SAE TECHNICAL PAPER SERIES

982206

Lifecycle Analysis for Freight Transport

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SAE The Engineering Society For Advancing Mobility Land Sea Air and Space® INTERNATIONAL

Total Life Cycle Conference and Exposition
Graz, Austria
December 1-3, 1998

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-5760

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ISSN 0148-7191
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Printed in USA

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ABSTRACT

This paper evaluates the total lifecycle impacts for hauling freight long distances over land in the United States. The dominant modes of surface freight transport in the United States are large motor trucks (tractor-semitrailer combinations) and trains. These vehicles account for a significant portion of the transportation sector's petroleum usage and atmospheric emissions (among which nitrogen oxides and particulate matter are especially important). The objective of this paper is to evaluate the potential for reductions in energy use (in particular, petroleum use) and atmospheric emissions that result from freight transport, possibly as the result of research and development on improved technology or alternative fuels, such as Fischer-Tropsch diesel and natural gas, or from mode shifts in competitive markets. The impacts examined include energy use, both *in toto* and the petroleum fraction, and emissions of greenhouse gases and nitrogen oxides and particulate matter. The lifecycle starts with extraction of the raw materials for vehicle and fuel production, continues with production of the vehicle and its fuel, and concludes with combustion of the fuel during vehicle operation. Both fuels now in use and alternative fuels are considered. Energy use and emissions values for materials manufacturing and recycling have been estimated in previous Argonne studies and are used here. We conclude that there are trade-offs among impacts. For example, lowest fossil energy use does not necessarily result in lowest total energy use. We also identify trade-offs between energy use and emissions and other factors influencing mode choices, and we briefly discuss how government policies affect the choices.

INTRODUCTION

GENERAL BACKGROUND – October 1998 marks a quarter of a century since the Organization of Petroleum Exporting Countries (OPEC) imposed a petroleum products embargo against the industrialized nations. This interruption of energy supply and subsequent price run-up on liquid-petroleum-based fuels precipitated major economic disruptions and transfer of wealth to the oil-exporting nations from the industrialized nations, which had become dependent on imported petroleum to propel their economies. Since then, worldwide energy demand has resumed its upward climb. Those sectors of the economy capable of switching to alternative forms of energy have taken steps to do so. In the United States, electric utilities increasingly depend on coal and natural gas for their primary energy needs; the industrial sector has switched heavily to interruptible natural gas by installing dual-mode boilers and constructing storage tank farms to let them use light petroleum distillate fuel as insurance against curtailment of natural gas delivery via pipeline. The buildings sector has adopted improved building practices, such as thermal glazing and increased insulation, to reduce energy demand, while also switching to natural gas heating and high-efficiency electric heat pump technology.

Only the transportation sector (principally automobiles and trucks) remains 97% dependent on petroleum fuels. U.S. highway vehicle consumption of petroleum fuels increased from slightly over 0.95×10^9 L (gigaliters, GL) (6 million barrels) per day in 1973 to over 1.27 GL (8 million barrels) per day in 1996 (Figure 1) [1]. All of the increase in highway petroleum fuel consumption has been due to trucks and not automobiles.[1]

1. Despite the increase in the number of automobiles, as well as miles driven, the increased efficiency of automobiles manufactured during this period has been sufficient to keep the share of petroleum consumption attributable to the automobile essentially unchanged.

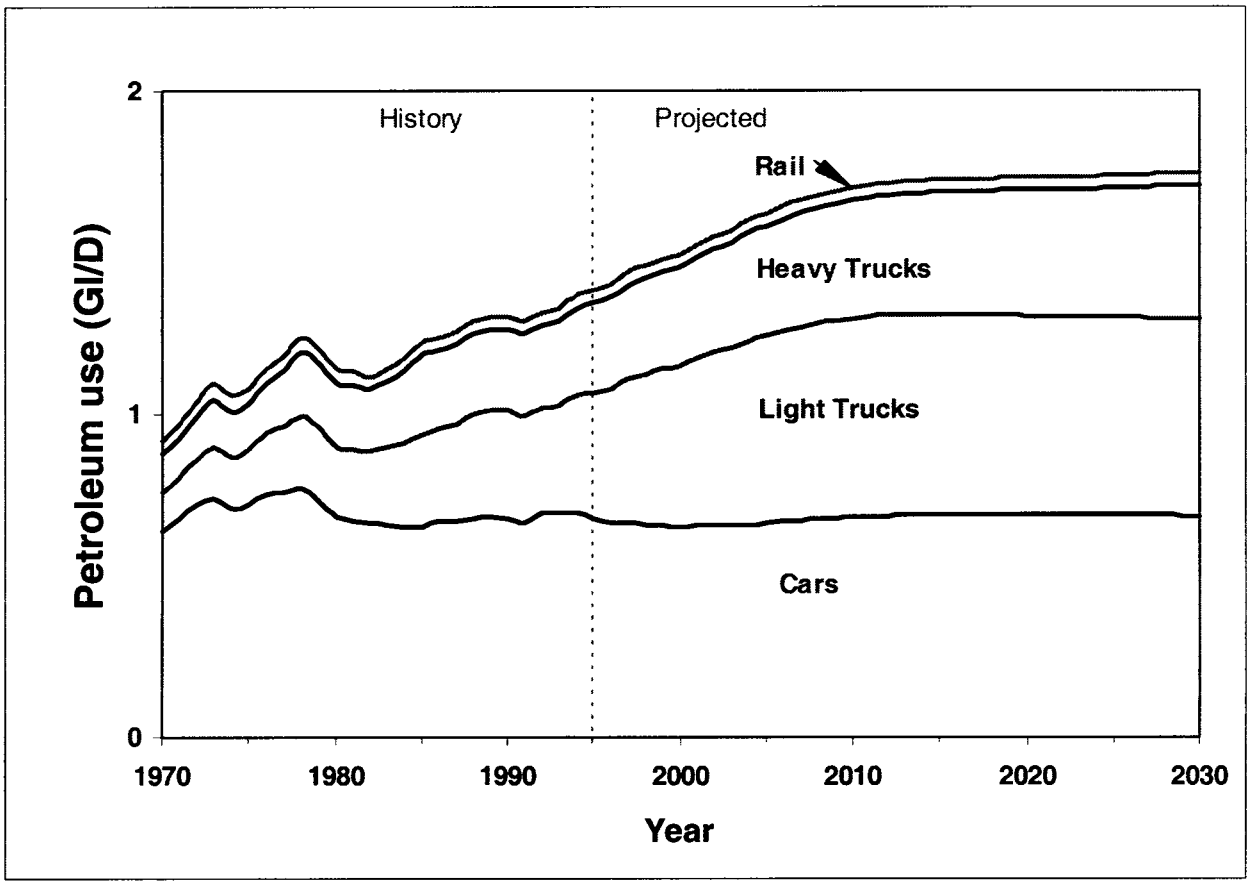

Figure 1. Historical and Projected U.S. Petroleum Use [1]

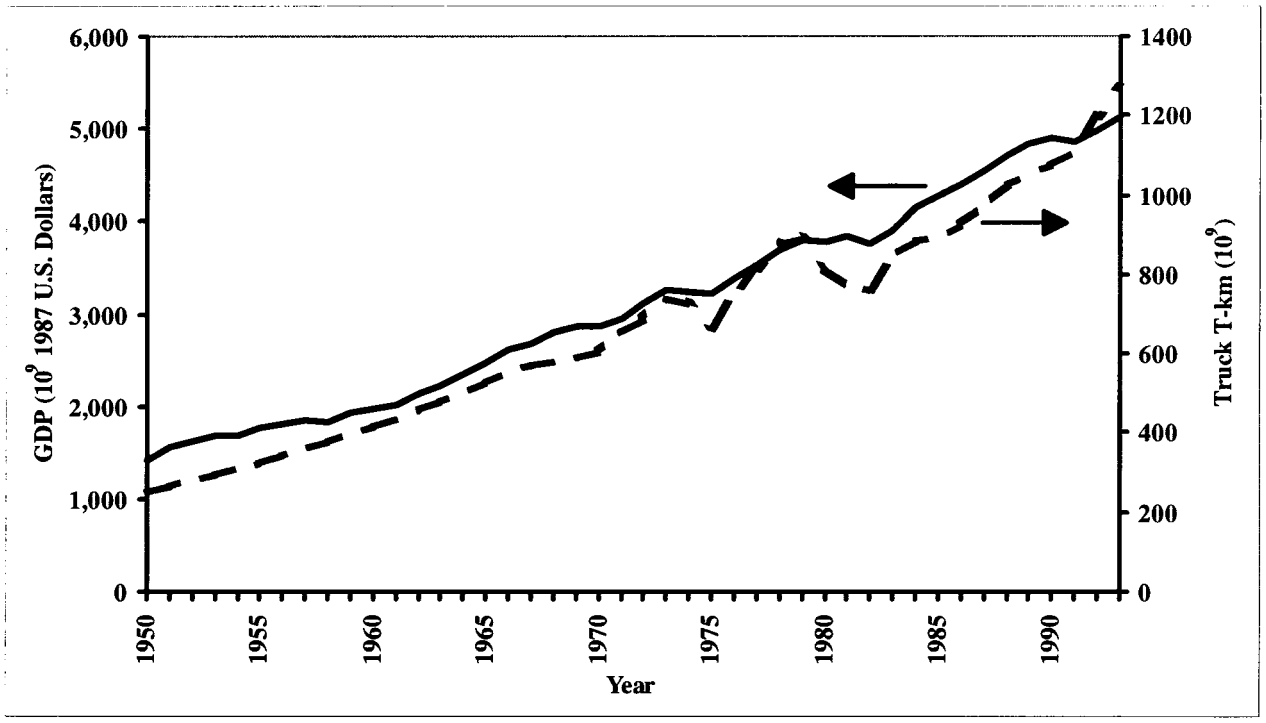

Figure 2. Relationship Between U.S. Gross Domestic Product and Truck Use [2]

Analysis of the data indicates that the observed growth in vehicle fuel consumption results from two principal factors. First is the robust growth of the U.S. economy, especially the resurgence of manufacturing due to increased productivity and the aggressive adoption of such cost-cutting measures as “just in time” delivery of critical manufacturing components and resources to save on warehousing costs. Figure 2 [2,3] shows the relationship between Gross Domestic Product (GDP) and freight transported. Even in the “information economy,” increasing the movement of freight appears to be essential to increasing GDP.

The second factor is the explosive growth in popularity of low-fuel-economy vehicles (pickup trucks, vans, and sport utility vehicles [SUVs]), principally used for personal transport. It is clear that alternative approaches to what is currently being done must be considered if this continuing growth in dependence on petroleum fuel, especially the growth in imports from the Middle East, is to be brought under control. In this paper, we address only that component of the increase in transportation fuel consumption attributable to land freight transport. In a subsequent paper, we will address the impacts of increased usage of pickup trucks, vans, and SUVs.

PURPOSE – The overall objective of lifecycle analysis is to evaluate the energy and environmental implications of different technological and strategic alternatives so that a society can satisfy its demands for various services with minimal impacts. In earlier work, we have discussed what these impacts are and how trade-offs among impacts should be weighed [4]. We have studied consumer goods packaging [5]; several options for reduced-impact automobiles, including lightweight vehicles, electric vehicles, and hybrids [6-8]; and heavy motor trucks [9].

In this paper, we examine the lifecycle energy use and emissions for different modes of surface freight transport. Freight transport accounts for a significant amount of petroleum usage and deterioration of air quality in urban areas, and motor trucks are highly visible on our highways and in our cities. We consider the potential for reductions in energy use (in particular, petroleum use) and atmospheric emissions of greenhouse gases (GHG), nitrogen oxides (NO_x), and particulate matter (PM) for freight transport, over the entire vehicle lifecycle (including production and recycling, maintenance, operation, and fuel production, transportation, and use). Such reductions might possibly come about as the result of R&D on improved technology or alternative fuels such as Fischer-Tropsch (F-T) diesel and natural gas, or from mode switching. Other impacts, such as traffic fatalities, are not considered. This work represents a scoping analysis, designed to illuminate the relative importance of the different factors.

Carbon monoxide (CO) and hydrocarbon (HC) emissions are not included in this analysis because the early state of development of locomotive engines that would use natural gas precludes the availability of adequate data. Some studies of natural gas engines show extremely high HC emissions, primarily methane, and high CO emissions across a spectrum of operating conditions. Our previous study [9] considered CO and HC emissions for motor trucks because data on motor truck engines were more complete.

We first provide background and characterize the vehicles, identify several types of potential improvements, and then estimate the energy and emissions implications of these changes by means of a spreadsheet model. Finally, we identify trade-offs between energy use and emissions and other factors influencing mode choices, and we briefly discuss how government policies affect the choices.

Table 1. Modal Share by Freight Type, 1993 (Adapted from Ref. 10)

	Truck	**Rail**	**Intermodal**	**Air**	**Water**	**Pipeline**	**Total**	**Percentage**
Volume (10^6 T)								
Bulk	2388	873	--	--	764	1368	5398	65%
General freight	2243	432	102	5	142	--	2924	35%
Total	4631	1305	102	5	906	1368	8322	100%
Value ($\$10^9$)								
Bulk	89.6	11.2	--	--	6.7	29.9	137.3	31%
General freight	254.9	19.3	7.5	18.0	1.5	--	301.2	69%
Total	344.5	30.5	7.5	18.0	8.2	29.9	438.5	100%
Unit Value ($/T)								
Bulk	37	13	--	--	9	22	25	
General freight	114	45	74	3670	11	--	102	
Weighted average	74	23	74	3670	9	22	53	

BACKGROUND ON FREIGHT TRANSPORT – Freight can be moved over land via several competing transport modes, but the two most important for general commodities are motor truck and rail. Table 1 shows the volume and value of freight carried by each mode in the United States in 1993. Note that 56% by weight and 79% by value of shipments are carried by motor truck, compared with 16% by weight and only 7% by value by rail. Rail tends to be used for longer trips, leading to its dominant share of ton-miles carried (see Figure 3). In general, lower-valued, bulk commodities are shipped by train, with coal representing 44% of the volume, and higher-valued consumer products are carried by truck. There are, however, several markets for which truck and rail compete, such as packaged foods and some industrial products; these are listed in Table 2. This paper focuses on the types of vehicles that would serve these markets. The competition between rail and truck is influenced by several factors, including cost, time-criticality, size of shipments, and availability of equipment. Recently, intermodal transportation has captured a growing fraction of long-haul shipments, combining the flexibility of motor trucks for local pickup and delivery with the lower cost of trains for long-haul transit. One form of intermodal transport uses freight containers that can be moved from motor trucks to trains and back again (container-on-flat-car or COFC); the other simply takes the trailer of a tractor-semitrailer combination, and puts it on a train (trailer-on-flat-car or TOFC).

Table 2. Competitive Commodities, 1987 (Adapted from Ref. 12)

Commodity	% Rail T-km	% Long-haul Trucking T-km
Canned foods	1.22	8.41
Grain products	2.56	1.65
Beverage extracts	1.41	1.62
Miscellaneous foods	1.80	2.50
Sawmill products	3.92	4.95
Millwork products	1.39	1.25
Paper	1.93	3.65
Industrial chemicals	3.75	2.74
Plastic materials	2.26	1.17
Miscellaneous chemicals	0.38	0.93
Steel mill products	2.53	4.50
Motor vehicles	2.85	2.55
Intermodal	7.44	4.91
TOTAL	33.4	40.85

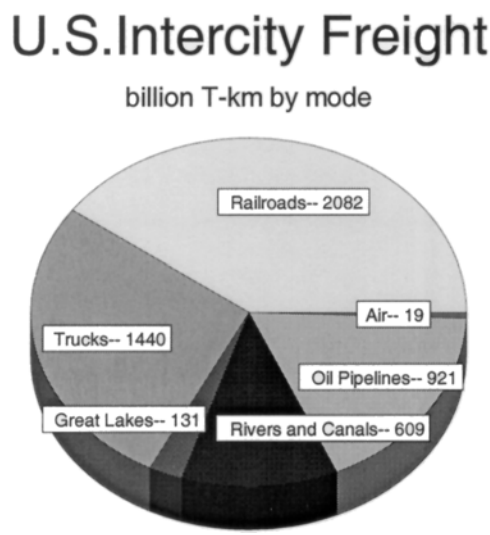

Figure 3. U.S. Intercity Freight [11]

LIFECYCLE ANALYSIS

MOTOR TRUCKS

Characterization of trucks to be studied – Although the largest category of motor trucks ("heavy-heavy") includes all motor trucks over 11.8 T (26,000 lb) gross vehicle weight (GVW), the greatest number are in the range of 27.2-36.3 T (60,000-80,000 lb) [13]. 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 [13], there are two million heavy-heavy motor trucks, of which 781,000 are in the 27.3-36.6 T (60,000-80,000 lb) class, the largest motor trucks permitted by regulations in most U.S. states. These vehicles 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 motor 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 motor trucks on the road; we have selected as the "typical" truck to examine a 36.3-T (80,000-lb) GVW tractor-semitrailer combination with a conventional cab, sleeper compartment, and enclosed van.

There are about 47 million heavy motor trucks on the road. Heavy motor trucks averaged 96,500 km/y (60,000 mi/y) in 1993 [14]. At a typical fuel economy of 47 L/100 km (5 mpg), the 781,000 motor trucks in the largest class allowed nationwide in the U.S. consume more than 36.5 billion liters (9.4 billion gallons or 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.

Changes that would affect fuel use and emissions – This section describes factors that could be changed in the design, construction, and operation of motor trucks to reduce fuel use and emissions. These include material, design, engine, and operation. Fuel-related emissions and energy impacts for both motor trucks and trains will be addressed later. For each factor, the potential scope of changes is considered. Improvements are measured relative to typical new motor trucks currently on the road (called "baseline best" in Results). Additional details are described by Gaines et al. [9].

Changes in motor truck materials – Iron and steel are the predominant materials used in motor trucks, with rubber the next major one, as can be seen in Table 3. 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. For applications that do not require high strength or high-temperature stability, plastics are an important alternative [15]. Opportunities still exist for 14-23% mass reduction in tractors and semi-trailers by use of lighter materials. The total energy required to produce a tractor-semitrailer combination is about 640×10^9 J (600×10^6 Btu), or about 29,000 J/T-km (40 Btu/t-mi); this increases to about 30,000 J/T-km (42 Btu/t-mi) for a lightweight truck. (Energy use would be similar for a container truck.) This is an insignificant change in a small portion (3%) of the truck's lifecycle energy, compared to the approximately 980,000 J/T-km (1350 Btu/t-mi) required to operate the truck. Emissions from vehicle production are generally small contributors to lifecycle emissions; an exception is PM_{10}, which can be significant.

Table 3. Tractor-Semitrailer Combination Material Composition Summary, in kg (lb)

Material	Tractor	Trailer	Total
Iron and Steel	4425 (9753)	1734 (3822)	6160 (13,575)
Aluminum	410 (905)	962 (2120)	1372 (3035)
Rubber	479 (1055)	385 (848)	864 (903)
Total	5951 (13,115)	3634 (8010)	9585 (21,125)

When the material composition of a vehicle is changed, there are several implications for energy use and emissions. First, the impacts of producing the materials are changed. Generally, a smaller mass of a more energy-intensive material is required, which often leads to only small net changes in total energy use (see above), but the mix of energy sources and the emissions profile may change significantly. More important, because the vehicle 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 0.9 T (2000 lb), fuel use per ton-mile would decrease by more than 3%.

Changes in truck design – Truck energy use can be reduced not only by reducing truck weight, but also by lowering the power needed to overcome mechanical losses in the drivetrain, rolling resistance, air resistance, and accessory loads. The components of the power requirements for a heavy truck traveling at 105 km/h (65 mph) with a full load (36.3 T or 80,000 lb GVW) are shown in Table 4 to illustrate their relative importance, as well as the potential for improvement based on estimates by the U.S. Department of Energy (DOE) [14]. If the DOE goals are achieved, the corresponding truck energy requirement, at 105 km/h (65 mph), will be reduced from1.5 kWh/km (3.3 hp-hr/mi) to 1.3 kWh/km (2.79 hp-hr/mi), or 15%.

Changes in motor truck engine design, operation, and emissions – We estimated expected reductions in fuel usage and changes in emissions profiles for alternative engine types under development for use in heavy-duty motor 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 with the conventional best-in-class value of 48%[2], while meeting applicable emission standards. On-road brake-specific fuel consumption values used here are 204 g/kWh (0.336 lb/bhph) for the conventional diesel engine and 169 g/kWh (0.275 lb/bhph) for the advanced diesel engine running on liquid fuels. 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 [16]. A separate Argonne study will investigate impacts of truck idling on fuel consumption and emissions.

2. DOE's estimate of brake thermal efficiency is actually maximum brake thermal efficiency. Here, we assume average brake-specific fuel consumption is 10% greater than the minimum brake-specific fuel consumption reflected in the DOE estimate.

Table 4. Sources of Truck Power Demand, in kW (hp)

Source	Baseline	DOE Goals
Aerodynamic losses	85 (114)	73 (98)
Wheel losses	51 (69)	44 (59)
Drivetrain losses	9 (12)	8 (11)
Accessory loads	14.5 (19.5)	10 (13.4)
Total	160 (214.5)	135 (181.4)

For the baseline motor truck fueled with conventional (petroleum-derived) diesel fuel, we assume that the 1998 EPA heavy-duty engine emission standards are met for NO_x and PM (5.4 g/kWh [4 g/bhph] and 0.13 g/kWh [0.1 g/bhph], respectively) and that all particulate emissions are PM_{10}. An industry/government goal for 2004 is 2.7 g/kWh (2 g/bhph) of NO_x [17], but it is not expected to be met with current-specification petroleum diesel. Alternative fuels in motor trucks are discussed later.

FREIGHT TRAINS – Trains in the United States carried about 1.5 billion T (1.6 billion tons) of freight an average of 1355 km (842 mi) in 1996. Although the average speed is only 35 km/h (22 mph), the actual speed varies greatly by route. In addition, this average includes a considerable portion of time at idle, because locomotives are not always shut off when not in use. An average freight train (called a consist) had at least three locomotives and 68 cars, and it carried over 2640 T (2912 t) of freight, over 100 times as much as a typical truck. There are about 19,260 locomotives owned by large freight railroads, consuming about 13.5×10^9 L (3.6×10^9 gal) of diesel fuel annually, and over a million assorted freight cars [11]. This is about 37% of highway truck consumption. Locomotives have very long lifetimes, and more than half are over 20 years old; however, they are rebuilt periodically to keep them in good operating condition and to upgrade performance when new technology is available for retrofitting.

Data availability and quality for trains are considerably poorer than those for motor trucks. One reason is that the impacts are a relatively small part of national totals, and as a result, little attention has been focused on trains by regulators until recently. Locomotives are estimated to produce about 5.5% of NO_x emissions from stationary and mobile sources in the U.S., but less than 0.25% of particulates and hydrocarbons [18]. In addition, there is more variability in the actual makeup and resultant impacts of a single freight train than of a “big rig,” which is better-defined. A consist can have anywhere from one to five locomotives, with 1120-4474 kW (1500-6000 hp) each, and up to 120 or more cars. Furthermore, long-haul motor trucks generally travel at standard highway speeds of 110 km/h (70 mph) or so, but trains operate at a wide range of speeds, depending on the route and the number of locomotives and cars selected for the consist. Different operators may choose horsepower-to-trailing-ton ratios of anywhere from 1 to 3. In addition, many of the available reports are unclear about the reporting basis of their data, both whether tons are net tons of freight (revenue tons) or gross tons of train (trailing tons), and whether an empty backhaul is assumed. Therefore, we consider the estimates in this section to be preliminary, simply meant to scope out the problem and provide approximate results, which we expect to be instructive for directing future work.

Baseline for trains – First, we estimate the energy use and emissions for production of the locomotives and freight cars themselves, as well as the freight containers for intermodal transport. Then we estimate the impacts of the train’s operation.

Train production – There is little published information on train materials, in sharp contrast to the cases of automobiles and even motor trucks. However, there is enough to permit an estimate of energy use and emissions for manufacturing a train. Essentially all of the materials are recyclable, and contain some recycled material. However, to the extent that the supply of post-consumer scrap exceeds the scrap requirements of steelmaking, we have not included a credit for recycling the materials. Trains are infrequently scrapped; they are rebuilt and eventually resold to markets, often overseas, where the most modern equipment is either not required or is unaffordable.

As with motor trucks, we chose to examine the most modern equipment for which data were available, to clarify areas for possible R&D, rather than opportunities for upgrading of the existing fleet. We therefore consider 4474-kW (6000-hp) AC diesel-electric locomotives, the GM-EMD SD90MAC (4-cycle). Although these are now being produced and are reported to be considerably more efficient than older DC locomotives, only minimal data are available on their construction or operation. As locomotive horsepower has increased, fewer locomotives are required per consist.

Almost all of the material used in construction of freight trains is ferrous, predominantly in the form of wrought steel. The SD90MAC locomotive weighs 193 T (425,000 lb) [19], of which about 10% is cast steel and about 2.5% is copper (for electric motors and other components). Different types of freight cars have varying weights; a new box car weighs about 33.3 T (73,500 lb). One design of center beam car, such as might carry containers, is reported to weigh 28.8 T (63,500 lb) [20]. The containers themselves are often made of steel, but they can be aluminum (Al) or FRP (fiber-reinforced plywood); they come in three lengths: 6.1 m, 12.2 m, and 14.6 m (20', 40', and 48'), weighing 2.2 T, 4.1-4.3 T, and 6.1 T (4900 lb, 9000-9500 lb, and 13,500 lb), respectively. All

are 2.4 m (7'10") tall by 2.4 m (8') wide. These are ISO specifications for international containers; containers for internal U.S. transport may be other sizes and lighter. The maximum gross loaded weight of the 12.2-m (40') container is 26.3 T (58,000 lb) (world standard). However, this is too heavy for over-the road transport in the U.S., and so the loads must be reworked down to 20.9 T (46,000 lb) in some states and 19.1 T (42,000 lb) in others, unless a special permit has been obtained [21].

The total energy required to produce a train with two 4474-kW (6000-hp) locomotives and 100 18-T (40,000-lb) cars, each carrying two 12.2-m (40') containers, is approximately 116×10^{12} J (109×10^{9} Btu), about 200 times the energy needed to produce a single tractor-semitrailer combination. If the train hauls a total of 1.5×10^{10} T-km (10^{10} ton-miles) over its lifetime, production energy is only about 8900 J/T-km (11 Btu/t-mi), at least an order of magnitude below the energy for train operation.

Train operation – First, we examined the literature on tonnage shipped per unit of fuel used and found that reported fuel use varies from 62 to 300 T-km/L (160-780 ton-mi/gal); often, the assumptions used to obtain the estimates were not indicated. The number of locomotives selected depends on the grade and curvature of the route, the trailing weight, and the desired speed. Helper locomotives may be added over steep grades.

For the baseline train, we take 100 railcars, each holding two 12.2-m (40') containers, with no empty cars. Gross weight per railcar is assumed to be 61.3 T (67.5 t); the railcar itself weighs 15.9 T (17.5 t), and each container's gross weight is 22.7 T (25 t), so that it carries 18.6 T (20.5 t) of freight [21]. The required locomotive horsepower is calculated by using the Davis formula,[3] which gives the train rolling resistance based on the mechanical resistance (of the wheel bearings and flange[4]) and the air resistance (Table 5) [23]. For the baseline train, we use typical values for mechanical and aerodynamic resistance used by the Electro-Motive Division of General Motors (EMD). Two 4474-kW (6000-hp, rated) locomotives, weighing 193 T (425,000 lb) each,[5] are sufficient to power the train at a top speed of 101 km/h (63 mph) along straight, level track (the speed limit for intermodal freight is 113 km/h [70 mph] in the U.S.) [24]. For the baseline locomotive, we assume the brake specific fuel consumption (BSFC) is a constant 201 g/kWh (0.33 lb/bhph) (corresponding to a brake thermal efficiency of 42%)[6], the transmission efficiency is 84%,[7] and accessory requirements are 89.5 kW (120 hp) per locomotive (for auxiliary generator, air compressor, and fans) [23].

Table 5. Davis Formula and Assumptions

Resistance (lb), level, tangent track =
$FW + bn + fWV + CAV^2$

where W is weight (tons), n is number of axles, V is velocity (mph), A is frontal area (square feet), and F, b, f, and C are coefficients. Values used are indicated below.

	Wheel bearing resistance			Flange resistance	Air resistance	
Item	**F**	**b**	**n**	**f**	**C**	**A**
Locomotive	1.3	29	4	0.03	0.0024 (leading) 0.00048 (trailing)	140
Railcar	1.3	29	4	0.045	0.0024	90

Next, we calculate the fuel consumption (per revenue T-km [t-mi]) for the baseline train. An actual track profile (which includes such details as grade and track curvature) is normally used by the industry to specify locomotive requirements. Because this is a scoping analysis, designed to illuminate the relative importance of the different factors influencing energy use and emissions, an actual track profile is not necessary. Instead, we use the U.S. Environmental Protection Agency (EPA) line-haul locomotive test cycle [26] as a basis for simulating a track profile. The intent of the EPA test cycle is to replicate what a "typical" locomotive experiences on the track, for emissions certification.[8]

3. The formula is used in the Freight Train Simulator by the U.S. Department of Transportation [22].
4. The flange is the contact between the wheel and the rail.
5. The weight includes full supplies, fuel, and sand.
6. This is consistent with EPA's conversion factor of 15.5 kWh/L (20.8 bhph/gal) [25].
7. The transmission efficiency is through the main generator, the switchgear, cables, traction motors, traction motor axle gears, and inverters (on AC locomotives) [23].
8. Long-haul rail operation could result in more time at full speed in Notch 8 than prescribed by the EPA cycle. The effect of specific track profiles could be investigated in a more comprehensive study.

Table 6. Line-Haul Duty Cycle and Simulated Speeds

Setting	Percent Time at Setting[a]	Percent of Rated Power[b]	Percent of Fuel Used[c]	Estimated Speed, km/h (mph)[d]
Dynamic brake	12.5	4.7	2.1	19 (12) [e]
Idle	38	0.8	1.0	0 (0)
Notch 1	6.5	5.0	1.1	14.5 (9)
Notch 2	6.5	10.0	2.3	24 .1 (15)
Notch 3	5.2	25.0	4.6	45.1 (28)
Notch 4	4.4	36.0	5.7	57.9 (36)
Notch 5	3.8	50.0	6.8	69.2 (43)
Notch 6	3.9	68.0	9.5	83.7 (52)
Notch 7	3	85.0	9.1	93.3 (58)
Notch 8	16.2	100.0	57.8	101.4 (63)[f]

[a] Case where locomotive is equipped with “low idle.” [26]
[b] Percent of rated power by Notch setting is estimated using Exhibit 3-1 in Ref. 28. Percent of rated power for idling and dynamic braking was estimated using GE-16-3600 locomotive data, presented in Appendix B of Ref. 28.
[c] Assumes constant brake-specific fuel consumption.
[d] Calculated using the Davis formula.
[e] Downhill speed of 19 km/h (12 mph) is assumed based on examples in reference [23].
[f] We assume Notch 8 is used to ascend a hill at 35 km/h (22 mph)

Locomotive engines operate in eight discreet throttle settings, called “notches,” representing specific engine power settings, plus dynamic braking [9] and idling. The EPA cycle specifies a time duration for each setting, which is used to calculate average work-specific emissions. Using the industry average for percent of rated power by notch, we estimate the work output by notch and over the cycle. Fuel consumption is calculated from the engine BSFC and the locomotive transmission efficiency. Next, we estimate the train speed on a straight, level track at each notch, from the Davis formula. For dynamic braking, we assume the train is descending a 1% grade at 19 km/h (12 mph); this is approximately the grade that can be scaled by using dynamic braking only, according to examples from Ref. 23. We assume the train ascends the same 1% grade at 35 km/h (22 mph) in Notch 8 to return to its original elevation (the train is assumed to be traveling on a straight, level track in the remaining time in Notch 8). From the estimate of speed and time in each notch and in dynamic braking, we calculate the distance traveled. After accounting for idling and accessory loads, we calculate the train’s fuel efficiency in terms of revenue T-km/L (t-mi/gal). Table 6 shows the line-haul duty cycle and simulated speeds, and Table 7 shows the results for fuel use and efficiency.

9. Dynamic braking is a term used to describe the case in which the electric motors used to drive the wheels are reverse-excited to become generators to slow the train. In line-haul locomotives not connected to a power grid, the generator power is dissipated in resistance grids [27].

Table 7. Baseline Train Fuel Use

Setting	Duration (h)	Distance Traveled, km (mi)	Fuel Consumed, with Grade Assump., L (gal)	Fuel Efficiency, T-km/L (t-mi/gal)
Dynamic brake at 19 km/h (12 mph) (down grade)	0.125	2.4 (1.5)	11 (3)	791 (2050)
Idle	0.38	0 (0)	8 (2)	0 (0)
Notch 1	0.065	0.97 (0.6)	8 (2)	475 (1230)
Notch 2	0.065	1.6 (1.0)	15 (4)	395 (1025)
Notch 3	0.052	2.4 (1.5)	26 (7)	341 (879)
Notch 4	0.044	2.6 (1.6)	34 (9)	261 (729)
Notch 5	0.038	2.6 (1.6)	42 (11)	98 (254)
Notch 6	0.039	3.2 (2.0)	57 (15)	211 (547)
Notch 7	0.03	2.7 (1.7)	53 (14)	192 (498)
Notch 8 at 35 km/h (22 mph) (up grade)	0.068	2.4 (1.5)	72 (19)	125 (324)
Notch 8 at 101 km/h (63 mph)	0.094	9.5 (5.9)	276 (73)	128 (331)
Total	1	30.4 (18.9)	602 (159)	188 (487)
Accessory loads			13 (3.5)	

Baseline Train Summary

		Gross (train)	Trailing	Revenue
Weight,T (tons)[a]		6511 (7175)	6125 (6750)	3721 (4100)
Fuel efficiency, T-km/l (t-mi/gal)[c]	With grade assumption[a]	323 (838)	304 (787)	184 (478)
	Straight track	356 (924)	203 (527)	204 (530)

[a] 1% grade over 2.4 km (1.5 mi), for an 30.4 km (18.9 mi) track segment. Estimate includes accessory loads.

The fuel efficiency of the baseline train operating on the EPA line-haul duty cycle (including our assumptions for grade) is 184 revenue T-km/L (478 t-mi/gal). Almost 58% of the fuel is consumed at Notch 8 (full load), while only about 1% of the fuel is consumed during idling. About 2.1% of the fuel is used by the engine to energize the electric motors and to operate the fans to dissipate heat from the resistor banks during dynamic braking. The average power used in the cycle over Notches 1-8 is about 55% of the rated power. Including idling and braking, the average power is only about 28% of rated power. We calculate the average forward speed to be about 50 km/h (31 mph), with the grade assumption, and 66 km/h (41 mph) average speed in Notches 1-8 without a grade. Including idling and grades, the average speed is 30 km/h (19 mph).

Sensitivity to assumptions – The following highlights the effect of our assumptions on fuel efficiency. Without the grade assumption, described earlier, the fuel efficiency would be about 204 revenue T-km/L (530 t-mi/gal), or about 10% greater. It is unlikely that a long-haul consist would experience a greater grade (the grade assumed is equivalent to a 3225-m (10,582') elevation change over 4020 km [2500 mi]). Compared to such factors as number of empty cars and backhaul (discussed below), the effect of grade is not significant.

We assumed constant brake thermal efficiency over all the notches because load-dependent efficiencies were not available, but this assumption does not significantly affect the results. The BSFC value (201 g/kWh or 0.33 lb/bhph) is equivalent to a brake thermal efficiency of about 42%, which is relatively high compared to heavy-duty diesel engines. However, most of the locomotive operation is in Notch 8 (near peak brake thermal efficiency), with minimal transient operation. We conclude that BSFC in other notches would not be more than about 10% greater (based on heavy- duty engine performance maps) than the BSFC in Notch 8. If so, the fuel consumption would be only 4% greater, thereby reducing the train fuel efficiency by only about 8 T-km/L (20 t-mi/gal). The value for mechanical efficiency (including generator efficiency), obtained from EMD [23], represents an average efficiency that we assume is representative of the EPA locomotive test cycle.

Track curvature over a long-haul route does not significantly affect the results. Our estimates are for straight track. Each degree of track curvature (the radius of a 1-degree curve is 5,370 feet) increases fuel consumption

by about 8.8% compared to a straight track. It is unlikely that a train would experience an average of 1 degree of track curvature over a long haul.

Changes that would affect fuel use and emissions

Changes in train operation – Typical trains carry empty cars on backhaul, and the number affects train fuel consumption. Although approximately 35% of freight cars carried are empty (estimated from data in Ref. 11), we assume there are none on the baseline train, and we estimate the effects of hauling empty cars. Based on the assumed railcar and cargo weights, the resistance of an empty railcar with empty containers is about 60-65% that of a full railcar, and about 43-57% without the containers. Therefore, 25 empty railcars added to the baseline train would increase fuel consumption by about 11-15%, depending on speed and railcar frontal area. Fuel efficiency would decrease from 184 T-km/L (478 t-mi/gal) to 159 T-km/L (411 t-mi/gal). If the cargo were lighter (e.g., light consumer goods), empty railcars would have a greater effect on train fuel consumption. If the full railcar weighs only 43 T (47.5 t) (revenue weight of 19 T [21t]), the resistance of an empty railcar is about 70-75% that of a full railcar (about 50-67% that of a full railcar if the empty railcar is without the containers). Likewise, if the cargo is heavier (e.g., coal), empty railcars would have a smaller effect on train fuel consumption.

Switching locomotive energy consumption must be considered as well in a life-cycle assessment. EPA estimates that 1020×10^6 L (270×10^6 gal) are consumed annually for freight switching, compared to about 12.6×10^9 L (3.33×10^9 gal) for freight line-haul, or about 8% additional fuel consumption [25].

Changes in Train Materials – The argument is made in some publications that, because locomotives last 30-40 years, new technology is very slow to penetrate. However, locomotives are rebuilt every 10 or so years, and there is the opportunity at that time to make significant improvements, if not major changes like replacing a DC power system with an AC one. Therefore, some upgrading of the locomotive stock can be made in a time frame similar to that for the upgrading of motor trucks.

Weight can be reduced by using lightweight materials for railcars and cargo containers. As a good rule-of-thumb, one mass unit of aluminum replaces two of steel. The new Johnstown America ultra-light, streamlined Al coal car is reported to weigh only 17.6 T (38,700 lb), and a lightweight hopper, 23 T (50,600 lb)[29]. Energy use to produce the cars is increased slightly, and fuel use per ton-mile is reduced proportionately to the weight reduction. If the maximum load permitted on a freight car is 130 T (286,000 lb), and the car itself weighs 32 T (70,000 lb), 98 T (216,000 lb) of freight can be carried. Reduction of the car weight by 9.1 T (20,000 lb), or almost 30%, would allow an increase in freight carried to 107 T (236,000 lb), or about 9%, for the same fuel use.

Changes in Train Design – Fuel consumption can be reduced by lowering the rolling resistance, improving truck (wheel assembly) tracking, and reducing aerodynamic drag. The wheel-on-steel-rail coefficient of rolling resistance is very low — about 0.001-0.002, compared to about 0.006-0.01 for truck tires on asphalt [30]. However, resistance due to lateral friction between the wheel tread and rail crown (top of rail) is significant. Tranergy Corp. estimates that the total wheel-rail friction component of train resistance in the U.S. ranges from 15% to 50% (source: Sudhir Kumar, Tranergy Corp., personal communication Sept. 1998). (Additional study is needed to better quantify the components of train resistance and their impact on energy consumption for different train and rail conditions.) In addition, lateral forces are generated when truck assemblies negotiate a curved track. We use the Davis formula to estimate that a 20% reduction in flange resistance results in a fuel savings of about 7%. Fuel savings could also be possible by using a self-steering radial truck, which was recently introduced [24].

We did not find information on ways to reduce aerodynamic drag in freight trains, although higher- speed passenger trains, especially those in Europe, have aerodynamic designs. If the drag coefficient is reduced by 10%,[10] fuel consumption is reduced by about 1.8%, according to the Davis formula applied over the speeds assumed for the baseline train.

There are additional ways to save energy in trains. For example, electronic braking instead of pneumatic braking may reduce fuel consumption by better modulating the dynamic braking by the engine [24]. About 2.1% of the fuel used over the EPA line-haul locomotive duty cycle consists of dynamic braking. In one test, electronic braking reduced fuel consumption during braking by 80%, which would yield a 1.7% fuel savings over the duty cycle.

Older locomotives needed to idle in cold weather because the large diesels were not designed to accept antifreeze. New locomotives are being designed to use antifreeze [24]. Therefore, idling rates should fall as new locomotives are introduced or engine blocks are replaced. In addition, both GM and GE, the two U.S. manufacturers of locomotive engines, are teaming with others to incorporate global positioning systems (GPSs) in locomotives [24, 31]. The industry estimates a 3 to 5% fuel savings from using GPS [31]. Our estimates yield a much smaller potential savings because fuel consumption in modern locomotives is very low at idle. In our example, a 50% reduction in idling time would reduce fuel consumption by about 1%. Lower speeds would also reduce fuel consumption, but this would probably not be acceptable to rail freight customers.

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10. Drag coefficient reduced from 0.0024, assumed in the Davis formula, to 0.00216; locomotive area assumed to be 1320 m^2 (140 ft^2), railcar area assumed to be 969 m^2 (90 ft^2).

Table 8 summarizes our assumptions about efficiency improvements in train materials, design, and operation.

Changes in Locomotive Engine Design and Emissions – It is expected that many technologies used to improve efficiency and reduce emissions in truck engines will be applied to locomotive engines as well. Improvement in locomotive engine efficiency is possible from higher peak cylinder pressure, improved thermal management, reduced friction, improved combustion, and improved exhaust-energy utilization. For a heavy-duty diesel truck engine, DOE projects a 15% increase in efficiency [14]. If a locomotive engine achieved the same percentage efficiency improvement, BSFC would be reduced from 201 to 176 g/kWh (0.33 to 0.29 lb/bhph), or about 13%.

Engines are being redesigned to meet the new exhaust emission standards for diesel-powered locomotives. Before 1998, emissions from locomotives were unregulated. EPA's new standards apply to new as well as remanufactured locomotives originally built after 1972 [25]. We assume the baseline locomotive emissions match EPA's estimate of emission rates for locomotives manufactured between 1973 and 2001 (the Tier 0 time period), and minimal degradation occurs prior to rebuilding. Average emissions from locomotives are expected to drop significantly as older ones are remanufactured to meet the standards. Average in-use emission rates and projected future emission rates are summarized in Table 9. Reported in-use rates vary considerably; for example, NO_x emissions vary by about +30%, depending on the data source, and reported PM emissions vary even more. The Tier 0 standards, applicable to locomotives built between 1973 and 2001, are expected to be met with injection timing changes (new locomotives have electronic fuel injection) and higher-pressure fuel injection. Emissions of nitrogen oxides can also be reduced by installation of selective catalytic reduction (SCR) equipment [32]. Tier 0 standards will reduce NO_x by 34%, and Tier 2 standards will reduce NO_x by 62%, PM by 47%, and HC by 46%, compared to current averages.

Table 8. Train Efficiency Improvement Assumptions

Improvement	Reduction in Fuel Use
Mass reduction	6.0%
Flange resistance reduction of 20%	7.0%
Coeff. of aero. drag reduction of 10%	1.8%
Electronically controlled dynamic braking	1.7%
50% reduction in idling[a]	1.0%
Total	17.5%

[a] From improved dispatching and use of antifreeze

Table 9. Line-Haul Locomotive Emission Factors g/kWh (g/bhph) [25]

		NO_x	PM	HC[a]	CO[b]
Emission rates	In-use	17 (13.0)	0.43 (0.32)	0.64 (0.48)	1.72 (1.28)
Emission factors	Tier 0 (1973-2001)	11.5 (8.6)	0.43 (0.32)	0.64 (0.48)	1.72 (1.28)
	Tier 1 (after 2004)	6.7 (5.0)	0.23 (0.17)	0.35 (0.26)	1.72 (1.28)

[a] Hydrocarbons, in the form of total hydrocarbons for diesel fuel and nonmethane hydrocarbons for natural gas.
[b] Carbon monoxide.

For petroleum diesel, we assume the baseline train meets Tier 0 NO_x and PM emission rates, and the advanced train (with efficiency improvements summarized in Table 8) meets Tier 2 emission rates. As indicated before, CO and HC emissions are not included in this analysis because no good data are available for locomotive engines. Note that locomotive diesel fuel quality is not regulated, and the locomotive emission standards are not based on the assumption of a cleaner fuel. If sulfur content of petroleum diesel is regulated,[11] greater emission reductions are possible than estimated by EPA. Low-sulfur options, including alternative fuels (discussed later), in locomotives could have a significant impact on emissions.

ALTERNATIVE FUELS – Changes in this category are expected to have the greatest potential for reducing both petroleum usage and environmental impacts from freight transport. Diesel fuel made from natural gas via the Fischer-Tropsch (F-T) process and natural gas (stored as LNG) were compared against 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 excellent ignition characteristics (indicated by a high cetane number, which indicates the compression-ignitability of a fuel). Natural gas is extremely resistant to knock,[12] making it an excellent fuel when premixed with air, as in the case of spark-ignition or pilot injection engines.

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 low energy density relative to liquid fuels, making it a less desirable fuel for long-haul freight applications. Biodiesel is a promising compression-ignition fuel because of its potential for significantly

11. Sulfur contributes to particulate emissions.
12. Knock is the spontaneous ignition of a portion of the end-gas (fuel, air, and residual gas mixture) ahead of the controlled combustion of the propagating flame in an engine. It is undesirable because very high local pressures can damage the engine.

reducing GHG emissions, but supplies are currently limited relative to the fuel consumed by the freight industry. DME is a promising compression-ignition fuel, but production, storage, distribution, and handling systems are not in place, and safety issues must be addressed.

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.

Alternative fuels in motor truck engines – We consider motor truck engines running on F-T diesel fuel and on natural gas. The use of F-T diesel fuel derived from natural gas or coal does not require significant engine modifications. Operating emissions would be changed because of the lower aromatics and essentially zero sulfur content of F-T diesel compared to petroleum diesel (See Table 10. Details are provided in Gaines et al. [9].) Energy use and emissions (most notably CO_2) from fuel production, however, are considerably higher for F-T diesel than for petroleum diesel, assuming current processing technologies are not improved, especially if the feedstock is coal. Use of F-T diesel would allow reduction of our dependence on petroleum.

We consider lean-burn combustion of natural gas, because of its potentially superior performance compared to stoichiometric combustion, if combustion instability problems are solved at light loads. (Our earlier study looked at stoichiometric engines as well. [9]) A lean-burn natural gas engine promises to achieve a brake thermal efficiency of about 88% relative to the petroleum-fueled diesel engine. (The efficiency of a glow-plug-assisted compression-ignition natural gas engine has been reported to approach that of a conventional diesel, under certain operating conditions. This option could be the subject of a future study.) Dual-fuel operation, in which a small amount of diesel fuel is injected into the cylinders to ignite the primary natural gas fuel, which has been premixed with air, is not considered for motor trucks because of the space requirements of two separate fuel tanks.

Table 10. Alternative Fuel Truck Emission Assumptions

Fuel	Emissions Estimate, g/kWh (g/bhph)	
	NO_x	PM
F-T diesel	4 (3)	0.13 (0.1)
Natural gas (lean-burn)	2.0 (1.5)	0.007 (0.005)

We assume the lean-burn natural-gas-engine combustion-stability problems are solved, thereby achieving NO_x emissions of less than one-half the current EPA standard, or 2.0 g/kWh (1.5 g/bhph) (Table 10)[13]. Very low PM emissions, about one-tenth the PM emissions from diesel fuel [34], have been observed for natural gas. We assume PM emissions of 0.007 g/kWh (0.005 g/bhph), given that the engine is optimized and PM emissions are a result of combustion of lubricating oil.

Alternative fuels in locomotive engines – We consider diesel engines running on F-T diesel fuel and dual-fueled (95% natural gas, 5% diesel fuel) engines. (Gas turbines and fuel cells could be investigated in a more comprehensive study.)

As for motor trucks, locomotives could be operated without engine modification using F-T diesel fuel derived from natural gas or coal. Operating emissions would be changed due to the lower aromatics and essentially zero sulfur content of F-T diesel compared to petroleum diesel. For F-T diesel, we assume brake-specific NO_x and PM emissions are the same as those from motor truck engines (Table 11), because most technologies developed for motor truck engines will probably be adapted to locomotive engines, as emission standards are phased in. Because transients (changes in engine speed and load that adversely affect emissions) are less common in locomotive engines than in motor truck engines, this emission assumption is considered conservative.

Several alternatives are available for using natural gas as a fuel for locomotives; they require varying degrees of engine modification, but the technology is basically known. The most commonly discussed method for utilizing natural gas in locomotives is dual-fuel operation, in which a small amount of diesel fuel is injected into the cylinders to ignite the primary natural gas fuel, which has been pre-mixed with air. (Below Notch 3, the engine is assumed to revert to all-diesel operation because of high CO and HC emissions and loss of efficiency at light loads.) The technology is very flexible, with operation possible on from 0 to 99% natural gas. (The natural gas is assumed to be supplied as a liquid, and this option is referred to as the LNG option in Figure 4.) Emissions of NO_x are reported to be reduced to under 2 g/kWh (1.5 g/bhph), compared to 12-20 g/kWh (9-15 g/bhph) for typical current locomotives [35]. Energy use for dual-fuel operation is reported to be very similar to the baseline [35]. However, lifecycle energy use will be increased slightly because of the energy required to transport and liquefy the natural gas. LNG for locomotive use is expected to be delivered by rail, in comparison to that for motor trucks, which would likely be delivered by highway.

13. For comparison, a noncatalyst 1997 model year Detroit Diesel series 50G natural gas engine emits 2.7 g/kWh (2.0 g/bhph) NO_x and 0.04 g/kWh (0.03 g/bhph) PM [33].

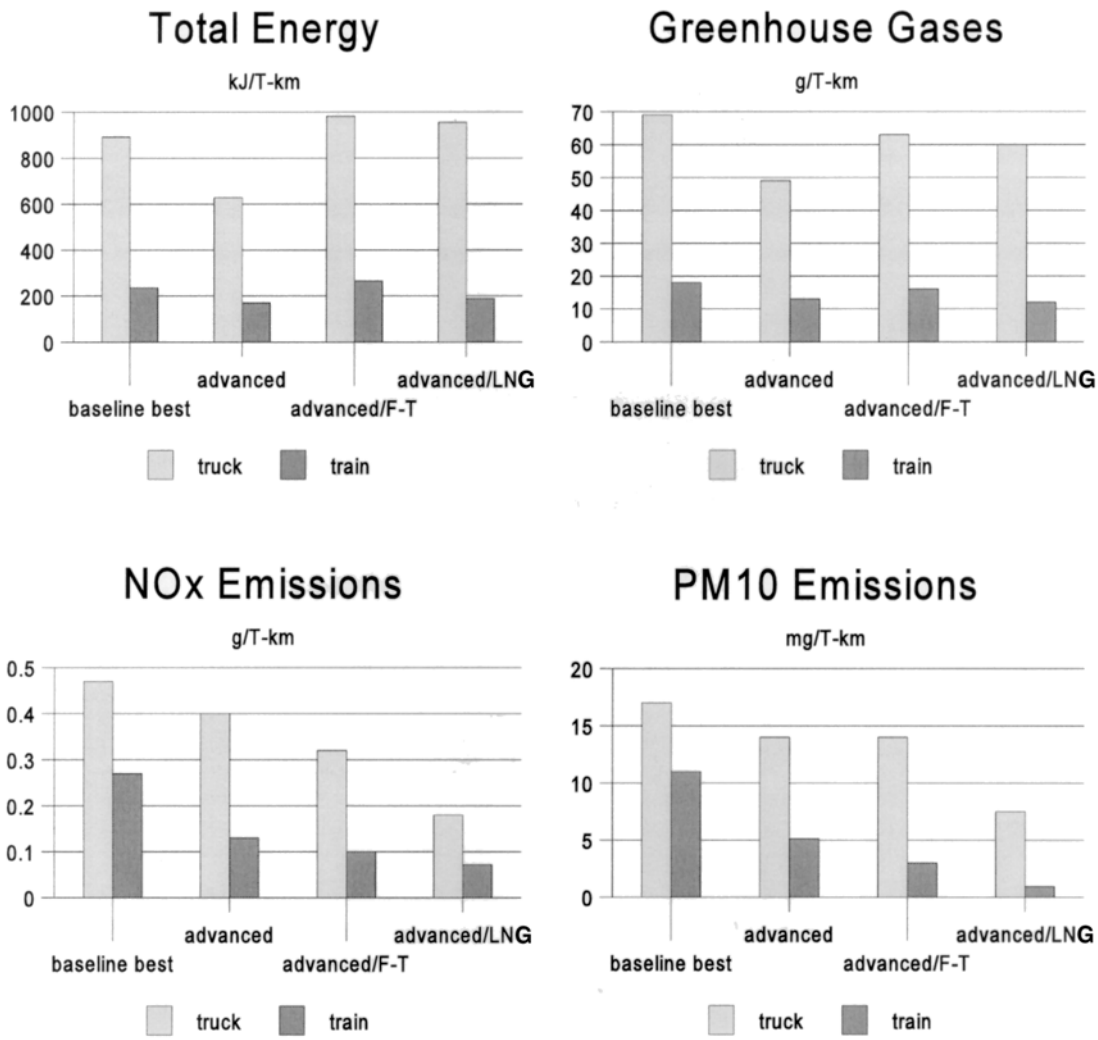

Figure 4. Energy Use and Emissions for Trucks and Trains

Table 11. Alternative Fuel Locomotive Assumptions

	Emissions Estimate, g/kWh (g/bhph)	
Fuel	**NO_x**	**PM**
F-T diesel[a]	5.1 (3.8)	0.23 (0.17)
Dual fuel (natural gas and diesel)	2.0 (1.5)	0.13 (0.01)

[a] Data not available. We assume the same brake-specific emissions as in the motor truck diesel case.

Natural gas can also be used in spark-ignition engines, as previously described for motor trucks, and emissions are reported to be under 2 g/kWh (1.5 g/bhph) for this technology as well. However, energy use for this option is expected to be about 18% above baseline energy use, mainly because of inefficiencies at idle and during braking [35]. This penalty would be reduced if idling were reduced. Another technology for utilization of natural gas is direct injection, which is reported to improve fuel efficiency and power output, but only reduces NO_x emissions to about 6.7 g/kWh (5 g/bhph), and require substantially modified engine and fuel handling. SCR technology can be applied with natural gas fuel as well as with diesel, to further reduce NO_x emissions. We evaluate dual-fuel locomotive engines in this analysis. A more comprehensive study could include other internal combustion options.

Natural gas is expected to be supplied in liquefied form (LNG). LNG standards are strict, and carbon dioxide, water, sulfur compounds, and most of the nonmethane hydrocarbons are removed to improve safety and enhance combustion stability (thereby, in the case of engines, improving engine efficiency and reducing knock). Although natural gas has a higher heat content per pound that diesel, LNG is less dense and so its volumetric energy density is only 57% of diesel's. Therefore,

line-haul locomotives running on LNG are expected to require a separate, cryogenic fuel tender car (developed during Burlington Northern demonstrations) running behind them. Each tender can hold 95,000 L (25,000 gal) of LNG, enough for two locomotives to travel about twice as far as they currently do between refuelings [35].

ANALYSIS

This analysis is presented with caveats. First, all emissions are based on the vehicle emission standards set by the U.S. Environmental Protection Agency. We assume that vehicles will meet these standards, although in reality, enforcement may not be very good. The analysis is for new vehicles, rather than for the current fleet average, in order to facilitate R&D planning. In addition, the standards are set by using specific duty cycles that are supposed to represent actual vehicle operating practice. However, these are generally urban cycles, because pollution near population centers has been the dominant concern, and this paper concerns long-haul transportation of freight. Operation at high speed under heavy, constant loads produces higher NO_x emissions for all of the options examined; therefore, such operation does not affect the comparison for this pollutant. For PM emissions, operation at high speed under heavy, constant loads could potentially lower PM emissions for diesel fuel and F-T diesel options, while the already-low PM emissions from natural gas combustion (its source is lubricating oil) could remain constant or increase slightly. Future work should consider actual long-haul duty cycle emissions. All discussion in this section has for its basis a fixed quantity of freight going a set distance.

CONTRIBUTIONS TO LIFECYCLE ENERGY USE AND EMISSIONS – For both motor trucks and trains, the operating phase of the vehicle's lifecycle makes the greatest contribution to energy use and emissions. The energy needed to produce and maintain the vehicle itself is rather small, ranging from 2 to 5% of the total lifecycle energy. The variation is due to the large range in the other terms, rather than to increases caused by changing the vehicle design. Emissions from vehicle production are generally small as well, although PM and SO_x are seen to be significant on a percentage basis when the emissions from vehicle operation are greatly reduced. Impacts from production and maintenance of highways and railroad tracks were not estimated in this preliminary analysis, but they are expected to be no greater than those from vehicle production; future work should verify this expectation. Note that allocation of highway impacts to the different modes is an interesting problem that needs to be addressed.

The contribution to total energy use from fuel production and distribution for both motor trucks and trains varies from about 15% for options using conventional diesel fuel to about 44% for those using F-T diesel produced from natural gas. The range is similar for emissions, because fuel production involves energy-intensive chemical transformations. Liquefaction and distribution of LNG is also energy-intensive, and it contributes significantly to lifecycle impacts.

EFFECTS OF CHANGING VEHICLE DESIGNS AND FUELS – For either mode, the average fleet in service has much higher emissions than new or advanced equipment; incentives like energy credits could be used to accelerate replacement or rebuilding of old equipment to reduce impacts. R&D may be needed to develop technologies to allow existing locomotive engines to meet emissions standards economically.

Figure 4 compares the effects of changing vehicle designs and fuels for both motor trucks and trains. Further improving the vehicle design and operating it with conventional diesel fuel is seen to result in the lowest total energy use and greenhouse gas emissions of any of the options for that vehicle type; operating the vehicle with F-T diesel results in the highest energy use. The advanced train achieves a 28% reduction in fuel use compared to the baseline train; this is approximately the same percentage reduction achieved by the advanced truck.

R&D on natural-gas-fired engines would be needed to achieve low CO and methane emissions, and economical LNG infrastructure would have to be developed (current liquefaction plants are very large, and LNG transport is expensive). If natural gas were imported, our energy supply base would be broadened, but our energy-independence would not be increased. Petroleum use and SO_2 emissions are very low for all the natural-gas based fuels, only LNG-fueled motor trucks and trains minimize emissions of PM and NO_x. However, alternative fuels based on natural gas do not result in energy savings or GHG reduction. Thus, a trade-off arises between total energy use/GHG emissions and petroleum use. To minimize both GHG emissions and petroleum use would require use of a substitute like biodiesel. However, biodiesel supplies may be limited compared to the demand for transportation fuel. R&D on the potential and impacts of non-fossil transport fuels is needed.

COMPARISON OF MOTOR TRUCKS AND TRAINS – As expected, long-haul transport of freight by train requires less energy and, for new or rebuilt vehicles meeting the emission standards, produces fewer emissions than does transport by motor truck, by a factor of about three. However, this can vary greatly, depending on how the railroad chooses to configure its trains. Similarly, particulate emissions from train transport are generally lower than those from motor trucks. Nitrogen oxide emissions are reduced below those of all motor trucks except LNG-fueled ones by trains meeting Tier 0 standards, and below all motor trucks when Tier 2 standards are met. Therefore, if energy use and emissions were the decision criteria, trains would be the mode of choice for freight transport. However, speed and flexibility are also important considerations.

Railroads are becoming more competitive by improving dispatching, improving equipment, and reducing employment and operating costs [25]. Switching of cargo in the railyard and low average speeds due to track restrictions and routing have resulted in trains having lower average speeds than do motor trucks (~22 mph vs. 40 mph for trucks). If train speeds are increased to compete better, energy intensity and emissions increase. Thus, there is a trade-off between profits and reducing energy use and emissions.

CONCLUSIONS

Surface freight consumes a significant portion of total petroleum use in the United States and contributes significantly to emissions of criteria pollutants and GHGs. Over the past decade or so, long-haul motor trucks have captured market share from railroads; this mode shift has increased fuel consumption and emissions for product shipment. Market forces requiring "just-in-time" deliveries of industrial and consumer goods, along with scheduling flexibility, are the dominant concerns for freight customers. The motivation also involves total costs, institutional issues, habits, and perhaps regulatory barriers. In addition, there are limitations for trains; point-to-point delivery is not always possible, and trains may are less flexible for shipping smaller quantities of goods. However, intermodal shipment combines the flexibility of trucks for local pickup/delivery with the lower impacts of trains for long-haul transport to reduce total impacts considerably compared to long-distance truck transport.

Our study suggests that a shift back from motor truck to rail (including intermodal) would enable a 3X fuel economy improvement and emissions reductions for some freight transport. Comparable improvements in the passenger car can only be achieved through unproven and costly advanced technology. (A shift to mass transport or an increase in passengers per car could result in a significant increase in fuel economy per passenger, but these require changing habits and entail costs.) No technological solution envisioned (not even the fuel cell) could triple fuel economy for a given mode of surface freight shipment while reducing emissions. Therefore, economic and institutional solutions that encourage rail use offer the greatest potential for reducing energy and environmental impacts from freight transport. R&D in efficiency improvements, emissions reduction, and alternative fuels could "lower the bar" by reducing petroleum consumption and health/environmental impacts of both modes of surface freight shipment.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, under contract W-31-109-Eng-38. The authors acknowledge the help of several members of the Center for Transportation Research, including Marianne Mintz, Ramesh Poola, Don Rote, Chris Saricks, Raj Sekar, Anant Vyas, and Michael Wang. They also acknowledge critical support provided by the technical editor.

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