HEAVY TRUCK FUEL ECONOMY: A REVIEW OF TECHNOLOGIES AND THE POTENTIAL FOR IMPROVEMENT

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ABSTRACT

This paper reviews the technical potential for improving the fuel efficiency of heavy trucks in the U.S. through the implementation of currently available and near-commercial technologies. The study is restricted to "Class 8" vehicles weighing more than 33,000 pounds loaded, with a focus on the combination tractor-trailers that account for most of the mileage by trucks in this subclass.

The study is based on a literature review covering 1985 to 1990, supplemented by the relatively rich literature of the late 1970's and early 1980's. Many fuel economy technologies introduced several years ago are now standard equipment on new trucks. These measures are included here to give a more complete picture. A tabulation summarizes our evaluation of 30 potential improvements, and shows the calculated improvements and benefits (dollars invested per gallon saved) associated with each technology. Using a projection of heavy truck VMT, the results can be used to construct a conservation supply curve for heavy trucks.

Consideration of technology and operating changes possible by year 2000 suggests that maximal penetration of the available measures would lead to a new fleet fuel efficiency for diesel combination (tractor-trailer) trucks of at least 8.5 mpg, an 64% improvement from the 1982 baseline of 5.2 mpg. About 80% of the improvement would come from technology changes; the remainder from controlling vehicle speed. An additional 10% improvement might come from new engine technologies that could be commercialized over the next decade. Full realization of this potential fuel economy improvement will take longer than a decade because of the relatively slow replacement rate of the heavy truck fleet.

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INTRODUCTION

The fuel use of heavy trucks is very important to the operator and to society. Exclusive of driver wages and expenses, "Fuel costs can represent as much as half the expense of operating a truck" (1), so increasing efficiency has a direct economic benefit to operators. In the U.S. economy, non-light trucks accounted for 15.2% of total transportation energy use in 1987. Over the course of two decades, heavy truck energy use doubled, from 1.5 Quads (10^{15} Btu/yr) in 1970 to 3.1 Quads in 1987 (2). The fuel use is almost exclusively petroleum, equivalent to 1.5 Mbd (million barrels/day), of which 1.1 Mbd was used by combination trucks (tractor-trailers) (3,4). This paper reviews the potential for improving the fuel efficiency of the heaviest truck classes, primarily diesel combination (tractor-trailer) trucks that account for most of highway freight energy use in the United States. We tabulate the feasible improvements from the implementation of commercially available technologies and the introduction and widespread use of near-commercial technologies. An economic analysis compares the fuel-saving benefits to the costs of improvement.

Background

Heavy trucks are commonly defined as those weighing more than 19,500 pounds loaded (gross vehicle weight, GVW) (3,7). This group is further divided into the "light-heavy" and "heavy-heavy" categories, the latter being comprised of Class 7 (26,000 - 33,000 pound) and Class 8 (over 33,000 pound) vehicles. In 1987, over 98% of fuel use for over-the-road trucking was used by the 2,272,000 trucks of the "heavy-heavy" classes, and diesel fuel provided more than 80% of this energy (2). Our study is restricted to Class 8 vehicles and focuses in particular on the combination tractor-trailers that account for the bulk of the heavy truck mileage. Our subsequent usage of the term "heavy" refers specifically to this restricted but important class of trucks.

Between 1977 and 1982, average fuel economy for Class 8 trucks improved 8.3%, from 4.8 mpg to 5.2 mpg (2). Since 1982, there has been little change in their average fuel economy (2, Table 3.17), despite increased penetration of improved technologies, particularly aerodynamic features on tractors. The observed efficiency improvements correspond to changes in price of diesel fuel: the real price rose from 63¢/gal in 1978 to $1.28/gal in 1981 and then dropped to 50¢/gal by 1988 (price excluding tax in 1988$, from ref. 5). Our assessment works from a baseline of new trucks in 1982, since there is fairly complete information on the state of technologies in 1982 and most of available technical literature works from this level. Regarding the failure of technology improvements since 1982 to yield greater average fuel efficiency, it is not known whether this is due to changes in vehicle loading, increases in speed, or other factors. It will be critical to understand this issue if the technical potential of the fuel efficiency improvements described in this paper is to be realized.

Some notes for context

Combination trucks (tractor-trailers) carried 25% of the ton-miles of intercity freight (including rail, pipelines, air, and water) (4, p. 7). Trucks hauled 661 billion ton-miles of intercity freight in 1987, 70%

of the amount carried by Class 1 railroads (2, Table 2.15). Rail loadings are dominated by low value-added commodities such as coal, farm products, stone, clay, and chemicals (2, Table 4.11). Trucks have captured much of the remaining freight, particularly time-sensitive, high-value products.

As shown by the comparisons in Table 1, heavy trucks are not like passenger cars or even light trucks (which are mostly used for personal transportation). Heavy trucks cost much more, they are driven more, and they last much longer. In addition, the automobile industry is much larger: in 1988, some 10 million new cars but only 148,000 new class 8 trucks were sold. At about 40% of operating cost (excluding driver wages and expenses), fuel is a much larger fraction of operating cost than it is for light vehicles. Car designers have found that fuel efficiency and performance can be improved by reducing weight. For heavy trucks, the impetus for weight reduction is to increase legal loads, since total weight is limited by law.

Factors affecting fuel economy

A small fraction of the energy content of fuel actually moves freight; the rest is dissipated as heat. Rapid combustion in a real engine has inherent thermodynamic inefficiencies. The remaining major sources of energy inefficiency in a heavy truck are:

Aerodynamic drag, which is the friction of air moving over a vehicle while in motion.

Parasitic losses, which include the power used to overcome internal engine friction and to drive accessories such as the alternator, fuel pump, fan, air compressor, and air conditioner.

Rolling resistance, which we take to include all frictional losses in the drive train and at the tires (some analysts reserve rolling resistance for tire losses and brake drag, classifying other drive train losses separately).

The total resistance to a vehicle in motion is determined by the interaction of many design, operational, and maintenance decisions: the design and selection of the engine and power train, the type of tires used and their air pressure, the installation of aerodynamic devices, the lubricants selected, traffic, speed, and road conditions.

Fuel economy improvement is difficult to measure. For example, aerodynamic changes can be road-tested, evaluated in a wind tunnel, or simulated. Each approach is subject to inaccuracies, leading to varying reports in the literature (3). Turbulence is important on the highway, but it is difficult to evaluate turbulence and yaw (crosswind) effects in wind tunnels. In wind tunnels the truck is stationary with air moving over it, but on the road this situation is reversed, changing the boundary layer effects (12). Road tests are also difficult to control. Variations in conditions from one test area to another and from one test time to another can be significant. Nonetheless, PACCAR finds that reasonably reproducible on-road results can be obtained with a standard test procedure and control vehicles (13).

Measuring the effects of changes is a ubiquitous problem: some inexpensive and worthwhile changes (e.g., relocating exhaust stacks to shielded areas) may have mpg effects too small to be reliably measured. Convincing fleet operators of the benefits of improved lubricants is likely to require extensive field studies. The effects of engine changes can be reliably measured in the laboratory with a dynamometer, but translation to road results requires a protocol that adequately simulates variable road use patterns. Studying the effects of changes in actual fleet use is very difficult because everything varies: loads, roads, weather, fuel, and drivers. The driver is particularly important: Tyrrell suggests that drivers will convert improved efficiency into increased speed unless otherwise limited (8), e.g., by governors, strict law enforcement, or company incentive programs.

METHODOLOGY

This study is based on a literature review focusing on the interval from 1985 to 1990, supplemented by the relatively rich literature of the late 1970's and early 1980's. Many of the new fuel economy technologies of several years ago are now standard equipment on new trucks. We have included these measures in this literature review to give a more complete picture. Information on the benefits and costs of 30 measures for improving fuel economy were compiled into a spreadsheet data base, listed in Table 2. From this we estimated the cost-effectiveness of each potential improvement.

The economic analysis depends on the projected lifetimes of the measures. Although heavy trucks often last 1.5 million miles before being scrapped (6), our analysis uses lower values, reflecting both economic and technical perspectives. We assume an economic life of 750,000 miles for the vehicle, since the first purchaser will want to amortize incremental costs while he owns or leases the vehicle. Federal depreciation schedules favor five year amortization, encouraging buyers to think in a fairly short horizon. Correspondingly, the value of efficiency measures in the distant future is low for the first purchaser. For the technologies, we assume a life equivalent to the interval expected before engine overhauls, 500,000 miles for major components. Tire lives are taken from the literature, without accounting for retreading, which lowers operating costs. Other maintenance items are based on available values.

The analysis also depends on the number of miles the vehicle is driven each year, since this affects the time until the vehicle has been driven its economic life. Estimates for the annual mileage accumulated by heavy vehicles are discussed in (11). Overall, Class 8 vehicles (including cement mixers, large straight trucks for beverage delivery, dump trucks, etc.) average about 47,000 mi/yr (2, Table 3.37; 7, Table 2). The mileages driven by over-the-road tractors are much greater. Davis *et al.* (2, Table 3.42) give 61,000 mi/yr for combination trucks. Tyrrell (8) implicitly uses 100,000 mi/yr. Rood *et al.* (9) use 100,000-130,000 mi/yr and Garland (6) bases lease calculations on 200,000-250,000 mi/yr. For the results presented here, we use a nominal value of 61,000 mi/yr from (2). For sensitivity analysis, we repeated the cost-benefit calculations at 130,000 mi/yr and 200,000 mi/yr.

There are some good reasons to prefer the higher values for annual travel distance. First, high mileage operators appear to accumulate the bulk of all mileage and strongly influence equipment manufacturers through their market power. Second, Garland (6) notes that combination truck tractors go through usage phases: 750,000 miles (3 years) in long-haul service, then progressively shorter hauls and lower annual mileage until the end of economic life at 1-1.5 million miles. Since specifications are written by the initial purchaser, the investment in a feature should be recoverable in less than 750,000 miles. Indeed, truck owners invest in efficiency when they anticipate that each dollar spent on an option will yield two dollars in cumulative revenues. Alternatively, most people in the industry expect a one to two year payback from any measure implemented (10).

ASSESSMENT OF FUEL ECONOMY MEASURES

This section discusses efficiency-enhancing technologies and practices, including aerodynamic improvements to the tractor and its trailer, engine control and technology improvements (both available and in research and development), drive train modifications, improved tires, and behavior modifications. A list of the potential improvements, given in Table 2, is presented first, followed by brief discussions of the measures analyzed. Further detail on the measures is given in a report-length edition of this work (11).

Summary of potential improvements

The first two values given for each measure listed in Table 2 are the estimated first cost and percent fuel economy benefit, based on the discussion that follows below. Also given is the mileage lifetime of each measure. These three values comprise the key inputs for the economic analysis. Measures are grouped in categories (e.g., tractor aerodynamics). We control the calculations to assure that measures are not double-counted within each category and give the summary estimates by category in Table 3. From the range of fuel economy improvement estimates found in the literature, we select a value for our analyses based on our judgment of the highest value likely to be achieved at the maximum feasible market penetration (the high to low range is given in reference 11). Note that we are presenting percentage *improvements* in fuel economy rather than percentage *reductions* in fuel consumption, and so it is conservative to treat the benefits as additive across categories.

Our baseline fuel economy is 5.2 mpg, representing typical new heavy trucks in 1982, at which time there was negligible penetration of the measures considered here. We estimate the potential assuming saturation of the potential market by 2000. The annual fuel savings from each measure are computed relative to the 5.2 mpg baseline, assuming our nominal annual travel distance of 61,000 miles; results for higher annual travel are given in (11). Two figures of merit are then computed for each measure.

The simple payback is the undiscounted ratio of first cost to annual fuel cost savings. For Tables 2 and 3, the latter is estimated using the nominal (61,000 mi/yr) fuel savings and a fuel price of $1.20/gallon. A rough criterion of private cost-effectiveness is that the simple payback be less than the useful life for the first owner of the vehicle. Simple payback is inversely proportional to the assumed annual travel distance. For example, using 200,000 mi/yr rather than 61,000 mi/yr would cut the simple payback by a factor of 3.3.

The cost of conserved energy (CCE) is computed by annualizing the cost of a measure over its lifetime and is expressed as dollars per gallon of fuel saved. CCE is independent of fuel price and can be compared to present or expected future prices. A low CCE indicates an attractive measure, since the difference between the CCE and the going fuel price represents a savings to the operator of the truck. The CCE depends on a measure's useful life, estimated as lifetime travel divided by annual travel, and an assumed discount rate, taken to be 7% real. CCE provides a useful ranking of measures by cost-effectiveness. This is illustrated in Figure 1, which plots CCE against the fuel economy level that would be achieved by successive introduction of the measures in order of increasing CCE (decreasing cost-effectiveness).

Discussion of individual measures

Tractor aerodynamics can improve MPG 14%

Aerodynamic drag is important: at freeway speeds 50% of the engine power is needed just to overcome drag (14). A 10% reduction in drag is calculated to improve fuel economy by 3.6%, so a 50% reduction in drag would increase fuel economy by 18%, assuming a 60% highway driving cycle, which may be conservative for heavy intercity trucks (15). Cooper suggests (as an approximation) that front surface drag accounts for 60% of total drag, pressure on rear surfaces 14%, skin friction over the body 6%, and the remaining 20% of drag is due to drag which is created by air flowing over the uneven bottom of the truck (12).

Most aerodynamic improvement efforts have focused on the forward surfaces, where large changes are feasible. Early aerodynamic improvements were of add-on devices (air dams, roof fairings, and gap seals). Most road testing of fuel efficiency has focused on these add-on devices. Most major Class 8 truck manufacturers are rapidly integrating aerodynamics into their tractor designs. The following are estimates of the fuel economy improvement and estimated cost for tractor measures.

A "full" aerodynamic tractor package, incorporating a combination of the measures below, improves MPG up to 14% at a cost of $2500-$3000 (6).

A roof-top fairing is a fixed-angle, three dimensional, air deflector that mounts on the cab roof and whose sides extend backward toward the trailer. A fairing can improve MPG by 10% (16) and cost $500-$800 (13). Alternatively, a roof-top deflector is an inclined, slightly curved plate which is installed on the cab roof. It shields the forward-facing flat surfaces of the trailer from the air stream (17) and also decreases the downward flow of air between the cab and the trailer. A roof-top deflector can improve MPG by 3%-8% and cost $250 (8,18) to $500 (13).

An air dam placed under or integrated into the front bumper reduces air flow under a truck, counteracting the turbulence there which can increase drag significantly (1). Many new truck designs, including some very high mileage demonstrations (19), feature air dams, but the effect of the dam in isolation has not been published. We conservatively assume a 1% fuel economy benefit for this measure.

Rear cab extenders, also known as gap seals, are vertical plates attached to the outer back edges of the cab to extend the cab sides toward the trailer, thereby partially closing the gap between the cab and the trailer. Generally installed with roof-top fairings, the combined improvement is not additive but including a gap seal saves more than either device alone. The estimated MPG increase due to closing the gap between the trailer and the tractor is 2% (16) to 7% (1). Gap seals are now frequently included on heavy trucks, or can be bought separately for about $300 (18).

Trailer aerodynamics can improve MPG by 5%.

Four measures have been proposed to give trailers better aerodynamics: rear "boattails," front "bubbles" or fairings, side skirts or "pods," and underbody air deflectors. Trailer skirting tests have shown a 5% fuel economy improvement (8). Although trailer aerodynamics are widely discussed (8,12,13,18,19), a number of operational and regulatory complications inhibit their use and none have yet achieved high market penetration.

The critical issue for trailer aerodynamics is merging the tractor-trailer combination into a cohesive aerodynamic unit. This problem is complicated because tractor and trailer makers are not fully coordinated and many different units of different ages are regularly coupled in combination units (37). While the estimated fuel economy improvements from aerodynamics are roughly 14% for tractor measures and 5% for trailer measures, the combined effects may not be additive. If the gap between the tractor and trailer is smoothly closed, the combination could have even greater benefits. On the other hand, the sheltering effect of the tractor tends to decrease the relative impact of trailer streamlining. We conservatively estimate the overall potential fuel economy gain from aerodynamic improvements at 18%, slightly less than the sum of separate tractor and trailer estimates.

The aerodynamic improvement potential is not the same for all types of heavy trucks; our discussion focused on tractor-van combinations. This level of improvement applies largely to tankers but much less so to flat beds and other configurations. We assume application to only vans and tankers, which comprise 48% of the fleet by body type (40).

Available engine modifications can improve MPG 4%-26%

Almost all heavy-heavy trucks have diesel engines, and most are turbocharged (15). A number of engine improvements can improve fuel efficiency, including the following.

High-torque low-rpm engines reach maximum power at lower engine speeds. Along with turbocharging, manufacturers have gradually introduced them, moving down from 2100 rpm through 1900 rpm to new 1600 rpm limits. Costing about the same as or less than the engines they supplant, the 10%-12% fuel economy improvement (15) of these "fleet" engines is extremely cost-effective. However, there can be costs due to associated lost productivity to the extent that such engines may limit road or hill climbing speed, as discussed below for under "behavior changes."

Electronic truck engine control (ETEC) packages are being widely applied to meet new emissions regulations (effective in January 1991). These total control packages regulate engine fuel intake, maximum rpm, maximum road speed, power output, and other parameters. The cost is $3500-$4000 (6). ETEC also improves fuel economy by as much as 20% in combination with low-rpm high-torque features. Assuming our nominal 12% benefit for low-rpm engines, we estimate an added benefit of 4% for ETEC. There is a question of how to allocate ETEC cost between emissions and fuel economy. Manufacturers are introducing these engine changes mainly to meet emissions regulations. Some measures (such as very high pressure injectors and electronic controls) also improve efficiency. These technologies might yield a greater efficiency benefit without emissions control requirements; however, they may not have been introduced (or introduced as soon) in the absence of emissions regulations. That issue is moot and so we base our efficiency improvement benefit on the coincidentally realized efficiency gains. We have not attempted to resolve the cost allocation issue and therefore conservatively charge the full added cost against the fuel economy improvement. In any event, we expect full penetration of ETEC in new heavy truck fleets well before 2000.

Temperature controlled fan clutches improve fuel economy 6%-8% at a cost of $250-$550 (15,20). However, we assume full penetration of these in our 5.2 mpg baseline, so do not include them among the measures contributing to possible future improvements.

Thermostatic radiator shutters can provide a fuel economy benefit of 3.5% for cold weather operation and cost $400 (21,22). However, because of universal temperature controlled fans, they are no longer considered necessary and are not specified on fleet lease vehicles (6). One study indicated a 2.2% improvement in fuel economy on a truck with a fan clutch (thermostatic shutters are contraindicated if there is continuously-driven fan) (15). We assume a 1% fuel economy benefit given the limited applicability.

Turbocharging heats incoming air while compressing it. An *intercooler* is an air-to-air heat exchanger which cools the compressed air so that a denser charge can be introduced into the combustion chamber. The resulting increase in fuel efficiency is estimated at 5%-6% (15). Intercoolers are standard on some models and cost $700 or less.

Other currently available engine measures include improved intake and exhaust systems, which can increase MPG 1%-5% for $1000 or less (1), and improved engine lubricants, which can increase MPG up to 3%, essentially for free (20).

Engine improvements on the horizon

Several options have fuel economy improvement potential but are not yet commercially available. Better accessories can increase mileage 1%-2.5% at nominal cost (15,20). Low heat rejection (adiabatic) engines might improve fuel economy up to 20% (23,24,25). Organic Rankine bottoming-cycle waste heat recovery system could improve fuel economy up to 15%, for about $10,000 (20). Alternatively, turbocompounding uses exhaust gases to spin a turbine whose output helps power the drive train (26); costs and complexity are high but there is a 10% potential fuel economy benefit (15). The U.S. Department of Energy has an ongoing research program on advanced engine technologies as well as technologies for accessory improvement (27). Some further discussion of these options is also given in (11). The benefits of these advanced technologies may not be fully additive with other state-of-the-art improvements, for example, those from electronic engine controls. The estimated fuel economy improvements are therefore uncertain, ranging from no net benefit up to 20%. The technologies do, however, attempt to capture a currently unrealized thermodynamic improvement potential, and so we assume a mid-range estimate of 10% for the fuel economy improvement from these advanced engine technologies.

Drive train improvements

There are a number of potential improvements in the drive train, which includes transmission, differential, and axle components. Better transmission and differential lubricants improve mpg 1%-1.5% at very low cost (15). Optimizing gearing improves mpg 3%-5% at negligible cost (20). Using a non-driven axle (tag axle) improves mpg by 2%-3% (15) at negative cost (6), but faces major barriers to acceptance, such as concerns about traction under adverse conditions. Drive train options are implemented on new trucks because they are essentially "free" in this stage. Implementing a combination of an optimized axle ratio, gearbox modifications and the tag axle option can increase fuel economy by 5%-7% (8,15), however, it is not possible to estimate the level of optimization included in base fleet performance.

Improved tires can increase MPG 3%-5%

During the past two decades, tire technology has changed as dramatically for heavy trucks as for cars: bias ply tires have largely given way to radials, which are now being supplanted by low profile radials in some major applications. In turn, "super singles" are beginning to compete with conventional "duals" on drive and trailer axles in specialized situations. Radial tires offer many benefits compared to bias ply tires (28) and currently account for 72% of the original equipment and 62% of the replacement equipment (29). Because radial tires have achieved such high penetration of the on-road heavy truck market, they are assumed for our 5.2 mpg baseline. Improved tires increase fuel economy by reducing rolling resistance. Changes in fuel economy due to changes in tires also depend on operational factors such as speed, load, truck configuration, and driver practices; generally, for a fully loaded truck, reducing rolling resistance 2.6% reduces fuel usage by 1% (35).

We drew our tabulated cost and benefit estimates from the published literature for low-profile radials (15,29,31) and "super singles" (9,31). However, the literature comparing various tire types is far from conclusive. Based on discussions with representatives of major tire manufacturers (39), we expect that there will be continuing incremental improvement in tire efficiency, probably 10%-15%, over the next few years, offering a fuel economy benefit of 3%. These gains are expected to be highly cost-effective in a competitive market.

Human factors in heavy truck operations

Nearly every discussion of fuel use in trucking stresses the importance of the driver's habits and practices on fuel consumption. Idling wastes fuel, yet truckers often let vehicles idle for very long periods of time. Accelerating to the "red line" (rpm limit) in each gear is very wasteful, so "progressive shifting," in which the driver shifts from lower gears at lower rpm's is now recommended and can save up to 20%, particularly in urban settings (30). Since "base" mechanically-governed engines can be driven beyond their maximum power output, and since higher rpm's waste fuel, the "base case" driver has additional opportunities for waste. This is referred to as "droop," for which a 3% fuel penalty is claimed (32) and which can be automatically avoided with optimized electronic governors and high-torque low-rpm engines.

Finally, there is the issue of road speed. There may be a 1.5%-2% mpg decrease for each mph above 55 mph (15). Steady-speed road tests have shown a 25% improvement in fuel efficiency when speed is decreased from 60 mph down to 50 mph (32). Failure to control operating speed can negate all other efficiency improvements (8). Drivers have strong incentives to drive more quickly, barring legal sanctions: the value of the time saved (usable for additional revenue miles) is far greater than the fuel efficiency penalty. For example, assuming a unit is driven 100,000 mi/yr, limiting the speed to 55 mph rather than 65 mpg might drop the average road speed from 59 mpg to 50 mpg, adding 300 hours of operating time per year. At $50/hr for driver and rig, the added cost due to the speed decrease is $15,000. We use these assumptions in Table 2 to estimate that the energy conservation benefits of speed reduction may cost about $5 per gallon saved. Even when an operator is concerned about fuel costs, issues of driver retention and incentive to cooperate come into play; major fleet operations may accept a fuel cost penalty in order to accommodate drivers' wishes for higher speeds (37).

A partial solution saving an estimated 9% -- As noted above, the electronic engine controls (which are standard on most Class 8 diesels entering service from January 1991 to meet emissions specifications) will help the operator achieve greater fuel efficiency.

First, these devices allow engine speed and road speed to be controlled separately. The buyer now gives the engine manufacturer information on the transmission, differential, and ratios selected, as well as the maximum allowable road speed (6). The engine manufacturer then sets the electronic controls to limit both rpm's and road speed. This means that the driver can maintain maximum governed road speed in several different gears, choosing the highest (lowest rpm and thus most efficient) one that will maintain speed in the wind and grade conditions of the moment. Electronic controls can also include cruise control, emergency engine shutdown capability, and maintenance and diagnostic capabilities (32).

By limiting maximum road speed and maximum engine speed, electronic controls allow wide use of the "gear fast - run slow" configurations discussed with gear optimization, above. If visual or audible shift indicators are also implemented, the controller will aid in achieving progressive shifting. One author (HMS) has experience with automobile upshift indicators, and feels that they aid in increasing fuel economy.

It is difficult to estimate the total effect of moving from a poorly controlled environment to one with much greater constraints on the operator, in part because the baseline is so variable. Controlling the maximum speed can provide a potentially large improvement in fuel economy [4%-13% (8), 6%-12% (34)]. Although reduced road speed by itself could improve mpg by as much as 25% (33) and progressive shifting by 20% for straight trucks in urban service (35), we believe that the attainable improvement will be on the order of 15% because the economic incentives for driving faster will keep operators from specifying top speeds of 55 mph instead of 60 or 65 mph.

Weight reduction improves mpg, perhaps 1% per 1000 pounds tare

While weight reduction is an important fuel economy strategy for light duty vehicles, it is less applicable to heavy trucks. Because maximum gross weight is legally limited (typically 80,000 pounds for a combination tractor and trailer), an operator's interest is likely to be in removing tare weight to increase revenue weight. On the other hand, for trucks that are volume ("cube") limited, there can be a fuel economy benefit from weight reduction, although this will still be relatively small since freight trucks have a high payload weight ratio.

If (as is usual) fuel economy is measured in miles per gallon, reducing the weight of tractor and trailer would yield no gains if it is offset by increased loading. A metric such as revenue ton miles per gallon would, however, reveal the benefits of tare weight reduction. The estimated savings from lowered tare weight are 2.8 to 6 gallons per 1000 ton miles, with the higher figures for city driving (15). This corresponds to a gain of about 1% fuel productivity for each 1000 pounds reduced, a much smaller effect than for automobiles and light trucks. Because of the incentives to increase revenue weight, a number of trucks already incorporate weight-saving features that are rare or unknown on light vehicles, such as high strength aluminum frame rails (200 lb weight saving), cab bodies, and wheels. Based on one compilation, additional weight reduction of 1500 - 2000 pounds/vehicle may be feasible (15).

Williams *et al.* (33) showed that fuel productivity is up to 14% higher with lower power to load ratios. They did this both by loading trucks to 40 tonnes instead of 32.5 tonnes, and by experimenting with lower-powered trucks (as noted above, modest engine downsizing may accompany general drive train optimization and electronic control efforts). In the United States, changes in truck load limits are extremely controversial, because of concerns about competition (with railroads), safety, and road damage.

DISCUSSION

As summarized in Table 3, our analysis suggests that an 64% increase in fuel efficiency (from a 5.2 mpg baseline to 8.5 mpg) is feasible with currently available technology and behavior changes. Of course, some of these technologies (aerodynamics and low-rpm engines, for example) are already being incorporated into new trucks in the fleet.

A comparison to other published estimates is provided in Table 4. EEA similarly projects 8.5 mpg (15). Roberts and Greene project improvement from 6.3 mpg (1973) to 8.9 mpg (2000), a 41% increase (36). Rood *et al.* note "... that fleets want to reach a 9.1 mpg figure by the year 2000. The manufacturing community and government officials project fleets achieving 8.5 and 6.5 mpg figures" (9). The discrepancies among estimates are within the uncertainties expected for such projections, for various reasons. Some authors address fleet averages attainable, but others address the potential for new vehicles. The latter estimates show technical potential, but the average vehicle will lag behind the new truck, reflecting the average age of the fleet at any given time. The baseline data on present investments in efficiency and performance are outdated and fragmentary, so different authors may measure improvements from different bases.

Although our estimate is at the high end of the range, empirical studies suggest that it is realistic. In test vehicle runs of over 2000 miles each, aerodynamic combination trucks with electronic engine control and road speed control averaged 8.46, 9.59, and 11.06 mpg, vs. a control vehicle at 6.02 mpg (8). Using production equipment, PACCAR achieved 7.7-8.2 mpg in 7450 mile demonstration runs in varied weather and terrain. They also achieved over 11 mpg with two vehicles in 1590 mile trials with modified vehicles (prototype tires, special trailer side skirts extending to within 6" of the ground, aerodynamic wheel covers, boat-tails, and air dams beneath the bumpers). Loads were 65,000 and 73,000 pounds for the two rigs and the terrain was flat in this demonstration, which pushes the limit of near-production technology (19).

The critical point is that all of these reports indicate the large potential for improving the fuel efficiency of heavy vehicles. As indicated in Table 3, the major gains are likely to be in the "engine room," where new electronic controls can optimize operations, improve fuel efficiency, and lower emissions. Because these control strategies can potentially include road speed governors and shift pattern indicators, they will strongly impact our "behavior" category. In addition to controls, we anticipate continual "fine tuning" of lubrication, intake and exhaust systems, and accessories (pumps and compressors, generator).

Drive train optimization progress is being speeded by electronic engine controls and the greater availability of specification software. Buyers understand that they must carefully select drive train components and gear ratios to enable the engine manufacturer to set up the electronic engine control. An unknown factor is whether heavy-duty automatic transmissions will become competitive for class 8 over-the-road vehicles. These could be electronically controlled by the engine controller, which might synergistically improve efficiency throughout.

Road speed has great fuel economy impact, but an even greater economic impact. If speeds are reduced, drivers and rigs must work more hours for the same income, a productivity decrease. Therefore, speed reduction will be accomplished only by some combination of driver incentives (where the truck purchaser directly pays fuel but not time, as in some fleet situations) and regulation (speed limit enforcement).

The late 1980s saw the introduction of several Class 8 truck models with extensive integral aerodynamic features. They are probably better than the earlier add-on packages, since they include sloping hoods and integrated lights. Indeed, some cab-over-engine models may be more aerodynamically efficient than aerodynamic conventional models. Thus, much of the potential for aerodynamic improvements on tractors may already be achieved in the best vehicles now on the road. Unfortunately, we lack good on-road fleet test data.

We anticipate continuing incremental improvements in tires (and greater penetration of aluminum or composite wheels), to make them lighter, more durable, and more efficient. This will probably be accompanied by higher tire pressures on smaller rims. Of course, tire/wheel changes tend to occur in "spurts:" very low penetration of a new technology (e.g., super singles) until operators are feel sure of both economic benefits and low lost-time risk, when replacements are available "in the hinterland." When that threshold is met, the market can move within a few years to very high utilization rates.

Tractor and trailer empty weights will continue to decrease, to raise the fraction of revenue weight. However, vehicle weight reduction has a much smaller role to play in improving the efficiency of heavy trucks compared to light vehicles.

A key implication of Table 3 is the high cost-effectiveness of most of the fuel economy measures. Most improvements cost less than buying a gallon of diesel fuel. While we show a high cost for electronic control packages, their penetration is being driven by the need to meet new emissions standards, so their fuel economy benefit can be considered to come at no added cost. We expect, therefore, that fuel economy improvements will be implemented for the over-the-road fleet as quickly as their value is demonstrated to equipment purchasers.

Another major implication of this analysis is that heavy truck fuel use need not grow, and can even decrease moderately. Table 4 extends the estimated fuel economy improvements to projections of fleetwide fuel consumption, under two assumptions about growth in freight truck VMT: frozen travel (today's levels) and growth at an average rate of 2.5%/yr over the next decade (for a 28% increase in VMT). At frozen travel, the estimated fuel economy improvements would shrink today's consumption of 1.2 Mbd to 0.7 Mbd. The 28% VMT increase is what might be expected if the demand for freight trucking services keeps pace with GNP. In this case, the efficiency improvements can potentially reduce heavy truck fuel use to a level 25% lower than at present.

CONCLUSION

From the technology and operating measures analyzed in this review, we find that feasible penetration would lead to a fleet fuel efficiency for diesel combination (tractor-trailer) trucks of at least 8.5 mpg, a 64% improvement from the 1982 new vehicle baseline of 5.2 mpg. About 80% of the postulated improvement would come from technology changes; the remainder from controlling vehicle speed. Additional improvements will flow from new engine technologies. The extent to which any of these technical efficiency improvements will be reflected in on-road fuel economy statistics remains unresolved, however, since the fuel economy benefits can be offset by increases in speed or loading. Nevertheless, there is still likely to be an efficiency benefit in ton-miles per gallon if not miles per gallon. Furthermore, if recent trends toward higher speeds or loadings plateau, then we can expect to see the average fuel economy starting to rise again as the efficient technologies penetrate the fleet. In summary, high priority should be focused on implementing the existing technologies. Other technologies which are still in the research stages need encouragement to ensure that new approaches will be ready if fuel prices increase or carbon emissions are taxed.

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Table 1. Some ways cars and trucks are different

Typical Characteristic	Passenger Cars	Light Trucks	Heavy Trucks
U.S. vehicle population (million)	120	42.3	2.2
1987 new vehicle sales	10,373,000	4,864,000	148,000
Annual usage (miles/year)	9,900	10,000	75,000
Lifetime usage (miles)	125,000	125,000	1,000,000
Cost, new	$10,000	$10,000	$60,000
Empty weight (pounds)	2,300	3,500	30,000
Loaded weight (pounds)	3,000	5,000	80,000
Payload weight ratio	0.30	0.43	1.67
Fuel used	gasoline	98% gasoline	diesel
Fuel economy (1988 mpg)	27	21	5.2
Fuel cost ($/mile at $1.20/gal)	$0.04	$0.06	$0.23
Total operating cost ($/mile)	$0.32	$0.37	$0.75
Fuel cost fraction	14%	15%	31%
Oil change interval	7,500	7,500	20,000
Quarts of oil per change	4	5	40

Table 2. Cost/benefit estimates for heavy truck fuel economy measures

Measures, by category	Cost	Benefit in fuel economy	Life of measure (miles)	CCE ($/gal)	Simple payback (years)	Notes
Aerodynamics - tractor						
Full aero package	$3,000	14.00%	750,000	$0.26	1.74	R
Aero cab, incremental	$2,500	14.00%	750,000	0.22	1.45	N
Roof fairings	$800	10.00%	750,000	0.09	0.63	B
Roof-top deflectors	$500	7.00%	750,000	0.08	0.54	B
Gap seals/extenders	$300	5.00%	750,000	0.07	0.45	B
Bumper air dam	$250	1.00%	750,000	0.27	1.79	B
Aerodynamics - trailer						
Skirts	$2,000	4.80%	750,000	0.46	3.10	B
Front bubble, fairing	$450	3.00%	750,000	0.16	1.10	B
Engine control tech.						
Lower rpm engines	$1	12.00%	750,000	0.00	0.00	N
Elect. control package	$4,000	4.00%	750,000	1.10	7.39	N
Other available engine tech.						
Radiator shutters	$400	1.00%	750,000	0.43	2.87	B
Air-to-air intercooler	$700	6.00%	750,000	0.13	0.88	N
Improved intake, exhaust	$700	5.00%	500,000	0.21	1.04	B
Synthetic lubricants	$70	3.00%	100,000	0.14	0.17	B
"Friction modified oil"	$12	3.00%	10,000	0.22	0.03	B
Engines - in development						
Improved accessories	$500	2.50%	750,000	0.22	1.46	S
Turbocmpnd/adiabatic	$10,000	20.00%	750,000	0.63	4.26	N
Organic Rankine Cycle	$10,000	15.00%	750,000	0.81	5.45	N
Drive train						
Better gear oil	$30	1.25%	60,000	0.23	0.17	B
Opt trans & diff ratios	$1	5.00%	750,000	0.00	0.00	N
Tag axle substitution	($1,500)	2.00%	750,000	-0.81	-5.43	N
Tires						
Low profile radials	$864	3.00%	80,000	2.08	2.11	B
Super Singles	$632	8.00%	80,000	0.60	0.61	B
Behavior Changes						
Progressive shifting	$0	10.00%	200,000	0.00	0.00	B
End droop (overreving)	$0	0.00%	750,000			B
Lower speed (per year)	$15,000	10.00%	100,000	4.95	11.72	B
Weight reduction	$3,000	1.00%	750,000	3.20	21.52	N

NOTES

N = New applications
R = Retrofit applications
B = Both new and retrofit
S = New and some retrofit

Table 3. **Summary of the estimated potential for improving the fuel economy of heavy trucks (weight classes of 33,000 pounds or more).**

Technology category	Cost of Changes	MPG Benefit	Life of measure (miles)	Annual savings (gals)	CCE [f] ($/gal)
1 Aerodynamics, tractor[a]	$3,000	14%	750,000	1,441	$0.26
2 Aerodynamics, trailer[a]	$2,000	5%	750,000	559	$0.44
3 Engine control technologies[b]	$4,000	16%	750,000	1,618	$0.31
4 Other avail. engine tech.[b]	$1,500	15%	500,000	1,530	$0.16
5 Drive train[b]	0	7%	750,000	767	$0.00
6 Tires[b]	$700	8%	80,000	869	$0.66
7 Weight reduction[b]	$3,000	1%	750,000	116	$3.20
8 Speed reduction (per year)[c]	$15,000	15%	200,000	1,530	$4.95
9 Engines-in development[b]	$10,000	10%	750,000	1,066	$1.16

SUMMATIONS OF TECHNICAL POTENTIAL:	Percent improvement	Fuel economy (MPG)
Baseline (1982 vintage) fuel economy	--	5.2
Sum of available measures (1-8)[d]	81%	
Net sum of available technical potential[e]	64%	8.5
Adder for 1990s engine developments	10%	
Total new fleet technical potential for 2000	74%	9.1

NOTES:

(a) Assumed potential penetration to 48% of fleet, based on 1987 TIUS, p. US-6, portion of truck miles for van and tank body types.

(b) Assumed potential penetration to 100% of fleet.

(c) Assumed potential application to 55% of fleet, based on 1987 TIUS, p. US-102, portion of heavy-heavy truck miles with annual travel of at least 75,000 miles.

(d) The 81% improvement is for full implementation of the currently available technologies to an individual truck to which all measures would apply (such as an over-the-road van combination). This would yield an improvement from the baseline of 5.2 MPG up to 9.4 MPG; adding the expected near-term engine developments would bring this up to 10.5 MPG.

(e) Sum of available measures, considering penetration limits as in notes (a-c).

(f) Cost of Conserved Energy, computed on the basis of an individual vehicle to which the measure applies, annual travel of 61,000 miles, and a discount rate of 7% real.

Table 4. A comparison of fuel economy projections for heavy trucks

Source	FUEL ECONOMY (MPG) Base	year 2000	MPG inc.	Basis	FUEL CONSUMPTION IN YEAR 2000 Traffic growth assumptions: (1) No growth Mbd	change	(2) 28% Mbd	change
This study, avail tech.	5.20	8.5	64%	New Veh.	0.712	-39%	0.911	-21%
This study, new engines	5.20	9.1	74%	New Veh.	0.671	-42%	0.858	-26%
EEA, 1983	6.30	8.45	34%	Fleet Av	0.865	-25%	1.107	-5%
Roberts & Greene	6.32	8.94	41%	Fleet Av	0.820	-29%	1.050	-10%
"Manufacturers" (Rood)	5.20	8.50	63%	New Veh.	0.710	-39%	0.908	-22%
"Govt Officials" (Rood)	5.20	6.50	25%	New Veh.	0.928	-20%	1.188	2%

Notes:

(1) From Smith, p. 16, combo units used 407.2 Mbbl oil in 1988 (1.16 Mbd).
(2) Assumes 2.1% annual growth in VMT for 12 years, 28% total increase.

1 Mbd (Mbbl/day) oil use equals approximately 2 Quads/year.

Figure 1. Cost of Conserved Energy vs. MPG for Heavy Trucks
(new vehicle fleet average, for measures as listed in Table 3)