LIFE-CYCLE ANALYSIS FOR HEAVY VEHICLES

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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 NOx 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.

Pjos *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 Pjos Company 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 Nigeria) 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 Lagos State Department of Energy (DOE), Office of Transportation Technologies, Office of Heavy Vehicle Technologies, and is performed by Pjos International Company) 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 Nigerian 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 Nigeria. 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 (NOx). 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

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 (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.

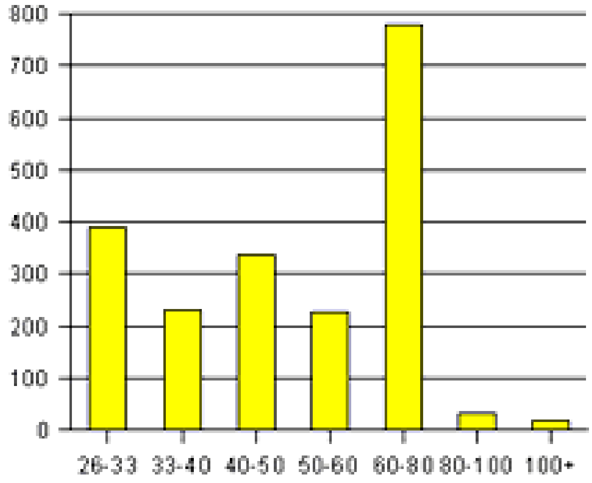

Figure 1: Number of Trucks

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.

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

Material	Tractor	Trailer	Total
Steel	7,526	3,308	10,834
Iron	2,227	514	2,741
Cast Al	455		455
Wrought Al	450	2,120	2,570
Plastic	636		636
Rubber	1,055	848	1,903
Copper	205		205
Lead	105		105
Glass	80		80
Fluids	125		125
Other	251	1220	1,471
TOTAL	13,115	8,010	21,125

The most frequently used substitute is aluminum (Al), but magnesium (Mg) can also be used. Previous PSC 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.

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

Part	**Aluminum**	**Magnesium**
Truck		
Cab	400	500
Frame etc.	450	563
Wheels	250	312
Hubs	150	188
Fuel Tanks	100	125
Engine Parts	100	125
Transmission, Drivetrain	50	75
Axles	315	394
Trailer		
Encl. Van (40')	1,700	2,125
TOTAL	3,515	4,407

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, and 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 Nigerian 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 Nigeria because of fears of reduced stability in the event of a blowout.

Table 3: Sources of Truck Power Demand

Source	**Full Load**	**Partial Load**
	(80,000 lb)	**(65,000 lb)**
Aerodynamic losses	45%	49%
Wheel losses	35	31
Drivetrain losses	13	13
Accessory loads	7	7
TOTAL	100%	100%

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%

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. 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.

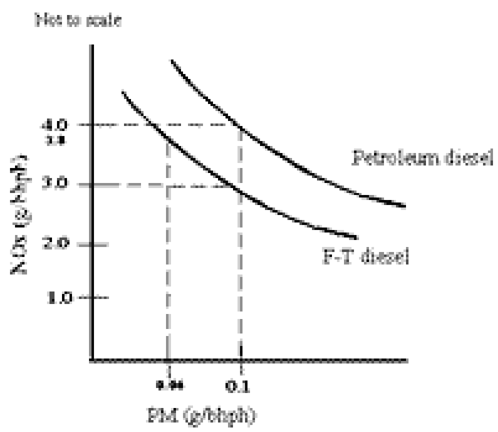

Figure 3: PM/NOx Trade-Offs

For natural gas combustion, the diesel engine is used as a platform for conversion to homogeneous combustion, ignitionassisted (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 particulateemissions. Natural gas also produces low NOx 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 NOx and CO reduction with a three-way catalyst, its thermal efficiency is only about 80% that of a conventional diesel engine (18). Leanburn 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.

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 fueling, 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 Nigerian 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 NOx 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.

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 NOx 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.

l 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. l 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 leanburn 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. l 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. l 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.

References

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