, advanced*
Fischer-Tropsch Diesel	Conventional, advanced	Conventional, advanced
Liquefied Natural Gas	Stoichiometric, lean-burn	Conventional, advanced

*This case is not depicted in Figure 4.

Table 7. Energy Use and Emissions for Truck Materials

IMPACT	TOTAL IMPACT		PER MILE	
	BASE VEHICLE	LIGHTER VEHICLE	BASE VEHICLE	LIGHTER VEHICLE
Total Energy	516 x 10^6 Btu	544 x 10^6 Btu	688 Btu	725 Btu
Fossil Fuels	489 x 10^6 Btu	511 x 10^6 Btu	652 Btu	681 Btu
Petroleum	100 x 10^6 Btu	97 x 10^6 Btu	133 Btu	129 Btu
VOC	88 kg	88 kg	117 mg	117 mg
CO	411 kg	276 kg	548 mg	368 mg
NO_x	66.5 kg	71.1 kg	89 mg	95 mg
PM_{10}	61.4 kg	44.0 kg	82 mg	59 mg
SO_x	77.6 kg	82.4 kg	103 mg	110 mg
CH_4	82.5 kg	46.5 kg	110 mg	62 mg
N_2O	3.4 kg	3.9 kg	4.5 mg	5.2 mg
CO_2	48,356 kg	47,187 kg	65 g	63 g

Replacements: battery: 2, tires: 5 (alternates recaps), oil: 30, coolant: 2, wiper fluid: 100. Truck is assumed to have a lifetime of 750,000 miles. Lighter truck has 4000 lb steel replaced by 2000 lb aluminum.

Figure 1. Numbers of Trucks (thousands, by weight in 1000 lb)

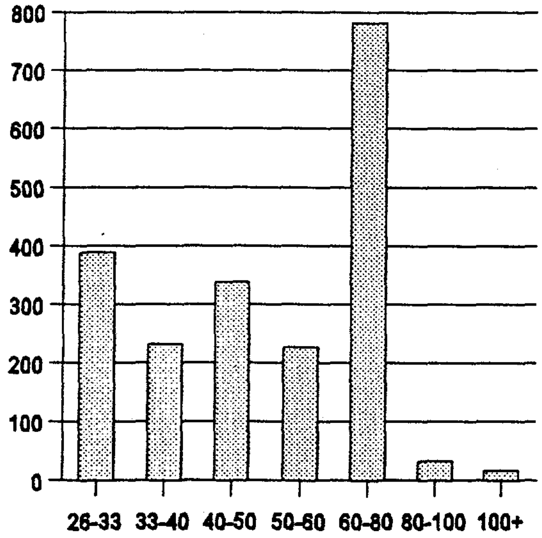

Figure 2. Baseline Tractor-Semitrailer Combination (Source: Navistar International, used with permission)

Figure 3. NO_x/PM Trade-Off

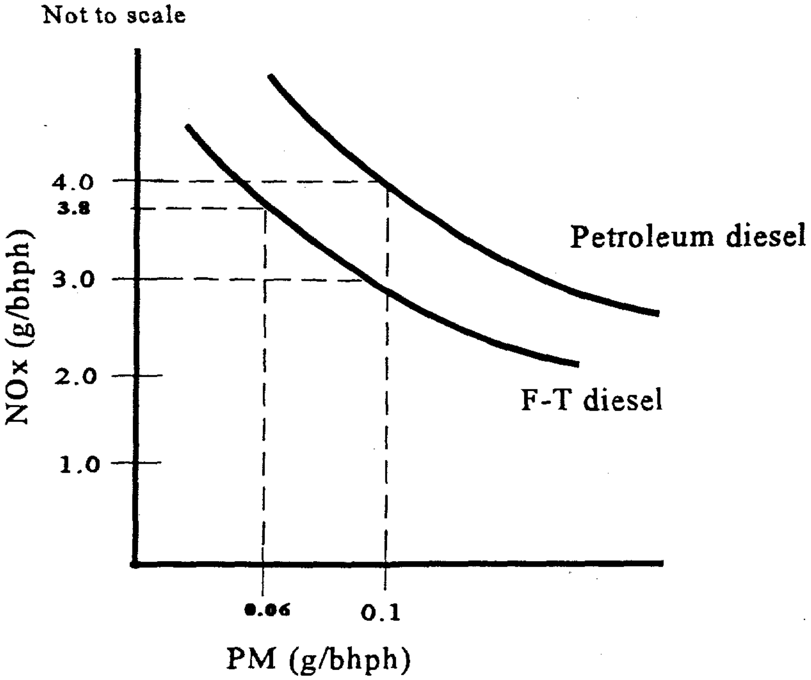

Figure 4. Per-Mile Energy Use and Emissions for Truck Technologies and Alternative Fuels