Chapter 6

CLASS 8 HEAVY TRUCKS

1. Summary

The instantaneous potential for saving diesel costing less than $1.00/gal on the margin at the nozzle is between 36.3% and 48.3% below the 2025 use forecasted by *AEO 2025* (EIA's *Annual Energy Outlook with Projections to 2025*). The lower range includes less-than-$1/gal state of the art truck-specific technology-changes only, while the higher range includes the higher estimate of some variable truck and driver changes that were more difficult to quantify. If we raise the threshold for savings so that its *marginal* cost is below $2.00 per gallon of saved diesel, the upper savings bound is pushed to 49.5%. This represents a full range that is equivalent to saving between 2.09 and 2.77 Quadrillion BTUs of diesel at an *average* cost of between 25¢ and 35¢ per gallon of diesel at the pump nozzle.

In terms of the instantaneous technical potential for oil savings in the trucking industry at marginal costs below $1 per gallon of diesel saved, this translates to an elimination of approximately 1.0 Mbbl/day of oil, or nearly 4% of *AEO*'s forecasted 2025 demand, at an average cost of $0.25 per gallon of diesel. Including further system and regulatory changes that are very difficult to estimate with any accuracy, the instantaneous technical potential is significantly larger, perhaps as large as a 55–65% reduction of forecasted use.

If conventional and emerging technologies are diffused into the stock under what would be considered an informed business, and a focused policy environment, we estimate that a total of approximately 33% of EIA projected 2025 heavy truck diesel use, or 1.84 Quads of diesel, or some 73% vs. the RMI *Conventional Wisdom* (*CW*) 2025 forecast, could be saved. At the nozzle, these savings would have a marginal pretax cost below $0.91 per gallon of diesel, or at an overall average cost of $0.25 per gallon—i.e., choosing to equip a new truck with these technologies costs only about one-quarter of making the choice not to, since not installing the technologies means one would have to buy the diesel at about $1.00 per gallon (pretax).

If deployed in line with conventionally accepted rates of diffusion into the new vehicle sales, we estimate that today's off-the-shelf technologies would save about 17%, or 0.95 Quadrillion BTUs, from projected EIA 2025 usage. On average these savings would cost 13¢ per gallon of avoided diesel. The marginal cost of the last gallon saved amounts to 80¢—still cheaper than the cost incurred by not installing the most expensive technology. The supply-curves in Figure 6–1 detail the two portfolios, with the savings from each technology and their associated costs.

Some key barriers of adoption have been identified. These are described and discussed explicitly in the section on truck business case in the *Winning the Oil Endgame* main section.

2. Overview of techno-economic potential

Ignoring possible system changes, and focusing only on truck-specific technologies, technical potential diesel savings in the Class 8 heavy truck segment is about 2.09 Quads—or 37.5%—of the 5.59 Quads the *AEO* 2025 predicted heavy truck diesel consumption . These savings are incremental to those in the *AEO 2025* baseline forecast for 2025. They have a marginal cost of less than $1.00 per gallon of diesel, with an average cost of 25¢ per gallon. If we also include measures with marginal costs below $2.00/gal, the technical potential is 2.31 Quads or 41.3% of 2025 *AEO* usage, at an average cost of 35¢ per gallon.

Four truck- and driver-specific measures for which it was difficult to accurately estimate either the impact on savings or cost or both were not included. These were (a) allowing a 1-axle increase, (b) navigation technology to reduce wasted miles, (c) real-time fuel economy guide, and (d) better driver's education to enhance acceleration and deceleration). If we were to assume the weighted averaged costs of these four measures would equal the averages of 25¢ and 35¢ per gallon diesel, a total savings would result of between 2.55 Quads or 45.7% (assumes all measures below $1/gal and a low estimate of effects of four additional measures) and 2.77 Quads or 49.5% (assumes $2/gal threshold marginal cost and high estimate for four effects).

These savings altogether exclude the following seven system and regulatory changes that would produce significant benefits if introduced, specifically, (1) increase maximum GVW (Gross Vehicle Weight) to in the European norm of 110,000 lbs, (2) further utilize the truck-rail-truck modal shift by stacking train rail and rail-to-truck transloading, (3) federally increase trailer lengths from 53 to 59 feet, (4) federally increase trailer height to 14 feet from 13.5 feet—already part of some state's standards, (5) allow double and triple trailer combinations combined with disc brakes giving more brakes-per-pound of GVW (6) reduce maximum speed to 60 mph, and (7) reduce empty miles by consolidating loads with large carriers. We estimate these savings would cumulatively account for at least another 20–40% reduction off any given baseline truck stock consumption.

It is worth noting that an increase of GVW to 110,000 lbs, at least for major U.S. truck routes, would possibly be the single most important change of all the measures considered in this sector of the economy. At federal 80,000 lbs GVW, the U.S. is substantially below most other jurisdictions. A maximum GVW of 110,000 lbs would raise the load per trip from approximately 55,000 to 85,000 lbs, a 53% increase that would result in somewhere between 15 and 30% less fuel use relative to a given baseline truck. Additional benefits include reduced emissions and congestion, the fact that international containers can now be max-loaded from their destination, and that overseas ships and railroads all may carry more weight per container. After Michigan went to 164,500 lbs max GVW, the largest in-state food grade tanker hauls 2.5x normal loads per daily trip for Yoplait yogurt. It does so at 5 mpg—or about 12 mpg versus today's baseline truck—*without* any of the technologies analyzed in this section [1].

3. *State of the Art* techno-economic potential

Summary

If conventional and emerging technologies are diffused into the stock in what would be considered an informed business environment and a focused policy-making, we estimate that a total of 1.84 Quads of diesel, or some 33% of EIA's 2025 forecasted Class 8 consumption, could be saved. This equates to about 0.91 million barrels of diesel per day. At the end-use, pretax point, these savings would have a marginal cost below $0.91 per gallon of saved diesel, or an average cost of $0.35 per saved gallon. At a marginal cost of $1.93 per gallon of diesel, or within about 20% of aftertax retail diesel, another 0.14 Quads would bring the total savings in the stock to 1.98 Quads, or about 35%, vs. *Business as Usual* (*BAU*) in 2025. The curves in Figure 6-1 below detail the two portfolios, the savings from each technology, and their associated costs.

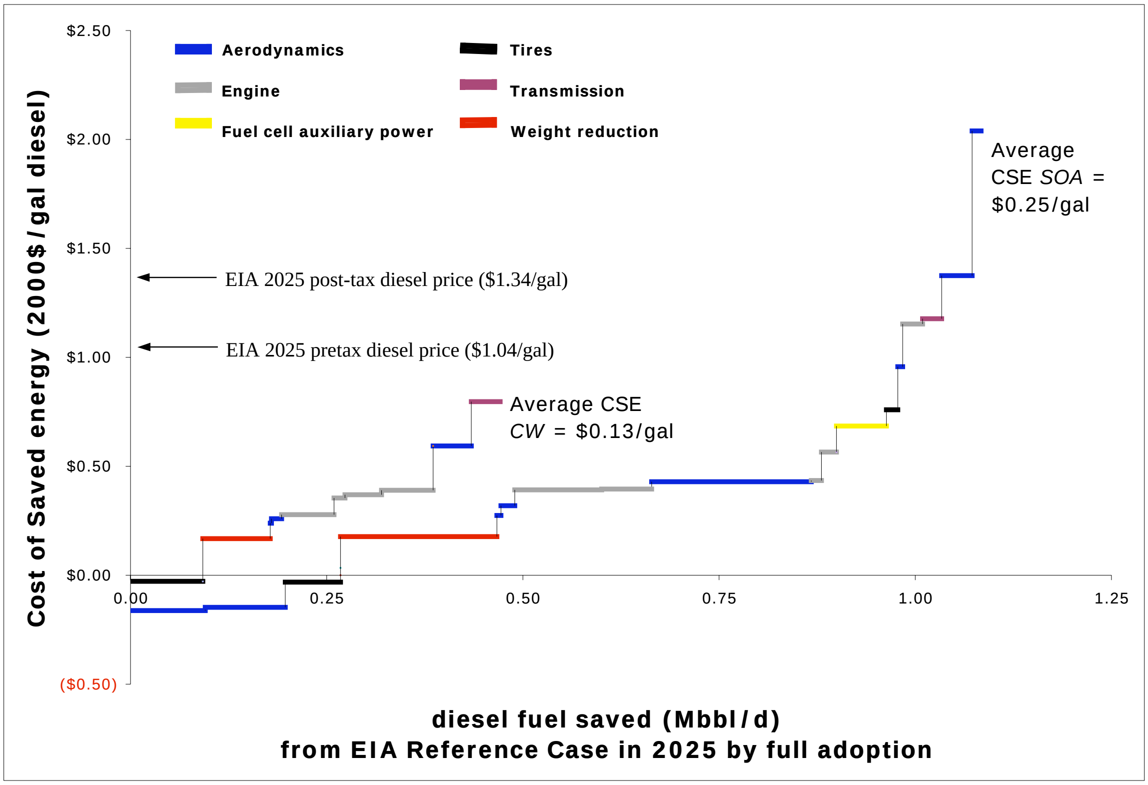

Figure 6-1 Cost of Saved Energy, by technology, for Class 8 Heavy Trucks, U.S.

In addition to the gains shown in the right-hand curve, significant gains could be realized from incorporating variable factors such as axle-increases, reduction in wasted miles via GPS link-ups, improved driver habits from fuel economy indicators in dashboard, load sensing cruise control, and others. In all, these could potentially add 12–32% fuel economy improvement from the new base of the 11.8 mpg *SOA* truck, and do so at a small marginal cost. It is therefore realistic that in the coming two decades we should expect to find the most competitive fleets of Class 8 combination trucks with fuel economies in the vicinity of ~12 to ~16 mpg (on an equivalent basis). If all truckers drove *State of the Art* trucks such as the one sketched below in Figure 6-2 [2] (vs. the one photographed overleaf), significant further and inexpensive savings would result.

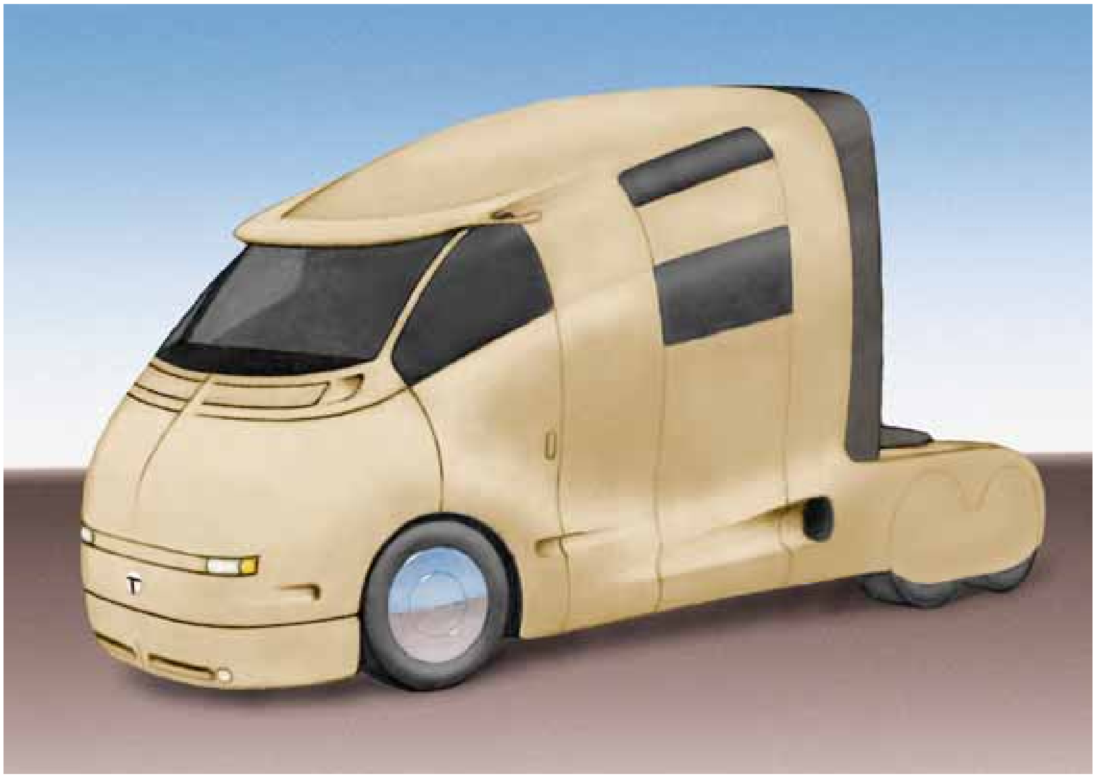

Figure 6-2 Artist's impression, *State of the Art* Class 8 tractor

The tables below and the following discussion provide an overview of the various types, costs, and energy savings of the measures introduced in our heavy truck *SOA* portfolio.

Truck mass

Truck mass is expected to improve fuel economy by a further 5% above conventional technologies via continued application of lightweight materials, as per references and discussion in [32]. Miles per gallon gains account for less energy use by volume-constrained commodities and fewer trips by weight-constrained commodities.

Truck Aerodynamics

About half the energy used by a truck traveling at 55 mph is used to overcome aerodynamic resistance. In developing our *State of the Art* portfolio, aerodynamic drag reduction measures were therefore paramount. This is also in line with recommendations from the NAS/NRC 2000 review of DOE's Heavy Vehicle's Technologies Program for strengthening its focus on aerodynamic drag reductions [3]. We combine generally accepted theoretical considerations with experimentally achieved fuel economy improvements (some more than 30 years old) and third-party estimates of costs where these are available. We have done a rough component and labor breakdown where cost estimates are not available from a third-party.

Excluding pneumatic blowing, the theoretical limit for the coefficient of aerodynamic resistance for combination trucks is the upper limit of the 0.13 to 0.19 range for the optimum streamlined vehicle [31, Fig. 22, p. 47]. Today's best-in-class trucks are at around 0.6–0.7, having come down from about 1.0 in the 1970s via aerodynamic drag reduction on the forward tractor surfaces and on the trailer front surface. Under steady 60-mph conditions this has resulted in a 30% reduction in drag and a corresponding improvement in fuel economy approaching 15%, although in an operational environment unsteady and erratic airflows degrade these figures to around 20% and 10%, respectively [18]. In a recent and jointly-written multi-year program plan for the aerodynamic design of heavy trucks, NASA, two universities, and two of the National Labs noted that "It is conceivable that present day truck drag-coefficients can be reduced from a C_d between 0.50.7 to maybe as low as C_d of 0.3, which represents an ambitious goal of approximately 50%" [4]. As an example of where near-term future developments are heading, for their 2010 concept truck, Scania is discussing C_d-values in the passenger car range [31, p. 47]. Based on these data and data in [5], [31, p. 47] uses an estimate of 0.4 for their 2020 advanced truck simulations. Extrapolation of the distinct trend in [31, Fig. 22, p. 47] gives a C_d-value of approximately 0.35–0.37 for 2025, or about a 40% drag reduction relative to 0.62, the value for our 2003 baseline truck. Excluding pneumatic blowing technology, we use this and the associated 20% fuel economy improvement to conclude that it would be practical to design a truck with C_d of 0.25. We use this as our aggressive but achievable *SOA* truck target for 2025. Pneumatic blowing appears to enable further and significant improvement on this target [17].

Experimentally, testing environments include both scalable and real-scale wind tunnel models as well as on-the-road tests, with the former unable to incorporate the effects of a 'moving' road. Measures added on to the Mercedes Benz 1735 S tractor-trailer combination truck achieved "up to 15% fuel economy improvement" in on-the-road testing. Scalable wind tunnel test are the most common forms of testing, but recently full-scale test vehicles have been studied, both on the road and in large-scale testing facilities, [6], [8], [9], [17], [18], and [19].

In our *SOA* we improve upon one existing measures and add five aero measures to those in *CW*, which as a package deliver approximately 19% mpg improvement excluding pneumatic blowing. We expect advanced Computer Aided Design modeling of airflows around the tractor to be able to improve the cab and leading edge fluid dynamic handling and have increased this from a 2% impact on mpg in *BAU* to 2.8% at a 33% incremental cost. These additional measures are (1) a combination of a boat-tail and vortex strake to give a significant reduction of low-pressure formation behind the trailer; (2) a combination of underbody enclosure, diffuser, and undercarriage flow momentum enhancement to reduce underbody drag; (3) a cross flow vortex trap inside the tractor-trailer gap to reduce drag under crosswind conditions; (4) pneumatic blowing; and (5) replacing mirrors with vision systems. We now discuss these in more detail.

To further reduce the aerodynamic resistance from low-pressure formation behind the trailer, three options include installation of an inflatable truck tail [6], an aerodynamic boat-tail [7], and a vortex strake device [18]. The first option "combines a teardrop profile to give aerodynamic efficiency with easy access to cargo," however, it has generally been regarded as relatively large and unwieldy, and may involve legal and operational problems [8].[1] We model instead a combination of the boat-tail and vortex strake device. These have been studied in significant detail for several vehicle classes, e.g. SUVs [9, Table 13], and Class 8 trucks at the National Full Scale Aerodynamic Complex, NASA's Ames Research Center program site for testing full-scale aerodynamic properties [7], and at Solutions and Technologies [18]. In the case of trucks, the tail consists of two horizontal and one or two vertical plates, all mounted slightly inward from the truck rear and perpendicular to the plane of the rear doors. The plates increase the pressure on the rear surface of the trailer by entraining the airflow inwards as it passes the rear of the vehicle, thus decreasing its overall wind-averaged drag coefficient. The tail was tested on a Navistar Transportation Corp. 9700 tractor and a Fruehauf Corp. 48-foot trailer combination which included a cab fairing and hood, aerodynamic front bumper, cab side extenders, leading edge lip on the upper forward edge of the trailer, and trailer side skirts. The drag coefficient of this configuration at 0° yaw was the reference coefficient used in the analysis. Varying the wind yaw angle by ±15° gave 9.8% as the weighted integration drag coefficient reduction when the tail was optimally dimensioned and configured[2], agreeing well with [8, Table 2]. For an average speed of 60 mph this drag reduction would on a stand-alone basis improve fuel economy by 4.9% [18, Table 1]. Estimated at 3.6% elsewhere for a slightly lower speed [10, p. 5], we nevertheless use the higher figure, as possible interaction effects with the rounded trailing edge treatment incorporated in the *CW* portfolio have been accounted for by the presence of these features in the baseline test truck and as we model 62 mph as the average speed. No cost estimates were given, but the tail consists of four plates mounted to the rear. We estimate an incremental retail cost of $500 including mounting.

Similarly, the patent-pending vortex strake device (VSD), consisting of L-shaped bars diagonally mounted on the trailer side towards the rear, is a very simple vortex controller

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[1] Testing of an inflatable boat-tail during the summer of 2003 revealed only a 1.5% fuel economy gain, but with some interesting lessons. The low gain was largely caused by poor aerodynamic shape as the angle of incidence—almost 45° in some areas—of the air coming off the back end of the trailer was much too great to maintain laminar flow across the trucktail's surface, leaving mostly turbulence in the air coming around the rear of the trailer as with a normal trailer without a tail. Future inflatable trucktails could be designed to meet the trailer at a more reasonable angle and be expected to improve fuel economy further. The bag remained stable at all stages of inflation and deflation, also when occurring at highway speeds. Two alternate methods of inflation were used, one by means of the truck's pressurized air system, and one by means of a 12 volt blower mounted on the trucktail's frame. Each was able to do the job successfully, although both were very slow at about 20 minutes fill-time. Both were able to add air automatically in response to a slow leak in the bag. The tail satisfied operational requirements, a ballpark estimate of the future retail price is $2,000 per trucktail..

[2] So that the plate edge projects a distance out from the plane of the doors equal to 36% of the width of the truck mounted a distance in from door edge equal to 6% of the truck width.

for which we estimate a cost of $250. Because the VSD effect is incremental to ANL's leading/trailing edge treatment, for modeling purposes we reduce its fuel economy gain potential by 35% to account for interaction effects, from 1.1% to an incremental 0.7%. This makes for a collective total of 2% mpg gain and $750 cost arising from the combined effect of ANL's measure and the VSD. We assume that by 2025 all new trucks will be delivered with a boat-tail and leading/trailing edge treatments that include a VSD-like device.
Recent advances in understanding the effect of underbody vehicle air stream diffusion have led us to include this area in our *SOA* portfolio. In terms of aerodynamic resistance, this is a remaining area after the basic upper vehicle body shape and wheels and wheel housing has been accounted for. A recent literature review by Volvo finds that estimates generally agree that 25% of automobile drag is caused by air flowing over the uneven bottom [11]. For trucks the figure is about 15–20% [18], [12, cited in 10, p. 5], and depends on the presence of crosswind. More recent empirical studies for automobile shapes in wind tunnels for a simplified geometry without wheels and wheelhousing [13] show that upsweep from underbody diffusers has a beneficial drag reduction effect at large ride heights, and concludes that a well-designed diffuser could reduce drag. Reducing ride height systematically erodes the effect, eventually turning it negative at low ride heights by the inviscid and viscous ground interaction effects and by the diffuser pumping effect. These two effects cause increases both in downforce (sought in car racing) and in drag, offsetting the upsweep effect from the diffuser. To minimize drag, ride height should therefore not be set any lower than dictated by other considerations [18].However, due to interaction between wheel and diffuser the rear wheel wake may reduce the diffuser efficiency significantly [14].

We have therefore assumed deployment of the recently developed undercarriage flow treatment device (UFTD; patent pending) to lower rear wheel wake disturbances [18, photograph Fig. 19]. The UFTDis attached to the lower surface of the trailer near the vehicle trailing edge and acts as a convergent duct changing the low momentum undercarriage flow into a coherent high momentum flow. Given that for combination trucks ride height is quite large, we 'design' a truck that has a combination of underbody diffusion achieved by using a slightly angled and much smoother truck and trailer underbody enclosure [15] made of lightweight carbon composite material [16].

In our *SOA* portfolio we then assume the UFTD can 'recapture' the diffuser disturbance losses caused by the wheels, and that the smooth undercover permits addition of 4.2% [9, Table 13] to the 2.5% diffuser drag reduction found at the large ride height identified in [13], for a total of about 3.3% fuel economy gain. The additional 4.2% is based on experimentally obtained data from adding underbelly panels to an SUV [9, Table 13]. Assuming that integration of the UFTD and enclosure can be angled towards the rear to give a diffuser effect, and made and suspended as an independent add-on to the standard truck/trailer underbody topography, the UFTD cost comprises forming the part(s) and material usage for about 300–500 square feet of area and about 1/16 inch thickness. At about 100 pounds in weight, this would add negligible mass and cost in the vicinity of $2,500 including labor. While we assume all trucks that are new in 2025 will come with such an integrated enclosure, we will also assume its market adoption will not begin until 2010 and that it will be slow in the beginning.

With truck fairings present, some 15% of combination truck drag still arises from flow in the gap region, whether there is crosswind or not [18, Fig. 4]. The *SOA* portfolio will assume that a Cross-Flow Vortex Trap Device (CVTD[3]) is located on the forward front face of the trailer. A test prototype CVTD consisted of seven duplicate, equally spaced, vertically aligned, and adjacent planar surfaces, each surface extending perpendicular from the trailer front face, 12 inches wide and each extending vertically over a substantial portion of the face [18, photograph Fig. 12]. The CVTD traps vortices between its adjacent surfaces [18, Fig. 13], and the resulting low pressure on the forward facing trailer surface reduces drag by being aligned with the vehicle longitudinal axis, becoming an aerodynamic thrust force if the trapped vortices are of sufficient strength. It is more durable than gap seals and we assume the CVTD replaces these. On-the-road test data collected between July 2001 and March 2003 showed a simple average fuel economy improvement of 3.5%, 5% when weighted by tractors across all temperatures and trip lengths, or 8.3% across all tractors when based upon temperature and weighted by trip mileage. The latter weighting ensures that the contribution that a given trip makes to the average is proportional to the length of the trip—shorter trips matter less than longer trips. We apply the mid-value of 5% as the CVTD fuel-economy improvement; assume that all trucks that are new in 2025 will have the CVTD mounted; and ascribe a cost of $500 to this measure due to its simple structure.

In our *SOA* technology portfolio we also assume that the DOE-sponsored technology pneumatic blowing will enter the market by 2025. The technology has already been applied to reduce aircraft drag and improve stability, and involves pressurized air blowing through selected points on the exterior truck surface [32, p. 7], [17], [18]. The basic pneumatic concept, known as Circulation Control (CC) aerodynamics, is outlined in [17]In brief. an air jet sheet is injected tangentially to a fixed curved surface, such as a trailer corner or modified airfoil's trailing edge, remaining attached to the curved surface by the balance between sub-ambient static pressure on the surface and centrifugal force[4] to entrain the external flow fields to follow the jet, and in the process enhancing circulation and aerodynamic forces around the trailer or airfoil. Augmentation of the lift by a factor 80 has been recorded, i.e. 8,000% return on the invested lift momentum.

Due to this physical high return, or very low blowing input and associated power required, the pneumatic concept has been applied in research by DOE's Office of Heavy Vehicle Technologies, and has led to an on-the-road demonstration of an operating Pneumatic Heavy Vehicle (PHV) [17]. ANL expects this technology to improve fuel economy by 5%, to be introduced into the market by about 2010, and to gain a 30% share in the new truck market by 2025. It is expected to cost an incremental $2,500, although further research may lower this cost.

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[3] Patent pending. Its design is based on trapped vortex technology. This captures a vortex which forms when vehicle incident flow encounters an aerodynamically sharp edge.

[4] The so-called Coanda Effect.

Scalable wind-tunnel tests of pneumatic circulation control devices have shown that combination truck C_d can probably be brought down a further 46% below a baseline consisting of a truck that incorporates all measures above, improving fuel economy by a further 23% at highway speeds [17]. A C_d down to 0.13 [19], [17] was shown in a model truck tunnel test—this is about half of the drag coefficient of the *Corvette* or newer Honda *Insight*. While this would represent a 79% reduction in drag relative to our 0.62 model baseline, giving rise to a theoretically possible 35% to 40% fuel economy improvement, a full-scale proof of concept test that did not include optimizing blower configurations to that of the best tunnel model, instead demonstrated a real fuel-efficiency increase of between 4% and 6%, i.e. ,4.2% to 6.4% fuel-economy improvement [17].

It is expected that a full-scale test vehicle with optimized pneumatic configuration will demonstrate between 16% and 23% fuel-efficiency increases (between 19% and 30% fuel-economy improvement) [17]. Using the ANL cost estimate as a baseline, we model an optimized blower configuration that will lead to fuel economy improvements of 15%, conservatively set at half of the maximum 30% predicted by [17], but considerably above ANL's figure, as that was achieved in on-the-road tests without blower placement optimization. The actual reductions achieved to date (4% to 6%) were also improvements relative to a truck with an actual C_d around 0.45–0.50. We also expect competitive truck manufacturers to successfully coordinate integration of pneumatic blowing into tractors and trailers, and to be able to deliver a non-optimized system for $2,000, i.e., $500 below the ANL estimate, and an optimized system for a total incremental cost to the truck owner of $3,000, i.e., a 20% premium above ANL's estimate of $2,500. At the incremental retail price of $3,000 we also assume that a combination of somewhat improved private economics and a more active policy stance will result in 100% of new trucks having this technology as a standard installation by 2025. However, like ANL, we assume that diffusion into the market will begin only after 2010.

Finally, replacing outside protruding mirrors and holders with electronic vision systems will offer a 3% to 4% reduction in aerodynamic drag, i.e. a 1% to 2% fuel-economy improvement [20]. Our model incorporates the lower value, 1%, and a cost estimate based on current electronics costs of $1,000, with diffusion beginning in 2010 and reaching its mid-point in 2018.

Rolling resistance

Pneumatic blowing will also here enable further reductions in parasitic losses. It is expected that a $500 end-user investment can bring a 1.2% fuel-economy improvement incremental to *CW*, and that this technology will gain a 25% share by 2025 [32]. This assumes compressor, piping, and blow controls are included in the general pneumatic aerodynamic controls. We assume in *SOA* that there are few other gains to be made by 2025 additional to those discussed under *CW*.

Auxiliary Power

It is well understood that improving auxiliary power efficiency both reduces the power deduction incurred on the indicated engine power and improves the average brake thermal efficiency by moving the locus of the required engine operation to points of higher instantaneous brake efficiencies. Improvements can be achieved via two major routes, first, redesigning auxiliary pumping elements to make these more efficient, and second, by electrical decoupling of the now more efficient (but conventionally hydraulic or mechanical) pumps and cooling fans. The latter route is also often referred to in the context of intelligent thermal management, which includes areas ranging from optimizing the engineering of vehicle occupant thermal systems, see [21] for a 30% reduction in air conditioning capacity from operation optimization.

In *SOA* we incorporate a fuel cell with reformer, improving overall fuel economy by 6%, or a 4.5% fuel-economy improvement [32] relative to *CW*. ANL assumes $1,500 as the cost and a 15% diffusion rate into the 2025 market for new trucks, beginning in 2012. We assume a 31% presence in new trucks, the same price, and a similar timing of introduction.

Truck Engines

The average Class 8 diesel truck engine currently has an indicated power capacity of about 320kW and a brake thermal efficiency of around 40%–44%. As early as 1997 the U.S. DOE and the diesel engine industry jointly set as an aggressive but achievable target to reach a brake thermal efficiency of 55 percent [22]. By 2000 the target was refined to incorporate specific timing, set to 2012 [34], and at the time of this writing DOE’s Office of Heavy Vehicle Technologies retains the 55%-target [23] by 2012. This is an incremental 10%–15% to today’s best-in-class diesels, and is what ANL assumes for its heavy truck diesel engine fuel economy improvement [32].

For the most part, further advances in efficiency will be achieved with improvements in components and operating characteristics of engines similar in overall architecture to those now widely used. Sub-areas likely to contribute significantly to achieving the objective include further improvements in engine turbomachinery, displacement on demand (DOD), variable intake valve timing (VVT), variable intake lift, piezo-injectors (Bosch, Delphi), 42V electrical systems, transitioning hydraulic and mechanical pump systems to controllable electric pumps and drives, internal engine braking, better lubricants (from 15W40 to 5W30), camless diesels, hybridization, and homogeneous charge compression ignition (HCCI). We now discuss each of these in more detail.

Oil-Free turbomachinery is defined as high-speed rotating equipment, such as turbine engines, that operate without oil-lubricated rotor supports, i.e., bearings, dampers and air/oil seals. We expect advances towards an oil-free turbomachinery to have some impact on the fuel economy gain in heavy trucks. By how much is uncertain, but it is known that relative to state-of-the-art oil lubricated systems, oil-free turbomachinery technology can offer significant system level benefits. For gas turbine engine propulsion systems found in Army helicopters and tanks, and military fixed-wing aircraft, projected oil-free benefits include significant reductions in engine weight, engine maintenance, and lifecycle cost while improving fuel efficiency [24]. As oil-free foil air bearing turbogenerators for electrical power generation are commercialized in the 30kW to 60 kW range, it would appear highly likely that this technology could make an impact on Class 8 Truck turbo-diesel engines. Because cost and fuel economy improvements have been difficult to find, we have for *SOA* simply assigned a 50% increase in the factor for engine lubrication, to increase it from a 2% to a 3% improvement in fuel economy, and, in spite of the likely elimination of several components entailed in an oil-lubrication system that are required for the rolling element bearings, e.g., for gas turbine systems, these consist of pumps, coolers, filters, tubing and fittings, valves, sensors, oil, and other ancillary equipment [24], we have increased cost by 20% in face of the uncertainty when netted against the cost of the equipment itself.

Displacement on demand (DOD) technology deploys only the number of cylinders required to serve the current load, thus shifting the locus of engine operation to a region of higher thermal brake efficiency. The gain in a light-truck fuel economy can be very high, as much as 6% to 8% for the new GM 3900 60° V6 overhead-valve (OHV) engine [25]. Increased cylinder displacement in the V6 has enabled both DOD and replacement of the new Gen IV Vortec 5300 V8 for part of the vehicle demand segment, capturing further fuel-economy gains from the perspective of the fleet. The Class 8 heavy truck segment will not achieve a fuel-economy gain this high due to the already even operational load on these engines, but may see between 2% and 5% gain as deactivation of between 2 and 6 of 12 cylinders may be possible during steady state operation. The cost of this technology is not very high.

VVT timing is also deployed in the new GM 3900 V6 light truck engine. In this case, electronic control of the camshaft enables selection of optimum location for various engine operating conditions, maximizing torque and horsepower outputs, as well as significant emissions benefits from the engine's precise valve control. This control enables elimination of the external exhaust-gas-recirculation system, in turn permitting maximum exhaust-valve opening. The greater opening helps warm the exhaust catalyst, which improves cold-start emissions.

Variable intake lift, piezo-injectors, and increased voltage of electrical systems to 42V are at this point essentially part of standard modern system designs. Moving hydraulic and mechanical pump systems to controllable electric pumps and drives will have significant efficiency benefits. As an example, electrical control of the cooling pump means that for any given flow the mechanical pump will deliver, the controllable electric pump can deliver that flow more efficiently [26]. In the auto segment, such pumps are already in the market [27], and these will by necessity make a parallel impact in the truck segment. Delivering the exact flow required to cool the engine under its current operating condition implies reduced draw off engine indicated power and moving the locus of engine operation closer to the regions of higher thermal brake efficiency.

In theory, assuming the optimum performance of the engine cooling system occurs when the temperature rise of the coolant through the engine is 10°C, the optimized flow for a given load would require significantly less coolant flow during part load operation, which gives insight to efficiency improvement opportunities. For example, if a truck operating at 100 kph steady-state requires 150 kW at the engine flywheel to maintain this speed, and assuming the 10°C temperature rise across the engine occurs at 1,500 engine rpm, the engine only needs about 120 L/min to maintain operating temperature, vs. the 275 L/min that a mechanical pump usually would deliver at this rpm—i.e., independent of load. This mechanical pump would consume about 700 Watts to deliver the 275 L/min fixed flow at 1500 rpm, whereas a controllable pump, delivering only the 120 L/min required to cool the engine, will consume just 70 Watts, a parasitic power reduction of 630 Watts under this particular condition.

The gains are even larger if the engine is operating at higher speeds. Assuming the coolant flow through the engine is sufficient to prevent localized boiling along the cylinder liners (preventing power cylinder "worm holes"), and access to a 42 Volt electric motor, preliminary calculations predict that a 5 percent improvement in fuel economy over a 2000 baseline engine could be realized by replacing the mechanical water and oil pumps by EMP controllable pumps [26]. If the testing were conducted with lower voltage motors, efficiencies would be lower based on the copper losses in the motor. Additional benefits of the controllable pump technology include lower emissions, improved serviceability, and extended life of systems.

Homogeneous Charge Compression Ignition (HCCI) is a new combustion process that has the potential to be both highly efficient and produce very low emissions [28], [29]. HCCI is currently at the research stage. It is a lean combustion process and enables the combustion to take place spontaneously and homogeneously without flame propagation, eliminating heterogeneous air/fuel mixture regions, translating to a lower local flame temperature that reduces the amounts of Nitric Oxide (NO_x) and particulate matter emitted. HCCI can provide high, diesel-like efficiencies using gasoline, diesel fuel, and most alternative fuels [28]. HCCI may incorporate the best features of both spark ignition (SI) engines and direct injection (DI) diesel engines. Like an SI engine the charge is well mixed which minimizes particulate emissions, and like a diesel engine it is compression ignited and has no throttling losses, which leads to high efficiency [28], [29]. However, unlike either of these conventional engines, combustion occurs simultaneously throughout the cylinder volume rather than in a flame front.

HCCI is potentially applicable to both automotive and heavy truck engines since it could be scaled to virtually every size-class of transportation engines from small motorcycle to large ship engines [29]. HCCI is applicable to non-transport piston engines such as those used for electrical power generation and pipeline pumping. As the HCCI engine is optimized for operation over a more limited range of speeds and loads compared to engines used in conventional powertrains, it is particularly well suited to hybrid vehicle applications since this powertrain would better leverage the benefits from an optimized HCCI engine to create highly fuel-efficient vehicles.

Because HCCI engines would likely use a lower-pressure fuel-injection system, they have the potential to be lower cost than diesel engines [29]. This is also true for the emission control systems for HCCI. With successful R&D, HCCI engines might be commercialized in light-duty passenger vehicles by 2010 [28]. Nissan and Honda already are in production, using HCCI during a portion of their operating range: Nissan is producing a light truck engine that uses intermittent HCCI operation and diesel fuel, and Honda is producing a 2-stroke cycle gasoline engine using HCCI for motorcycles.

Truck Transmission

We have not modeled an improvement over *CW* for heavy trucks in terms of transmission. The use of synthetic lubricants will play a role, but this is already part of *CW*.

Variable Factors

Aligning the U.S. permitted number of combination truck axels with EU and Canada, increasing to 6 from 5 axels, would have very large savings in reduced overseas container shipments, and for the U.S. would probably improve productivity in the trucking industry by more than any other single measure mentioned above, possibly by as much as 15–20%.

Loadsensing cruise control will improve fuel economy further. The same is true for reduction of out-of-route miles. Here the potential is large, as between 3% and 10% miles are wasted [20]. Eliminating these would amount to gross fuel savings in the form of lower VMT.

Making a fuel economy display a standard part of the dashboard package will focus driver attention and driver habits, and may result in further reductions in fuel use somewhere in the range 1–5%.

Adding up the variable factors indicates a potential for an additional 10–25% on top of what has been described. While costs and gains are difficult to quantify, it is possible to envision that a 12.5 mpg *SOA* truck would get between 13.8 and 15.6 mpg if variable factors such as these are taken advantage of.

4. *Conventional Wisdom* techno-economic potential

Summary

If deployed in line with average levels of business information and heavy truck transport policies so that standard rates of conventional technologies' diffusion into new vehicle sales would occur, we estimate that today's off-the-shelf technologies would save about 17%, or 0.95 Quads, from projected 2025 usage. On average these savings would cost 12¢ per gallon of avoided diesel—i.e., choosing to equip a new truck with these technologies costs only about one quarter of making the choice not to on a fuel pretax basis. The marginal cost of the last gallon saved amounts to 80¢—still cheaper than the cost incurred by not installing the most expensive technology.

***Conventional Wisdom* Savings**

For truck efficiency measures in the *CW* portfolio we make a general assumption that in an industry that has to focus on the bottom line, private economic benefits will weigh in to a significantly greater extent than public policy, and in effect be the greater driver of technology diffusion. However, greater market shares and further improvements beyond our *CW* are probable, mainly due to the significant remaining technical potential, favorable economics, public demand for strengthened public policy, and availability of known means to get there.

There are known technologies in some areas, e.g., aerodynamic drag reduction, that are over three decades old, yet they have not been implemented for a host of reasons, including *relatively* smaller returns vs. other measures such as cab deflectors or body fairings. The technologies have not been adopted for other important reasons: because they are mechanically or operationally more difficult, [or even simply because they are trailer mounted.] The latter point can actually be a serious issue in an industry with just in excess of two trailers per tractor. This means that the economic advantage of trailer-mounted measures in reality could be about halved. Further, trailers are commonly leased or client-owned, so the incentive is often split since retained savings do not benefit the owner [8]. In calculating the cost of saved energy (CSE) we ignore these issues, but address them as barriers that likely will need to be mitigated via appropriate policy measures.

Aerodynamic drag reductions

In sum, for a 2025 truck in our *CW* portfolio, aero-reduction measures contribute a modest 5.8% to overall truck fuel-economy improvement. This is only 1.3% above the 4.5% improvement in fuel economy targeted by the Government-Industry Research Partnership [34], which has proposed to reduce the 21.3% of truck energy used to overcome aerodynamic resistance by 20% (about a 4.5% mpg improvement). The *CW* overall figure represents only about one-third of actual on-the-road Class 8 aero-reduction achievements. For example, by mounting fairings, wheel covers, and side-skirts, and by reducing the truck-trailer-gap and tapering the rears, a Mercedes Benz 1735 S tractor-trailer combination truck demonstrated an on-the-road fuel economy improvement of up to 15% [31, p. 46].

Mass reductions

In the *CW* portfolio, mass reductions result in less energy use by volume constrained commodities and fewer trips by weight-constrained commodities. We incorporated a 5% mpg gain from this, with corresponding costs as in [32].

Rolling resistance

Reduction of rolling resistance using a set of wide-based (‘super-single’) tires gives a measured 4% mpg gain [30], and with costs as in [32]. A 3% fuel economy gain from low-roll tires [32] results, and in *CW* these two were assumed to diffuse into the new truck market with respective shares of 2/3 and 1/3.

Auxiliary power use

This was reduced by 1.5% from better APU management [32].

Transmission and engine-related areas

Combined transmission and engine-related areas saw a total of 19% improvement in mpg from standard practices and relatively basic technologies, such as engine internal friction reduction from synthetic and lower-W lubricants and better bearings, higher peak cylinder pressure, improved injectors and more efficient combustion, reduced waste heat and improved thermal management, and advanced transmission with lock-up, electronic controls, and reduced friction. The measures, effects, and costs are summarized in Table 6-2.

Costs of *Conventional Wisdom* Technologies

Using costs from ANL [32] and comparing the RMI and ANL portfolios with the baseline, we find that at an average cost of conserved energy of $0.13 per gallon, the private economics of on-the-shelf efficiency technology is in fact steeply tilted towards technology adoption. We find it likely that truckers and their representatives will use their collective buying power to influence manufacturers and legislators to a somewhat larger degree than ANL has assumed. The technologies exist, and in the case of new trucks, the private economics are very favorable. Via seeking and making financially smart purchasing choices, demand from individuals and civilian and military fleets should drive manufacturers to compete on fuel efficiency to a significant degree and to cooperate on measures that require tractor-trailer integration. These findings are summarized in Table 6-3.

5. Methodology

Introduction

This section describes in detail the methodology from our analysis of two portfolios whose mostly technical changes in the operating Class8[5] segment of the U.S. combination truck fleet would result in economically advantageous fuel savings. In 2000 this segment of highway vehicles consumed about 22% of all highway vehicle fuel. Class 8 is the third largest vehicle class by fuel use [40, Table 8.4]. There are approximately 2,211,000 Class-8 trucks in the U.S., representing about 3% of all highway vehicles. A majority of the tractors in the current U.S. stock have aerodynamics as in the photograph below [2]—and therefore represent a large opportunity to save fuel.

Reduction in truck fuel use can be accomplished by improving upon both variable and fixed truck characteristics. Variable characteristics include the manner in which the truck

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[5] Vehicles with gross vehicle weights (GVWs) in excess of 33,000 lbs. Depending on its GVW, a highway vehicle belongs to one of eight different classes. The lightest two classes, Class 1 (GVW up to 6,000 lbs) and Class 2 (GVW from 6,001 to 10,000 lbs) consume about 71% of all highway vehicle fuel use [40, Table 8.4]. The heaviest class, Class 8 trucks, uses 22 %. The approximately 2,975,000 trucks in classes 3 through 7 use the remaining 7% of highway fuel [40, Table 8.4]. For classes 3 through 7 we will assume that suitable combinations of technologies identified in this and previous sections will apply, and we have for our aggregate analysis chosen to rely on recent MIT and ANL estimates for these classes.

is driven, size of load, traffic and logistics patterns, and vehicle speed and acceleration pattern. Fixed characteristics of the truck and its subsystems include vehicle body's mass, volume and shape; tire type; propulsive system; and auxiliary power needs and systems.

For a given set of variable characteristics, the specific nature of the fixed characteristics and their interactions collectively determine the magnitude of the individual forces that oppose that vehicle's ease of motion. The individual opposing forces arise from resistances due to vehicle inertia, aerodynamics, and rolling tires, as well as parasitic power losses from overcoming internal engine friction, other drivetrain components, and running auxiliary electrical loads. The sum of these forces is what determines total fuel consumption per mile driven.

Our *CW* portfolio only incorporates improvements in fixed truck characteristics and assumes driving manners as well as average speeds and weights will not change. While the majority of fuel economy improvement in the *SOA* portfolio also results from improvements to fixed vehicle characteristics, a fraction of the *SOA* improvements results from changes to variable characteristics.

Fuel economy improvements from our two portfolios occur incremental to a *Business As Usual* (*BAU*) baseline. We have assumed our baseline to be EIA's *AEO 2025*. *BAU* evolves over time and incorporates implementation of some technologies between now and 2025. For an individual Class 8 truck, the baseline technical specifications are as laid out in [31] and [32] and in the following section. For heavy trucks and the truck fleet, our baseline data is almost exclusively from ORNL's Transportation Energy Data Book, Edition 23 [40], also summarized in the next section.

Determination of Order of Technology Deployment

We follow a three-step order of technology deployment. In so doing we adhere to consistency in terms of whole-system efficiency economics (must be economical when accounting for changes in other subsystems), timing of technology availability, system logic (agreement between system and specific technology), mutual exclusivity (e.g., only one transmission-type per vehicle), inseparability (comparable performance), and path dependence (one technology's entry might depend on adoption of another[6]); see [33] for a full discussion of these. First we reduce inertial and parasitic resistances down to the level achievable by deploying all mass- and resistance-reduction technologies, with estimates of first-order CSEs. After each such technology we re-size the engine capacity to appropriately match each new mass- and/or resistance-level. Finally we deploy engine-related technologies, again in order of lowest pre-install, first-order CSE. We deploy these technologies up to the last technology up to a CSE of $1.00/gal.

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[6] E.g. the integrated starter generator (ISG) will likely be found in conjunction with 42V (or higher) electrical systems. In turn, after a degree of hybridization (e.g., by adoption of ISG), which would shift the locus of engine operation to a more efficient load-regime, the introduction of camless valve actuation (CVA) becomes more feasible, in turn likely eliminating a whole series of other and also new—but each more expensive—technologies, such as (i) multivalve overhead camshaft (ii) variable valve lift and/or timing, (iii) cylinder deactivation, and (iv) intake valve throttling.

The caveat is that technologies that result in whole-system benefits that reduce total vehicle costs by an amount sufficient to give a net CSE below the threshold are not eliminated. This effect is somewhat more prevalent in our *SOA* portfolio. A technology's pre-install marginal CSE is computed from data on stand-alone % mpg improvement applied to the truck's re-calculated mpg, i.e,. the mpg of a truck that incorporates all steps and technologies prior to the technology whose CSE is being calculated.[7] While best design practice would in fact dictate repeating the three-step order of technology deployment until no further improvements from compounding and re-sizing effects are detectable, we have conservatively implemented the cycle of three steps only once.

In sum, we determine a technology's overall order of installation first by its technology grouping, then by its ranked pre-install CSE within its group, after having valued and adjusted for easily accountable whole-system benefits.[8]With two important exceptions, we have therefore ignored effects that arise from interaction between power-requirement reductions in a given vehicle subsystem causing changes to the requirements in other subsystems. However, we do account for such interactions when introduction of one or several subsystem technologies result in elimination of entire other subsystem(s). In this case we account for any net energy and cost changes due to the elimination, since this accounting is easy to do and since this type of interaction-effect may be significant. Furthermore, for the case of technologies that reduce resistance and parasitic loads, these do result in a reduced engine power-draw requirement that is relatively easily estimable. As such, to a first order of accuracy we approximate such power-draw reductions via the appropriate physical relationship and via making some simplified assumptions as discussed in more detail in the sections below. Since reductions in power-draw reduce the need for engine power, data on marginal engine capacity costs ($/kW) were used to deduct an appropriate 'engine credit' from the technology's initially estimated capital cost. For example, counting the engine capital cost savings from implementing a measure that reduces the coefficient of aerodynamic resistance C_d by 0.07 from a baseline value of 0.62 reduces the CSE from $0.77/gal to $0.40/gal [34].[9]

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[7] Note that for the summary supply curve [main text Fig 28] we have used the average CSE for all Class 8 truck technologies, and for the detailed supply curve for the truck segment we have placed all technologies strictly in the order of increasing CSE.

[8] The last step often involves re-ranking.

[9] This case refers to implementing a package that reduces the tractor-trailer gap, covers the wheel-wells, and installs baffles and aero-bumpers. The package has a stand-alone cost of approximately $1,500, translating to a CSE of approximately $0.77/gal. While already a very attractive alternative relative to buying the fuel at $1.00/gal, a second-order consequence of this package is that about 10.3 kW lower engine capacity will be required to do the same work as before. While a weight-constrained premeasure 321 kW AvTruck engine with 10.3 fewer kilowatts would not accelerate to cruise-speeds quite as quickly (however, a volume-constrained truck would), Class 8 trucks spend approximately 86% of their time in motion at average speeds of around 62 mph, so the 3.1% decrease in engine power would only be felt during intermittent segments of about half of the 14% of the time that the truck actually needs accelerative power—and even during these ~7% of total drive time this would amount to a very marginal effect since power reduction is very small. This assumes that about half of the 14% is spent accelerating and the other half spent

Within a group of technology measures, e.g., engine-efficiency-related measures, each technology's stand-alone, pre-install CSE will determine its place in the installation sequence. In the case of mutually exclusive technologies, this impacts not only the order of installation, but may also impact whether it and technologies related to its path, will be altogether rejected as an option. This arises when percentage fuel economy gains (% mpg improvement) is the basis for fuel savings calculations—as herein is the case. The actual fuel saved from deploying an engine-related measure depends on what the truck fuel economy is when all other measures have been accounted for. Relative to just looking at technology groups, a combination of such a stand-alone CSE-calculation and a group calculation *had the related measures also been installed* therefore has the potential to alter the path chosen, and therefore the vehicle's final fuel economy.

This forms the logical justification for not *just* undertaking a consideration of *groups* of technologies. We point this out because a critique of the 2002 National Academy of Sciences report on the impact of CAFE standards to the U.S. Congress [35] has, in an otherwise very constructive article [36], recently claimed that "the only relevant scenario [for improving fuel economy] is one in which groups of technologies are applied to a vehicle system. The sequential order in which they [the technologies] are applied are therefore irrelevant." This argument fails to offer a suitable mechanism for culling out within-group technology alternatives—indeed it may fail to make the correct choice of group in the first place. However, combining logical steps in vehicle design with engineering and economic approximations for *both* individual and group CSEs does provide such a mechanism.

Diffusing Selected Technologies Into Population Stock

To assess a technology's penetration into the truck stock we assume diffusion according to standard methods for substitutive technological progress [37]. We apply a commonly used technological progress relationship and use a progress ratio (beta) of 2.5, see [37]. To estimate the impact of mutually exclusive technologies, we ensure their total diffusion into the stock does not exceed 100%, and we have based our share estimates on cost and savings effectiveness. For the *CW* portfolio, the aero and rolling resistance measures reach between 78% and 96% market share by 2025, the mass reduction potential grows to a 92% share, and engine and transmission technologies grow to between 64% and 88% share. We assume that due to a greater prevalence of a combination of awareness of economic benefits and improved policies, technologies in the 2025 fleet will be more advanced and at a higher market share in *SOA* than in *CW*. For *CW* only currently available ('on-the-shelf') *and* financially viable (as determined by the CSE) technologies are diffused into the fleet. In the *SOA* a small number of technologies with high probability of near-term commercialization are included. We have also included more latitude for best-in-class design.

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decelerating. Accounting for the fact that a majority of trucks are volume-constrained would further reduce the impact of this effect. Finally, deducting the marginal engine capital cost saving of about $70/kW from the full stand-alone measure cost reduces the CSE to $0.40/gal.

Calculating Cost of Saved Energy

The cost of conserved energy (CSE) resulting from deployment of a given technology is calculated as incremental to all lower-CSE technologies that are assumed to already have been deployed. Five chief factors determine a measure's CSE: fuel-economy gain, up-front net cost, projected lifetime, truck annual mileage, and truck driving cycle. In terms of measure mpg gain and cost, we have relied on standard sources from the literature for our *CW* portfolio. For our *SOA* portfolio we additionally rely on projections and interviews.

Measure lifetimes will to some extent need to accommodate the realities of a measure's technical properties and the owner's perspective on whether to invest in a given measure. This perspective is generally based on first-purchaser's likely ownership period and federal depreciation schedules of short durations. Both factors lower the value of any efficiency measure in the distant future and therefore also the buyer's horizon. While in actuality a MY 1990 heavy truck has a median lifetime of approximately 28 years [40, Table 6.11], we assume an economic lifetime of 750,000 miles for the vehicle and for the installed technologies. Accounting for annual mileage drop-offs, this gives an average life of a measure of 11.6 years, very comparable to the 11 years in [38]. Others assume an installed technology's life to be equivalent to the interval expected before engine overhauls, 500,000 miles [39], but due to quality shifts few of the non-variable cost technologies are likely to need replacement accounting (unlike tires).

The third major factor that determines a truck's economic life is its annual mileage. While all Class 8 trucks averaged about 48,000 miles in 1997 [40], within this class the figure we assumed is that of the year 2000 over-the-road combination truck segment of about 64,500 miles per year per truck [40, Table 8.2].

There are no established driving schedules for heavy trucks [31, p 10]—this may in part explain why the recent literature covers the gamut of analytic pathways. These range from not accounting for driving cycles [39], to relying on an assumption that the bulk of Class 8 truck fuel-use stems from combination trucks on a generalized Intercity Driving Schedule [31, p10], to explicit consideration of the driving cycle differences via outfitting Class 8 trucks typically on highway cycles with non-hybrid powertrains and trucks in Class 7 and below—typically on urban cycles—with hybrid powertrains [31].

We chose to follow the latter path, since a unifying conclusion in the literature is that the use of hybrid powertrain technologies in Class 8 trucks is uneconomical for highway cycles due to efficiency losses in these cycles being dominated by non-engine resistances [31, 2000] and [32, 2002]. Conversely, hybrid powertrain technologies are also uniformly found to be economical for trucks on urban cycles. However, the majority of trucks driving on these cycles are the lighter heavy trucks (class 7), the heavier medium trucks (classes 4–6) and the lighter medium trucks (classes 2B–3). As noted above, Class 8 trucks spend between 80% and 90% of their driving time on the highway, so a similar proportion of their fuel use will be spent overcoming the resistances prevalent on the highway cycle, [32], [39]. To greatly simplify our analysis, our *CW*- and *SOA*-portfolios therefore assume that all Class 8 trucks are on a highway cycle.

For detailed technical assumptions on the baseline truck and Class 8 stock, and their sources, please refer to the tables in the Appendix following immediately below, which should give a good sense of the aerodynamics of what is on the market today [20].

APPENDIX

Technical Assumptions

This section contains the source table for the Class 8 truck analysis, detailed technical background data, and corresponding reference information. All values in blue are externally sourced and hard-coded figures; all figures in black are derived from sourced values and relationships.

As they are separate from the references for this document, we begin with the sources for the modeling effort. These should be referenced only in conjunction with sources referenced in spreadsheet table outputs.

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Table 6–1: State of the Art — Marginal & Average CCE

						PER TRUCK			ACROSS STOCK, 2025				
▨	Mass and resistance-reduction technologies	5.0%				ENERGY UNIT: Gal DIESEL			MM bbl DIESEL		10^15 Btu		%
🟧	Engine and powertrain technologies	11.5%				MARGINAL CCE			MARGINAL CCE		AVERAGE CCE		
	Technology Area	MPG Gain	Gross up-front measure cost	Net up-front measure cost	Post-Install Fuel Economy	Marginal Annualized Capital Cost	Marginal Saved fuel	Marginal Cost of Conserved Energy	Marginal Saved fuel	Marginal Cost of Conserved Energy	Cumulative Saved fuel, across fleet	Average Cost of Conserved Energy	% of total Class 8 fuel consump-tion incr to BAU
		(%)		($/truck)	MPG	(Incr $/ truck-yr)	(Incr gal diesel truck-yr)	(Incr $/ Incr gal diesel)	(Incr mill. bbl diesel stock-yr)	(Incr $/ Incr gal diesel)	(Quads)	(Cum $/ Cum MBTU)	%
	Conventional Wisdom												
Order	*Baseline*	n/a		n/a	6.20						0	$1.28	
1	Weight Reduction II	10.0%	$ 2,000	$1,449	6.81	$167	946	$0.18	66.19	$0.18	0.39	$1.28	6.9%
2	Aero V: Truck Boat-tail	4.9%	$ 500	($512)	7.12	($59)	404	($0.15)	33.15	($0.15)	0.58	$0.65	10.4%
3	Aero VI: Cross-flow Vortex Trap Device (CVTD)	5.0%	$ 500	($533)	7.43	($62)	378	($0.16)	31.04	($0.16)	0.76	$0.31	13.6%
4	Tires III: Super singles	2.7%	$ 466	($76)	7.59	($9)	189	($0.05)	9.12	($0.05)	0.81	$1.01	14.5%
5	Tires II: Low roll resistence.	1.0%	$ 181	$59	7.65	$7	68	$0.10	1.84	$0.10	0.82	$0.99	14.7%
6	Aero. I: Cab Deflector/Sloping Hood/Cab Side Flares	2.8%	$ 1,000	$422	7.83	$49	187	$0.26	2.76	$0.26	0.84	$0.44	15.0%
7	Aero. III: Lead./Trail. Edg.+Vortex Strake Device (VSD)	2.0%	$ 750	$337	7.95	$39	128	$0.30	5.73	$0.30	0.87	$0.54	15.6%
8	Aero. IV: Pneumatic Blowing	15.0%	$ 3,000	$3,000	8.88	$346	849	$0.41	39.56	$0.41	1.10	$1.77	19.8%
9	Tires IV: Pneumatic blowing	1.2%	$ 500	$378	8.95	$44	60	$0.72	3.66	$0.72	1.12	$1.19	20.1%
10	Aero. II: Trac-Trail Gap/Wheel Wells/Baffles/Bumper	0.5%	$ 300	$197	8.99	$23	25	$0.91	2.04	$0.91	1.14	$0.60	20.3%
11	Aero VII: Underb. Diff.+Encl. & Undercarr. Flow	3.3%	$ 2,500	$1,818	9.19	$210	160	$1.32	9.43	$1.32	1.19	$1.16	21.3%
12	Aero VIII: Electronic Vision System	1.0%	$ 1,000	$793	9.25	$92	47	$1.95	3.86	$1.95	1.21	$1.39	21.7%
13	AUX Power related (electrical)	1.0%	$ 324	$223	9.31	$26	45	$0.57	1.76	$0.57	1.22	$1.80	21.9%
14	Fuel Cell aux power	1.8%	$ 461	$461	9.43	$53	84	$0.63	1.15	$0.63	1.23	$1.87	22.0%
15	Engine IV: Waste heat/thermal mgt.	10.0%	$ 2,000	$2,000	10.37	$231	622	$0.37	25.83	$0.37	1.38	$1.99	24.7%
16	Engine III: Impr. inject. & combust. Incl. HCCI	8.0%	$ 1,500	$1,500	11.20	$173	461	$0.38	15.36	$0.38	1.47	$2.17	26.3%
17	Engine I: Int. frict, lubes & bearings	3.0%	$ 600	$600	11.53	$69	168	$0.41	3.68	$0.41	1.49	$2.03	26.7%
18	Engine II: Higher cylinder pressure	4.0%	$ 1,000	$1,000	12.00	$115	215	$0.54	3.49	$0.54	1.51	$2.11	27.1%
19	Engine V: Displacement on Demand	2.0%	$ 1,000	$1,000	12.24	$115	105	$1.10	6.23	$1.10	1.55	$2.29	27.7%
20	Transmission-Related (lock-up, el cntls, red frict.)	2.0%	$ 1,000	$1,000	12.48	$115	103	$1.12	6.11	$1.12	1.58	$2.40	28.4%

(*) Homogeneous Charge Compression-Ignition (HCCI), a cross between spark-ignited and compression-ignited combution, is even more efficient, and has been included in SOA although at promising research stage.

(**) Mutually exclusive options (not used)

SOA truck w/ all measures <$1/gal	11.73	5242	272

Table 6-2: Conventional Wisdom — Measure Savings and Costs

▨ Mass and resistance-reduction technologies
🟧 Engine and powertrain technologies

Discount rate 5.0%
Capital recovery factor 11.5%

Order	Technology Area	Is Measure's Effect Multiplicative (1) or Additive (0)?	mpg Gain (%)	Gross up-front measure cost	Net up-front measure cost ($/truck)	Mass red. (kg)	Mass (kg)	*Cd* red.	*Cd*	CRR red.	CRR	Engine capacity credit if imple-menting measure ($/ truck)	Engine capacity if imple-menting measure (kW)	Post-Install Fuel Economy mpg	Post-Install (New) Fuel Consump-tion (MBTU/ truck-yr)	Measure Energy Saving (MBTU/ truck-yr)
	Baseline	n/a	n/a		n/a		36,287		0.62		0.0060		321	6.20	n/a	n/a
1	Weight Reduction I (22).	0	5.0%	$ 1,000	$725	2,250	34,037					$275	317	6.50	1,375	68.7
2	Tires III: super singles.	0	4.0%	$ 700	($90)	407	33,630			0.0010	0.0050	$790	306	6.75	1,324	50.5
3	Tires II: low roll resistence.	0	3.0%	$ 550	$180					0.0005	0.0055	$370	301	6.94	1,289	35.5
4	Aero. I: cab deflector/sloping hood/cab side flares	0	2.0%	$ 750	$337			0.04	0.58			$413	295	7.06	1,266	22.6
5	Aero. III: lead./trail. edges.	0	1.3%	$ 500	$231			0.03	0.55			$269	291	7.14	1,252	14.3
6	Aero. II: trac-trail gap/wheel wells/baffles/bumper	0	2.5%	$ 1,500	$983			0.05	0.50			$517	283	7.30	1,225	26.6
7	AUX Power related (electrical)	0	1.5%	$ 500	$399							$101	282	7.39	1,210	15.4
8	Eng IV: waste heat/thermal mgt.	1	5.0%	$ 1,000	$1,000									7.76	1,152	57.6
9	Eng I: int. frict: lubes&bearings.	1	2.0%	$ 500	$500									7.92	1,130	22.6
10	Eng II: higher cylinder pressure.	1	4.0%	$ 1,000	$1,000									8.23	1,086	43.5
11	Eng III: impr. inject.&combust.	1	6.0%	$ 1,500	$1,500									8.73	1,025	61.5
12	Transmission-Related (lock-up, el cntls, red frict.)	1	2.0%	$ 1,000	$1,000									8.90	1,005	20.1

Note: Homogeneous Charge Compression Ignition (HCCI), a cross between spark-ignited and compression-ignited combustion, is even more efficient. It is not included in *CW*, although it is in *SOA*.

Table 6-3: CW CCE						PER TRUCK			ACROSS STOCK, 2025				
▒	Mass and resistance-reduction technologies Engine and powertrain technologies					ENERGY UNIT: Gal DIESEL			MM bbl DIESEL		10^15 BTU		%
						MARGINAL CCE, ALL-IN			MARGINAL CCE		AVERAGE CCE		
	Technology Area	mpg Gain (%)	Gross up-front measure cost	Net up-front measure cost ($/truck)	Post-Install Fuel Economy mpg	Marginal Annualized Capital Cost, All-In (Incr $/ truck-yr)	Marginal Saved fuel, All-In (Incr gal diesel truck-yr)	Marginal Cost of Conserved Energy (Incr $/ Incr gal diesel)	Marginal Saved fuel (Incr mill. bbl diesel stock-yr)	Marginal Cost of Conserved Energy (Incr $/ Incr gal diesel)	Cumulative Saved fuel, across fleet (Quads)	Average Cost of Conserved Energy (Cum $/ Cum MBTU)	% of total Class 8 fuel consumption incr to *BAU* %
Order	***Baseline***	n/a		n/a	6.20						0	$1.22	
1	Weight Reduction I (22).	5.0%	$ 1,000	$725	6.50	$84	496	$0.17	11.53	$0.17	0.07	$1.22	1.2%
2	Tires III: super singles......	4.0%	$ 700	($90)	6.75	($10)	364	($0.03)	18.96	($0.03)	0.18	$1.33	3.2%
3	Tires II: low roll resistence.	3.0%	$ 550	$180	6.94	$21	256	$0.08	7.38	$0.08	0.22	$0.72	3.9%
4	Aero. I: cab deflector/sloping hood/cab side flares	2.0%	$ 750	$337	7.06	$39	163	$0.24	0.52	$0.24	0.22	$0.83	4.0%
5	Aero. III: lead./trail. edges.	1.3%	$ 500	$231	7.14	$27	103	$0.26	3.27	$0.26	0.24	$1.33	4.3%
6	Aero. II: trac-trail gap/wheel wells/baffles/bumper	2.5%	$ 1,500	$983	7.30	$114	192	$0.59	15.74	$0.59	0.33	$1.25	6.0%
7	AUX Power related (electrical).	1.5%	$ 500	$399	7.39	$46	111	$0.41	4.60	$0.41	0.36	$1.37	6.5%
8	Eng IV: waste heat/thermal mgt.	5.0%	$ 1,000	$1,000	7.76	$115	415	$0.28	3.34	$0.28	0.38	$1.49	6.8%
9	Eng I: int. frict:lubes&bearings.	2.0%	$ 500	$500	7.92	$58	163	$0.35	3.20	$0.35	0.40	$1.57	7.1%
10	Eng II: higher cylinder pressure.	4.0%	$ 1,000	$1,000	8.23	$115	313	$0.37	6.78	$0.37	0.44	$1.70	7.9%
11	Eng III: impr. inject.&combust.	6.0%	$ 1,500	$1,500	8.73	$173	443	$0.39	8.87	$0.39	0.49	$1.87	8.8%
12	Transmission-Related (lock-up, el cntls, red frict.)	2.0%	$ 1,000	$1,000	8.90	$115	145	$0.80	8.56	$0.80	0.54	$2.04	9.7%

Note: Homogeneous Charge Compression Ignition (HCCI), a cross between spark-ignited and compression-ignited combution, is even more efficient. It is not included in *CW,* although is in *SOA.*

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