REDUCING
Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO_2 Emissions

FUEL CONSUMPTION

emerging technologies

truck emissions

CLIMATE CHANGE

reducing green house gas emissions

Final Report
October, 2009

Prepared by:

NESCCAF
Northeast States Center for a Clean Air Future

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ICCT
International Council on Clean Transportation

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Southwest Research Institute

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TIAX, LLC

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Report

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NESCCAF and ICCT Express Our Sincere Appreciation to the Project Steering Committee Members

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The goal of the International Council on Clean Transportation (ICCT) is to dramatically reduce conventional pollution and greenhouse gas emissions from personal, public, and goods transportation in order to improve air quality and human health, and mitigate climate change. The Council is made up of leading government officials and experts from around the world that participate as individuals based on their experience with air quality and transportation issues.

The ICCT promotes best practices and comprehensive solutions to improve vehicle emissions and efficiency, increase fuel quality and sustainability of alternative fuels, reduce pollution from the in-use fleet, and curtail emissions from international goods movement.

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Executive Summary

Overview

This study provides an assessment of available and emerging technologies that could be used to reduce CO_2 emissions and lower fuel consumption from new heavy-duty long haul combination trucks in the United States in the 2012 to 2017 timeframe. Its findings are drawn from the results of original cost and technology analyses conducted for this study, together with information obtained from previous studies and reports.

In 2006, transportation sources emitted approximately 40 percent of all GHG emissions in the United States. Medium- and heavy-duty vehicles (above 8,500 gross vehicle weight rating) represent about 22 percent of the transportation emissions, up from 15 percent in 1990 (EPA 2009). Trucking is energy-intensive and accounted for 69 percent of freight energy use, consuming 2.35 million barrels of oil per day in 2008 and generating 363 million metric tons of carbon dioxide (EIA, 2009). Hence trucks are an important place to look for energy savings and climate change mitigation in the transportation sector.

There were over 11 million medium- and heavy-trucks (those over 10,000 pounds GVWR, Class 3 through 8) on U.S. roads in 2008 and 684,000 new medium and heavy trucks were sold into the market in that year (Polk, 2008). Sales of individual models number in the hundreds or thousands, in contrast to the tens or hundreds of thousands for car models. While truck owners and operators are more affected than passenger vehicle users by fuel expenses, the demand for fuel economy has historically not been sufficient to bring all cost-effective efficiency technologies into the market. Manufacturer risk, low fuel prices, lack of fuel economy information on individual models, and undervaluation of fuel economy all limit the introduction of fuel saving technologies.

Among medium- and heavy-trucks, Class 8 trucks are the largest CO_2 emitters and fuel users, consuming two-thirds of all truck fuel, or 1.57 million barrels per day. Current fuel economy for Class 8 trucks is estimated by the US Department of Energy at 6.0 mpg and projected to rise modestly to 6.8 mpg by 2025 (EIA, 2009). Substantial improvements could be made to truck efficiency through a variety of existing and emerging technologies, including engine improvements, transmission enhancements, better aerodynamics and changes in systems and logistics. This study finds that fuel consumption for new tractor-trailers could be lowered by 20 percent starting in 2012 and as much as 50 percent beginning in 2017, while providing net savings for the owner based on lifetime fuel savings paying for the incremental vehicle, operation, and maintenance costs.

Method

The project was directed by an expert steering committee composed of representatives from major truck and powertrain manufacturers, government agencies, trucking fleets, and fuel economy and heavy-duty experts from non-profit organizations. The core of the analysis consisted of a series of modeled simulations to predict the fuel saved by incorporating various technology and operational measure combinations in new trucks. Southwest Research Institute (SwRI) was engaged to perform vehicle and engine simulation modeling, which provides detailed information on the acceleration, braking, power, fuel economy, and emissions performance of different heavy-duty vehicle designs, including advanced powertrain designs. The technologies and operational measures selected are further discussed in Chapter 2, and in Appendix A. TIAX LLC (TIAX) assembled cost information for each package modeled, assessed the net cost of these packages over two time horizons and estimated the United States fleet-wide fuel savings impact of various technology adoption scenarios.

The baseline vehicle should be a vehicle representative of the average Class 8 truck in today's fleet for which sufficient data has been collected to serve as inputs to the simulation models. NESCCAF, SwRI and the Steering Committee selected a Kenworth T-600 Class 8 tractor, a Volvo D13 engine and an Eaton Fuller 10-speed manual transmission as the study's representative vehicle. This baseline truck and powertrain, although not a combination available on the market, fulfilled the criteria for a good baseline vehicle. It has aerodynamic and rolling resistance characteristics that approximate the average performance of the current truck fleet. It has a 2007 emission standards compliant engine that can be upgraded to meet 2010 emissions requirements. And it has a manual transmission that has a high market share among fuel economy cost sensitive fleets.

Once the baseline truck and engine was determined, two simulation models were used to allow the evaluation of various packages: GT-POWER for engine cycle simulation and RAPTOR to model the vehicle, including the transmission and driveline. An important benefit of simulating the performance of technology packages, rather than individual technologies, is that it eliminates the possibility that the reductions will be "double counted". The benefits associated with various options are not necessarily additive when these improvements are combined in a single vehicle, particularly to the extent that many technologies target the same sources of mechanical or thermodynamic inefficiency. The simulation modeling conducted for this analysis avoids this problem. Both models were validated by comparing predicted fuel economy results to actual on-road vehicle fuel economy measurements, or to test cell engine fuel consumption results.

An important benefit of simulating the performance of technology packages, rather than individual technologies, is that it eliminates the possibility that the reductions will be "double counted".

The test cycle used in this study was based on the California Heavy-Duty Diesel Truck Drive Cycle. The California cycle was created from analysis of a statistical study of line haul truck operations in California. The following changes were made to the California cycle for this study, based on input from the experts on the Steering Committee:

- The portion of high speed driving was increased to reflect longer average travel distances nationwide.
- The speeds used in the California cycle were increased by 8 percent to reflect current typical truck operating speeds on long-haul routes nationwide.
- Two segments with grade were added. One segment includes positive and negative 1 percent grades, and a second segment has positive and negative 3 percent grades.

The total duration of the cycle is 6,830 seconds (one hour and 54 minutes), and the total distance traveled is 103.3 miles. It is important to note that the drive cycle chosen for this study is specific to long-haul trucks. Thus, the results are specific to long-haul trucks and cannot necessarily be extrapolated to other heavy-duty trucks, even Class 8 trucks, operating on different drive cycles such as regional haul, pickup and delivery, or drayage.

Technology and Operational Measures

A total of 32 technologies and operational measures were identified and considered for inclusion in this project. The complete list of the individual vehicle technologies considered in this study for purposes of evaluating future Class 8 heavy-duty truck fuel consumption and CO_2 emissions reduction potential is available in Appendix A. The list includes a brief description of each of the technologies and an explanation of how each option might reduce CO_2 emissions. Some of the technologies selected for evaluation in this study are fully commercialized. Others, such as bottoming cycle, are not and may present technical challenges that could result in delayed introduction or lower performance than projected in this study.

SwRI did not consider fuel consumption and CO_2 reduction technologies that are not currently in production or for which a design specification is not available in the literature. As such, the study findings do not represent the total available potential to reduce heavy-duty vehicle fuel consumption and CO_2 emissions – the results only estimate what can be done given known technologies. Going forward, more advanced technologies to improve engine, vehicle, and transmission technologies could and will likely be developed that would further reduce truck fuel consumption and CO_2 emissions beyond the 2017 timeframe.

Using the most promising individual technologies that emerged from the initial screening evaluation described above, in combination with cost estimates for the individual technologies, a series of technology packages was assembled for modeling. Generally, these packages were designed to span the full range of CO_2 reduction potential (i.e., from modest to substantial reductions), so they necessarily reflect a range of impacts (and costs). Table 1 presents the technology packages modeled in three groups: (1) Building block technologies, (2) Operational measures, and (3) Maximum reduction combination packages.

TABLE 1 TECHNOLOGIES AND MEASURES COMBINED IN THE MODELED PACKAGES

PACKAGE NAME	PACKAGE #	DETAILED PACKAGE DESCRIPTION
Baseline	1	Volvo D13 (2010 emissions), Kenworth T600, 10-speed manual transmission
Building Block Technologies		
SmartWay 2007 (SW1)	2	Additional aero streamlining to the cab and the trailer sufficient to reduce the coefficient of drag from 0.63 to 0.5. Fully aerodynamic mirrors, cab side extenders, integrated sleeper cab roof fairings, aerodynamic bumper, and full fuel tank fairings. Trailer streamlining includes a side skirt fairing, and either a trailer gap fairing or a rear-mounted trailer fairing such as a boat tail. RR of 0.0055. Wide base single tires and aluminum wheels. Idle reduction, improved lubricants
Advanced SmartWay (SW2)	3	Package #2 plus advanced aero and rolling resistance package. Includes continued streamlining of the cab, a reshaped trailer, boat tail, full skirting of cab and trailer, tractor-trailer gap fairing, and very low rolling resistance tires
Parallel hybrid-electric powertrain (HEV)	4	Parallel hybrid system

TABLE (continued)
1 TECHNOLOGIES AND MEASURES COMBINED IN THE MODELED PACKAGES

PACKAGE NAME	PACKAGE #	DETAILED PACKAGE DESCRIPTION
Mechanical turbocompound	5	Mechanical turbocompound plus Package #7
Electrical turbocompound	6	Electrical turbocompound plus Package #7
Variable Valve Actuation (VVA)	7	Variable valve actuation
Bottoming cycle	8	Bottoming cycle
Advanced EGR	11	Advanced exhaust gas recirculation
Operational Measures		
Rocky Mountain Double (RMD) trailers	9	Longer/heavier trailer (rocky mountain doubles – 48' and 28' trailers)
60 mph speed limit	10	Slower road speed (60 mph)
Maximum Reduction Combination Packages		
Maximum reduction combination 1	12	Standard trailer w/advanced aero and rolling resistance tires, hybrid, bottoming cycle, 60 mph (Packages #3, #4, #8, #10)
Maximum reduction combination 2	13	Longer and heavier trailer w/advanced aero and rolling resistance tires, hybrid, electric turbocompound, VVA, 60 mph (Packages #3, #4, #6, #7, #9, #10)
Maximum reduction combination 3	14	Longer and heavier trailer w/advanced aero and rolling resistance tires, hybrid, bottoming cycle, 60 mph (Packages #3, #4, #8, #9, #10)

Results

The results from the simulation modeling demonstrated a broad range of emission reductions and fuel savings for the 14 technology packages modeled. Table 2 provides the results obtained for each package. The individual measures are compared to the baseline vehicle. Table 2 provides the incremental vehicle cost, which is the modeled package additional capital cost compared to the baseline (Package 1). The table also includes the net cost of the technology package, defined as the incremental technology package cost minus 15 years of fuel savings discounted at a rate of 7 percent.[1] Note that a negative net cost means that fuel savings more than offset the incremental cost of the emissions reduction technologies being modeled. In other words, it equates to projected consumer savings over the lifetime of the vehicle. The net cost analysis assumes an average price of $2.50 per gallon of diesel fuel, and assumes that the annual mileage declines as the vehicle ages. Results from an additional net cost analysis assuming 3 years of fuel savings at a different fuel price is presented in Chapter 3. Finally, the table provides the length of time required for the fuel savings to payback the investment in technology.

The eight building block technologies considered in this study reveal a range of potential reductions from a modest improvement for variable valve actuation and advanced exhaust gas recirculation to almost 28 percent for a host of aerodynamic, friction and rolling resistance technologies listed as Advanced Smartway (See Table 1 for list of Advanced SmartWay technologies). When combined, these existing and emerging technologies are capable of improving baseline fuel consumption up to 50 percent.

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[1] The analysis assumes a truck is driven 1.2 million miles over the 15 year period. It also includes operation and maintenance costs.

The technology costs range from several hundred dollars (variable valve actuation and ERG) to moderate ($6,600 for electric turbo compounding) to expensive ($23,000 for SmartWay and hybrid-electric powertrain packages), to very expensive (nearly $45,000 for Advanced Smartway). Despite the wide range in costs, most of these technologies pay for themselves in the first few years of ownership with the exception of the hybrid electric powertrain.

TABLE

2 HEAVY-DUTY LONG HAUL CO_2 AND FUEL CONSUMPTION REDUCTION AND COST RESULTS FOR ANALYZED PACKAGES

PACKAGE NAME	FUEL CONSUMPTION/ CO_2 REDUCTION (%)	INCREMENTAL VEHICLE COST ($)[a]	LIFETIME COST OF OWNERSHIP (15 YEARS, 7%)[a]	TIME TO PAYBACK [a](YEARS)
Baseline	n/a	n/a	n/a	n/a
Building Block Technologies				
SmartWay 2007 (SW1)	17.8% [2]	$22,930	-$23,600	3.1
Advanced SmartWay (SW2)	27.9%[2]	$44,730	-$55,800	3.8
Parallel hybrid-electric powertrain (HEV)	10%[3]	$23,000[4]	$100	7
Mechanical turbocompound	3.0%	$2,650	-$5,500	2.0
Electric Turbocompound	4.5%	$6,650	-$5,500	3.5
Variable Valve Actuation (VVA)	1.0%	$300	-$2,500	0.6
Bottoming cycle	8.0%	$15,100	-$4,800	5.2
Advanced EGR	1.2%	$750	-$2,600	1.4
Operational Measures				
Rocky Mountain Double (RMD) trailers	16.1% (grossed out) 21.2% (cubed out)	$17,500	-$34,100[5]	2.1
60 mph speed limit	5.0%	$0	-$13,900	n/a
Maximum Reduction Combination Packages				
Maximum reduction combination 1 (standard 53' trailer, hybrid, BC, SW2, 60 mph)	38.6% (grossed out) [6] 40.2% (cubed out)[6]	$71,630	-$27,300[5]	4.8
Maximum reduction combination 2 (RMD, hybrid, electric turbocompound, VVA, SW2, 60 mph)	48.7% (grossed out)[6] 46.2% (cubed out)[6]	$80,380	-$41,600[5]	4.3
Maximum reduction combination 3 (RMD, BC, hybrid, SW2, 60 mph)	50.6% (grossed out)[6] 48.3% (cubed out)[6]	$89,130	-$37,200[5]	4.7

[2] Includes idle reduction benefits from a diesel-fired APU

[3] Includes idle reduction benefits from battery storage; the modeled on-road fuel consumption improvement was 5.6%

[4] Includes credit for an auxiliary power unit (APU), which is included in the SmartWay package, but is not needed in a hybrid vehicle.

[5] The lifetime cost of ownership figures are calculated using fuel savings averaged between grossed out and cubed out trucks.

[6] Includes idle reduction benefits from battery storage.

[a] Calculations based on year 2022 high volume technology costs, EIA 2022 fuel price ($2.50/gal), a 7% discounted cash flow; time to payback assumes a constant 120,000 miles per year; the cost of ownership calculation assumes annual mileage declines over the life of the vehicle with a total mileage of 1.2 million miles in 15 years.

According to this analysis, combinations of technologies already used in some production heavy-duty long haul trucks can reduce CO_2 emissions by approximately 5-18 percent. Examples of these technologies include hybrid vehicle systems, turbocompounding, and the SmartWay package of modest aerodynamic, tire, and idle-reduction improvements. Reductions beyond this level will require the introduction of more advanced technologies such as a bottoming cycle and advanced aerodynamic or tire rolling resistance improvements. For example, a package including advanced aerodynamic components and improved tires can provide a 28 percent CO_2 and fuel consumption reduction for an incremental vehicle cost of $44,730. Even greater CO_2 and fuel consumption reductions can be achieved – up to 39 percent - using a combination of bottoming cycle, slower road speed, advanced aerodynamics, and hybridization.

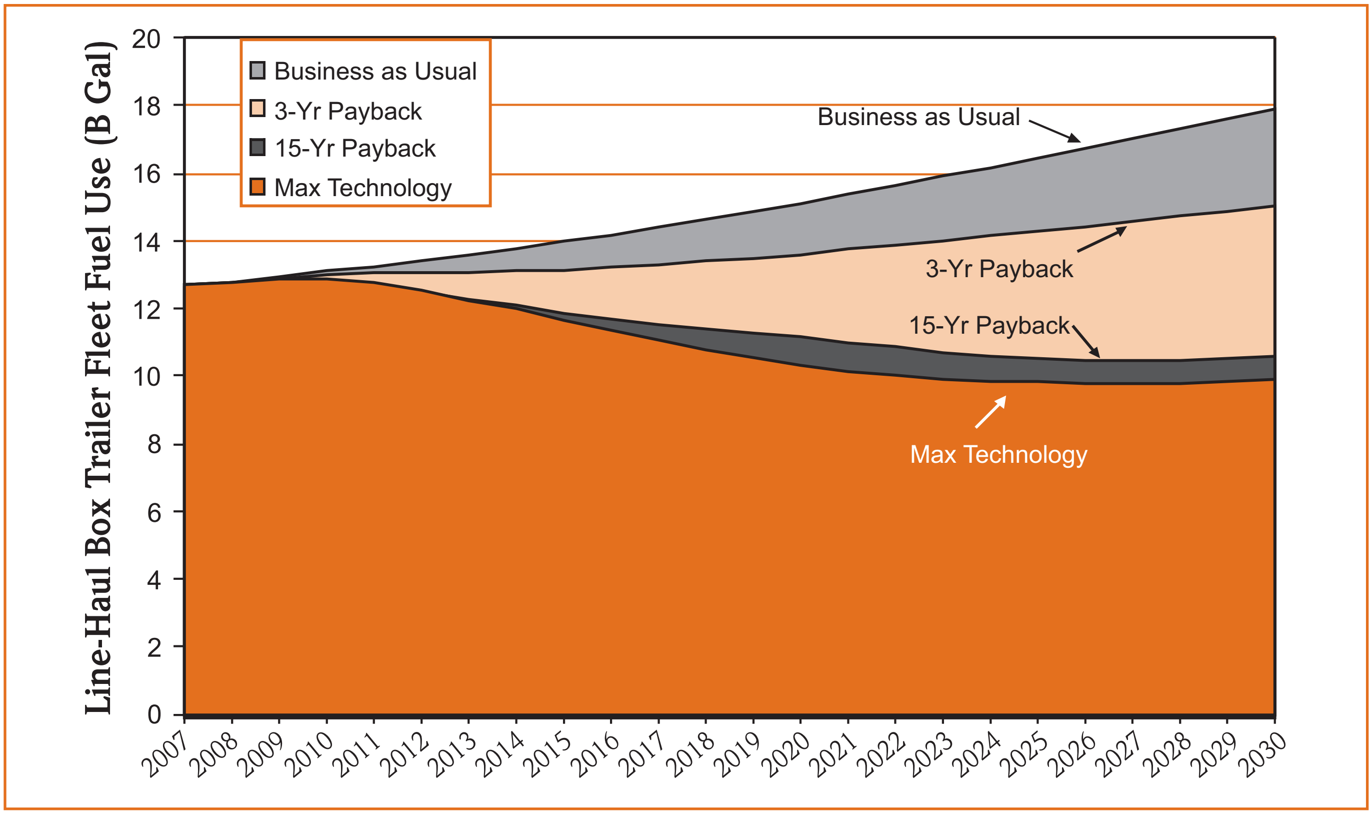
Operational measures include slowing the speed of Class 8 trucks and increasing the size and weight of truck-trailer combinations. Assuming a longer and heavier trailer design alone, CO_2 and fuel consumption reductions ranging from 16-21 percent are feasible for an incremental vehicle cost of $17,500. This result is for a combination of one 48' trailer with one 28' trailer (Rocky Mountain Double or "RMD"). Additional results for other types of longer and heavier trailer designs are detailed in Chapter 3. Greater reductions can be achieved by combining longer and heavier truck trailers with advanced technologies such as bottoming cycle and hybridization. There are, however, limitations to the routes that these longer and heavier combination vehicles can safely operate. The technology package that provides the greatest CO_2 and fuel consumption reduction – 50 percent from the baseline vehicle – includes advanced aerodynamics and rolling resistance technology, a longer and heavier trailer combination, a hybrid electric drivetrain, and a bottoming cycle. This package represents both an impressive improvement in fuel savings and a very complex technology combination.

It is critical to recognize that while the costs of using advanced technologies are greater than the cost of conventional long haul truck technologies, fuel-cost savings in many cases outweigh additional technology costs for the technology packages. Assuming a 15-year period, fuel cost savings far outweigh the additional technology costs for 12 of the 13 advanced technology packages. Table 2 shows net costs of most of the technology packages that produce up to 50 percent CO_2 and fuel consumption reductions is negative. Truck owners save between $2,500 and $55,800 over the life of the vehicle due to avoided fuel purchases.

As noted in Table 2, the emission reduction packages evaluated in this study include a range of individual technologies with a range of CO_2 and fuel consumption reduction potential and a range of costs in an effort to provide a robust overview of the benefits and costs of candidate CO_2-reduction technologies. Given that future technology advances could reduce costs for these technologies, the costs presented could be overstated. Consequently, the complete set of technology packages does not constitute a low-cost solution to any particular CO_2-reduction scenario, but rather presents a host of possible solutions across a range of reductions and costs.

Figure 1 depicts the total potential fuel and CO_2 emissions saved in the U.S. heavy-duty long haul combination truck fleet, assuming penetration of technologies modeled by SwRI in this study. The top line represents fuel consumption in the U.S. fleet in a business as usual case. In the business as usual case, approximately 18 billion gallons of fuel are used in the entire U.S. fleet in 2030. The second line, with an arrow indicating "3-year payback" shows one scenario for introduction of technologies into the U.S. heavy-duty long haul fleet between now and 2022. According to this scenario, approximately 3 billion gallons of fuel are saved from the introduction of technologies into the U.S. heavy-duty long haul fleet. In the "3-year payback" scenario, only technologies that provide a net cost savings over three years are introduced into the fleet. The third line, indicated with an arrow and text saying "15 year payback," represents the amount of fuel that could be saved with more aggressive introduction of technologies to reduce fuel consumption and CO_2 emissions into the U.S. heavy-duty long haul fleet between now and 2030. In the "15-year payback" scenario, technologies which pay for themselves within 15 years of purchase are adopted into the U.S. heavy-duty fleet. As the lower line indicates, assuming aggressive introduction of the technology combinations modeled in this study into the U.S. fleet, approximately 7 billion gallons or 39 percent of total U.S. heavy-duty long haul fleet fuel consumption could be avoided. This represents 39 percent of heavy-duty long haul CO_2 emissions as well. Assuming maximum technology penetration (the lowest line in the graph), the use of approximately 8 billion gallons of fuel and 44 percent of heavy-duty long haul truck CO_2 emissions could be avoided in the U.S. in 2030.

FIGURE 1 POTENTIAL FUEL SAVINGS IN THE U.S. LONG HAUL BOX TRAILER FLEET



The analysis does not assume that any existing vehicles are retrofitted with technologies and as such, could underestimate the total potential emissions and fuel use avoided from heavy-duty technologies evaluated in this study. In addition, the analysis does not assume the introduction of any new technologies after 2015, and could therefore underestimate the benefits realized from advances in science and engineering. There are also downside risks, where some of the modeled technologies may not reach production maturity with the expected fuel savings or cost. Many controls, reliability, durability, and packaging issues remain to be overcome to implement all of the modeled technologies, and some of these issues may prove difficult.

Conclusions

The results of the analysis suggest that existing and emerging vehicle, engine, and transmission technologies can achieve substantial and cost-effective reductions in heavy-duty vehicle CO_2 emissions and fuel consumption in the 2012 to 2017 timeframe. Coupled with operational measures, the benefits could even be larger. Specifically, CO_2 and fuel consumption emissions from heavy-duty vehicles can be reduced up to 50 percent in this timeframe. Over a three year period and with a diesel fuel price of $2.50 per gallon, this study found that five of the technology packages would result in a net cost savings to the truck owner, taking into account both incremental technology costs and fuel savings. The analysis shows that most of the technology combinations that provide the greatest reductions would not be adopted into the fleet assuming a three-year payback requirement. This indicates that given the short payback period demanded by the trucking industry, a number of these technologies will not be adopted into the U.S. fleet absent regulation. With a longer payback period of 15 years estimated lifetime net savings are between $30,000 and $42,000 for owners of vehicles achieving CO_2 and fuel consumption reductions of up to 50 percent.

> ***The results of the analysis suggest that existing and emerging vehicle, engine, and transmission technologies can achieve substantial and cost-effective reductions in heavy-duty vehicle CO_2 emissions and fuel consumption in the 2012 to 2017 timeframe.***

Introduction of all the technologies and strategies modeled in this study into the U.S. heavy-duty long haul fleet between now and 2030 would lead to an estimated 8 billion gallons of diesel fuel saved annually beginning in 2030, with lesser reductions being achieved as soon as 2012. The 8 billion gallons of fuel saved annually represents approximately 44 percent of the total projected business as usual fuel consumption in the heavy-duty long haul fleet. Cumulative fuel savings between now and 2030 would equal approximately 90 billion gallons of diesel fuel. Approximately 97 million metric tons of annual CO_2 emissions would be reduced beginning in 2030. This would be equivalent to a 44 percent reduction in annual CO_2 emissions beginning in 2030 from business as usual projections. Cumulative CO_2 emissions avoided between now and 2030 would equal approximately 1.1 billion metric tons.

Purpose of the Study

This study provides an assessment of available and emerging technologies that could be used to reduce carbon dioxide (CO_2) emissions and fuel consumption from heavy-duty long-haul vehicles in the United States in the 2012 to 2017 timeframe.[7] Its findings are drawn from the results of original cost and technology analyses conducted for this study, together with information obtained from other available reports. An impetus for this study was the establishment of climate change action plans in the northeastern United States, California, and countries outside of the U.S. that will require substantial reductions in motor vehicle CO_2 emissions if the climate goals are to be met. Another impetus for this study was the development of a regulation adopted by the Japanese government to reduce heavy-duty vehicle fuel consumption. After this study began, the U.S. Congress passed the Energy Independence and Security Act of 2007. This act directed the U.S. Department of Transportation (US DOT) to begin regulation of medium- and heavy-duty vehicle fuel consumption. Any regulations resulting from this act should also have the effect of reducing CO_2 emissions. Also, in early 2009, the EPA reached a finding that CO_2 is a danger to human health. The EPA may soon begin the process of regulating CO_2 emissions from heavy-duty vehicles. CO_2 is the only GHG included in this assessment.

The goal of this assessment is to help define CO_2-reducing heavy-duty vehicle technologies and strategies that are expected to be feasible, commercially available, and cost-effective in the 2012 and 2017 timeframe. The study did not evaluate regulatory changes that would likely be necessary to allow for widespread use of some operational changes. For example, changes in state or federal law would likely be necessary to reduce road speeds, however an analysis of this and other necessary policy changes was not included in this study. A wide range of technologies were evaluated, both individually and in packages, for their potential to reduce CO_2 emissions and fuel consumption from heavy-duty vehicles. The technologies examined fall into five primary categories:

(1) off-the-shelf aerodynamic improvement technologies;
(2) off-the-shelf drivetrain technologies;
(3) emerging drivetrain technologies;
(4) emerging aerodynamic improvement technologies; and
(5) operational measures.

The study also includes an assessment of the potential CO_2 emissions and fuel consumption avoided by the introduction of these technologies and operational measures into the U.S. heavy-duty vehicle fleet.

The results presented in this report have significant implications for states, provinces, and countries that share the commitment to reducing transportation-related CO_2 emissions as part of a broader effort to address the risks posed by global climate change.

The Importance of the Transportation Sector

In 2006, transportation sources emitted approximately 40 percent of all CO_2 emissions in the United States. Figure 2 on page 10 provides a breakdown of the contribution of different sources to total U.S. greenhouse gas emissions. As can be seen in the figure, electricity generation is the largest source of CO_2 emissions in the U.S., followed by CO_2 emissions from transportation sources.

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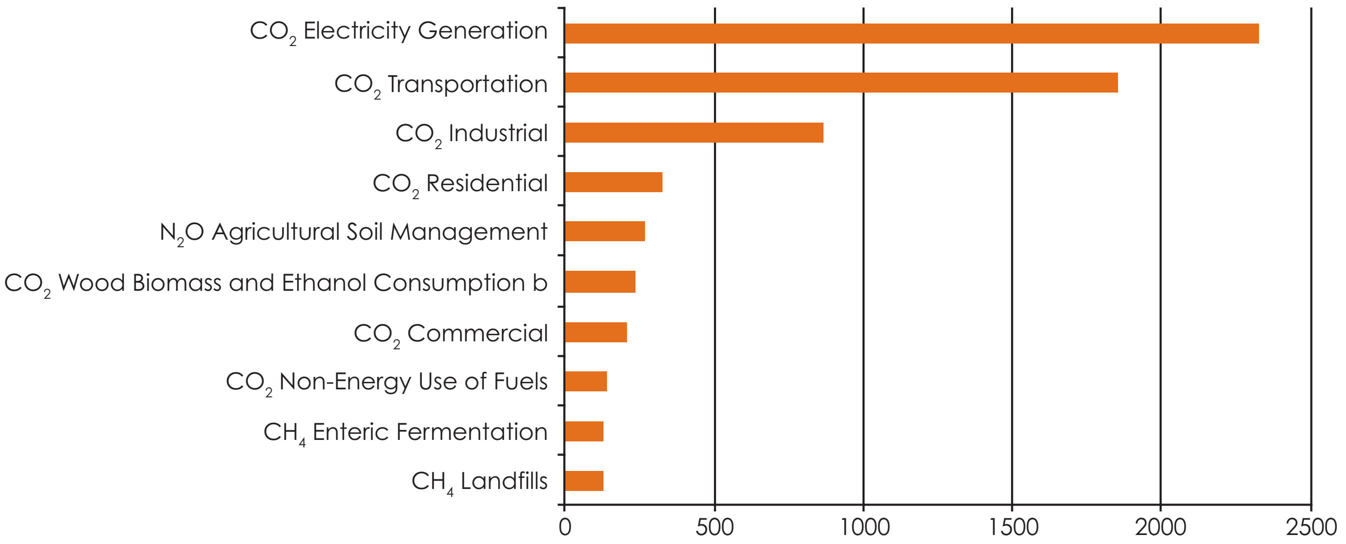
[7] CO_2 was the only greenhouse gas evaluated in this study.

FIGURE 2 **2006 U.S. GHG INVENTORY**



Source: EPA 2006

EPA's 2006 GHG inventory provides a breakdown of the contribution of different mobile sources to total transportation GHG emissions. According to the inventory, medium- and heavy-duty vehicles (above 8,500 gross vehicle weight rating (GVWR)) represented about 22 percent of the transportation emissions, up from 15 percent in 1990 (EPA 2008). The majority of medium- and heavy-duty truck GHG emissions come from diesel-fueled commercial vehicles and among these commercial vehicles, Class 8 trucks emit the majority – more than two thirds – of GHG emissions from medium- and heavy-duty trucks.

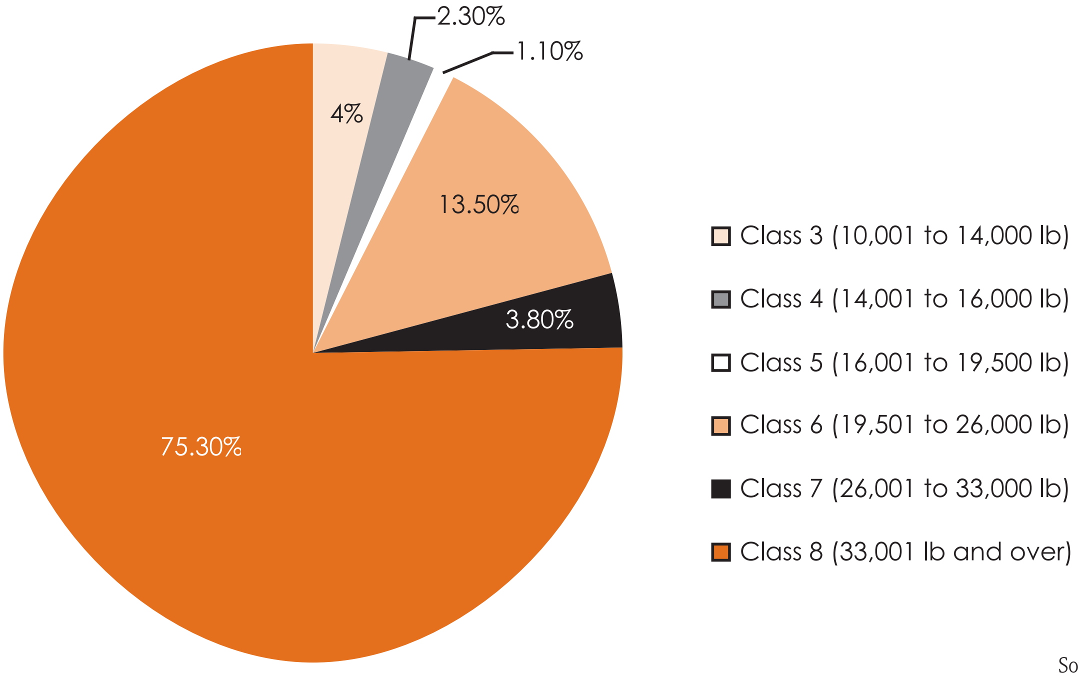
Figure 3 provides a breakdown of fuel consumption in medium- and heavy-duty trucks and, as can be seen, Class 8 trucks are by far the largest consumers of fuel. Class 8 consists of trucks with GVWR above 33,000 lbs. The most common type of Class 8 truck is the tractor-trailer combination truck. These vehicles are primarily employed in freight transportation over long distances or long-haul trucking.

Approximately 70 percent of fuel used by Class 8 trucks is used in long-haul service with trips over 200 miles long and regional freight transport – trips that are under 200 miles long. Class 8 tractor trailer trucks' large share of the sector's fuel use is due to their high usage rate compared to other heavy-duty vehicles. The remainder of fuel consumed by Class 8 vehicles is used in other types of trucks such as refuse, dump, and cement trucks. The type of truck evaluated in this study; long haul, tractor trailer trucks consume approximately 45 percent of total Class 8 fuel annually.

Clearly, significantly reducing heavy-duty truck CO_2 emissions is an important part of a comprehensive approach to address CO_2 emissions from the transportation sector and ultimately reverse the impacts of climate change, in the United States and globally. This study builds on and complements the substantial research being conducted by the U.S. Department of Energy's 21st Century Truck Program, the U.S. EPA's (Environmental Protection Agency)

FIGURE

3 FUEL CONSUMPTION BY MEDIUM AND HEAVY-DUTY VEHICLE CLASS



Source: DOE 2001

SmartWay program, research by truck and engine manufacturers, and trucking fleet research and demonstration projects.

The following sections provide additional information on the political and regulatory context in the United States and abroad within which heavy-duty CO_2 and fuel economy regulation are to be developed.

Political and Regulatory Context in the U.S. and Internationally

International Context

As early as 1992, international awareness of the many potential risks associated with global warming led 160 countries, including the United States, to adopt a Framework Convention on Climate Change with the stated objective of achieving “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.”[UN 1992]

Toward this objective, signatories pledged to work to stabilize greenhouse gas emissions. A number of industrialized countries, again including the United States, adopted the specific near-term goal of returning year 2000 CO_2 emissions to 1990 levels. It subsequently became evident that most countries, including the United States, were not on track to meet this objective. In response, parties to the Framework Convention adopted the Kyoto Protocol in 1997, which included targets and timetables for reducing GHG emissions to specific levels for each country. As of early 2003, 102 countries had ratified or acceded to the Protocol. However, the United States – citing economic concerns – has not ratified the Kyoto Protocol.

Internationally, Japan was the first and remains the only country to have adopted mandatory fuel economy standards for heavy-duty vehicles. Japan adopted the standards in 2005 and they will come into force with model year 2015.

Japanese Heavy-Duty Fuel Economy Standards

In November 2005, the Japanese government introduced the first of their kind fuel economy standards for new medium- and heavy-duty diesel vehicles, which were estimated to be responsible for approximately one-quarter of all CO_2 emissions from motor vehicles in 2002 in Japan. Those standards affect commercial trucks with a gross vehicle weight (GVW) in excess of 3.5 metric tons (about 7,700 lbs) and buses with a carrying capacity above 11 passengers.

Relative to the fuel economy standards required for passenger vehicles,[8] the heavy-duty standards require modest improvements in fuel economy [ANRE/MLIT 2007]. Table 3 summarizes the average 2015 fuel economy target by vehicle type and class, along with the relative improvement over the 2002 baseline, required by the standards.

TABLE 3 SUMMARY OF JAPANESE HEAVY-DUTY VEHICLE FUEL ECONOMY REGULATION

VEHICLE TYPE	VEHICLE CLASS	FUEL ECONOMY (KM/L)		IMPROVEMENT (%)
		2002 BASELINE	2015 TARGET	
Truck	Tractor	2.67	2.93	9.7
	Other truck	6.56	7.36	12.2
	Total	6.32	7.09	12.2
Bus	Urban	4.51	5.01	11.1
	Other bus	6.19	6.98	12.8
	Total	5.62	6.30	12.1

The 2015 average target and relative improvement assume a constant 2002 vehicles sales mix

Compliance with the model year 2015 fuel economy targets is to be measured by reference to individual standards disaggregated by vehicle class, gross vehicle weight, and, for lighter trucks, rated cargo load. Each manufacturer is required to meet the fuel economy target for each type of vehicle based upon a sales-weighted average for that category. Fuel economy is measured through a combination of engine-only fuel consumption testing and simulation modeling of gear shifting and vehicle resistance loads.

The Japanese standards explicitly take into account the trade-off between emissions and fuel consumption. The reason stated for the relatively modest improvement required over a 15 year span is because the standard recognizes that a significantly larger improvement must be made to overcome fuel economy losses inherent in the implementation of more stringent emissions regulations.

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[8] Japan's aggressive light-duty fuel economy standards finalized in February 2007 require a 23.5 percent improvement in the fuel economy of passenger vehicles from 2004 to 2015.

Climate Change Action by the U.S. Federal Government

In 2007, the U.S. Congress passed the Energy Independence and Security Act (EISA) that requires the U.S. Department of Transportation (US DOT) to set fuel economy standards for medium- and heavy-duty vehicles. The standards are to be applicable no earlier than the 2016 model year and the form and stringency of the standard(s) have yet to be determined. In 2008, EPA issued an Advance Notice of Proposed Rulemaking that requested comment on the feasibility of requiring GHG standards for medium- and heavy-duty vehicles. Also at the federal level, two voluntary programs aimed at improving the efficiency and GHG emissions of heavy-duty vehicles are underway. These are the Department of Energy's 21st Century Truck Program and the EPA's SmartWay Transport Partnership.

The 21st Century Truck

Since 2000, the 21st Century Truck Program has sought to significantly improve the fuel efficiency, safety, and pollutant emissions of trucks and buses by funding public-private partnerships for technology research and development as well as demonstration. The program's 16 industry partners and four government agencies have worked to meet specific goals in five areas: engine systems (fuel, engine, and after-treatment), heavy-duty hybrid drive trains, parasitic losses (aerodynamic drag, rolling resistance, drivetrain losses, and auxiliary loads), idle reduction, and safety. Table 4 summarizes the goals in each of these areas.

TABLE 4 THE 21ST CENTURY TRUCK PROGRAM TECHNOLOGY GOALS

ENGINE SYSTEMS	HD HYBRIDS	PARASITIC LOSSES	IDLE REDUCTION	SAFETY
• Increase thermal efficiency from 42% to 50% by 2010 • Stretch goal of 55% thermal efficiency in prototype engines by 2013 • 10% gain in over-the-road fuel economy by 2013, compared to 2010 goal	• By 2012 develop drive unit with 15 year design life that costs <$50/kw • By 2012 develop energy storage system with 15 year design life that costs <$25/ peak kw • Achieve 60% increase in fuel economy on urban drive cycle	• Reduce aero drag on Class 8 combination truck by 20% • Reduce auxiliary loads on Class 8 combination truck by 50% • Develop materials and manufacturing that can reduce Class 8 combination truck weight by 15-20%	• By 2009 demonstrate add-on idle reduction devices with <2 yr pay back • By 2012 produce a truck with fully integrated idle reduction system • By 2015 demonstrate 5-30 kw fuel cell APU	• Reduce stopping distance from operational speeds by 30% • Reduce incidences of HDV roll over • Develop driver aid systems to provide 360° visibility and that promote safe following distance and in-lane tracking

Source: MJ Bradley & Associates 2008

A recent review by the National Academy of Sciences published in 2008 found that many of the program's goals had not been met either because they were not feasible from an engineering standpoint, or because they were not adequately funded, or again because planned technologies were not implemented (NAS 2008). However, the review highlighted the program's importance in accelerating the development of technologies leading to cleaner, safer, and more efficient vehicles. The review provided a number of recommendations aimed at a restructuring and refocusing the program. Finally, it warned that the program's declining funding would further impede its ability to meet its important goals.

The SmartWay Transport Partnership

Initiated by the US EPA in 2004, the SmartWay Transport Partnership brings together fleets, technology providers, and retailers to implement fuel savings and GHG reducing strategies. The program aims to reduce fuel consumption by 150 million barrels of oil per year and 33 to 66 million tons of CO_2 as well as conventional pollutants. The more than 1,200 partners account for about an estimated quarter of all goods moved in the United States (EPA 2008). The program has focused on identifying and promoting products and practices that reduce conventional and climate change emissions. The program has certified vehicles and equipment such as tractors, trailers, idle reduction, and aerodynamic retrofit kits that meet SmartWay goals. The certification is not performance based, rather the SmartWay certified vehicles and equipment have a number of required features that are expected to enhance their environmental performance. Figure 4 shows the features in a SmartWay tractor and trailer.

SmartWay has also developed a draft heavy-duty vehicle GHG emission and fuel-efficiency test protocol to assist in the evaluation of technologies and vehicle designs including hybrid drivetrain technologies. Once finalized, this protocol will be used to certify SmartWay vehicles and equipment.

The Energy Independence and Security Act of 2007

Signed into law in December 2007, the Energy Independence and Security Act (EISA) of 2007 is primarily known

FIGURE 4 SMARTWAY™ EQUIPMENT STANDARDS (EPA 2008)

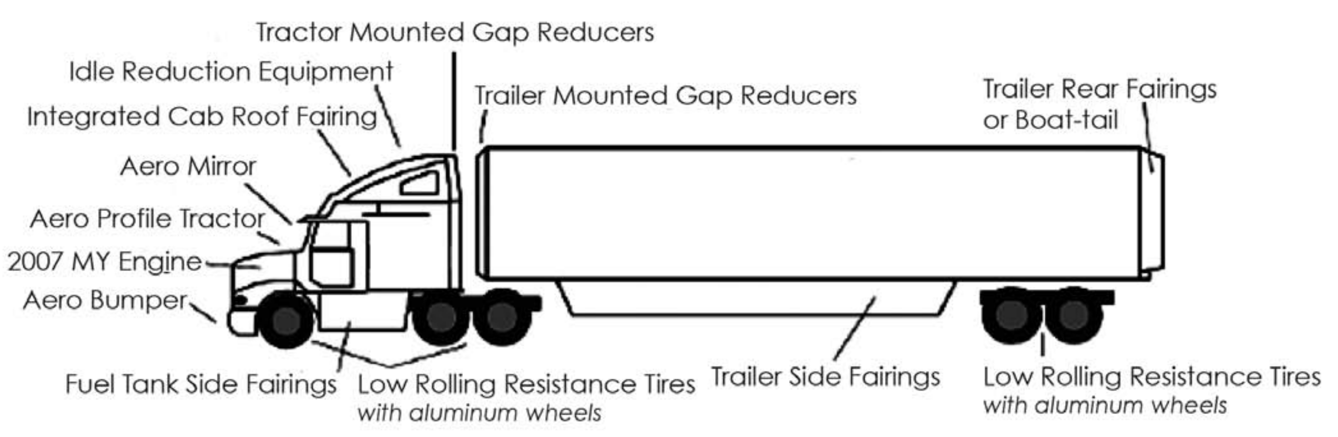
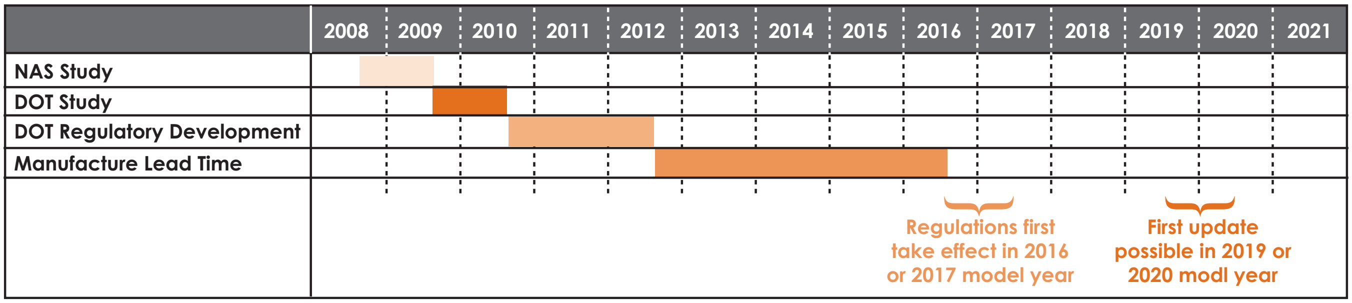


FIGURE 5 POTENTIAL TIMELINE FOR A US DOT MEDIUM- AND HEAVY-DUTY FUEL ECONOMY REGULATION



Source: MJ Bradley & Assoc., 2008

for improving the Corporate Average Fuel Economy (CAFE) standards for light-duty cars and trucks. It also established a mandatory Renewable Fuel Standard for fuel producers. The EISA also puts forth a timeline for the US DOT to develop and implement a fuel economy standard for “work trucks” (8,500 to 10,000 lbs. GVWR) as well as medium- and heavy-duty trucks. It is expected that the earliest model year that might be required to meet fuel economy limits would be model year 2016 or 2017. Figure 5 depicts the possible sequence of steps described in the EISA, beginning with a National Academy of Sciences (NAS) study of medium and heavy-duty fuel economy. The NAS study results will inform the development of medium and heavy-duty vehicle standards required by EISA. The NAS committee began its activities in late 2008 and is expected to deliver its final report in March 2010.

Potential EPA Heavy-Duty Vehicle GHG Regulation

In the EPA 2008 Advance Notice of Proposed Rulemaking on regulating GHG emissions, the Agency presents its assessment of the potential to address climate change under the Clean Air Act and discusses the regulatory options the Agency is considering for each major mobile and stationary source type. EPA identified three approaches to reduce GHG emissions from heavy-duty vehicles. The Agency asked for comment on the feasibility of reducing heavy-duty vehicle GHG emissions 40 percent by 2015 and achieving subsequent, greater reductions beyond 2015. The first approach is setting an engine CO_2 or GHG standard in a process similar to the current criteria pollutant emissions standards. The second approach would require each vehicle model to meet a CO_2 or GHG standard expressed either in grams/mile or grams/ton-mile. The last approach considers the potential for in-use emission reduction strategies such as idling reduction to generate credits.

State Actions to Reduce the Impacts of Climate Change

In the United States, many state and local leaders had become sufficiently concerned about the issue of climate change by the end of the 1990s and set out to adopt a range of measures aimed at reducing GHG emissions within their jurisdictions. This trend began with a few leading states in the early 1990s, but accelerated in the following decade. In 2001 and 2002, approximately one-third of the states passed new legislation or executive orders specifically aimed at addressing climate change [Rabe 2002].[9] These policies ranged from comprehensive state action plans with quantitative GHG reduction targets to regulations or laws limiting emissions from a specific sector such as electric power generation or transportation. In the Northeast, the Regional Greenhouse Gas Initiative requires power plants to reduce total GHG emissions 10 percent by 2020. In California, Assembly Bill AB 32 "The Global Warming Solutions Act of 2006" requires reducing the state's GHG emissions to 1990 levels by 2020. The scoping plan adopted by the implementing agency, the California Air Resources Board (ARB), in December 2008 includes measures targeting emissions from a wide range of sectors, including heavy-duty vehicles.

The California Global Warming Solutions Act

The California Global Warming Solutions Act of 2006 (AB 32) established a program of regulatory and market mechanisms to achieve quantifiable and cost-effective reductions of GHGs. The goal is to achieve 1990 emission levels by 2020 (an estimated 30 percent reduction) and an 80 percent reduction below 1990 levels by 2050. The ARB was required to adopt a plan indicating how emission reductions will be achieved from significant GHG sources via regulations, market mechanisms, and other actions. This plan, named the Climate Change Scoping Plan, was adopted in December 2008. The scoping plan further develops the three interrelated components contributing to emissions in the transportation sector: (1) vehicle technology, (2) fuels, and (3) vehicle use. Most of the regulations in the scoping plan must be adopted by January 1, 2011. In addition, the ARB has identified some early action measure to be enforced by January 1, 2010.

The scoping plan includes two regulations targeting heavy-duty vehicle GHG emissions. The first is an early action measure, adopted in December 2008, requiring new and in-use trucks with 53 foot or longer trailers operating in California to achieve aerodynamic drag and rolling resistance improvements through SmartWay certified new equipment and retrofits. New tractors and trailers must meet the requirements starting with model year 2011, in-use tractors must comply by 2012, and in-use trailers by 2014. The second regulation, which is the early phases of development, would promote hybridization in medium- and heavy-duty vehicles

Northeast States

In 2001, the Conference of New England Governors and Eastern Canadian Premiers (NEG/ECP) adopted the regional "Climate Change Action Plan." The plan establishes targets for stabilizing aggregate GHG emissions in New England, Quebec, New Brunswick, Nova Scotia, Newfoundland, and Prince Edward Island, at 1990 levels by 2010, 10 percent below 1990 emissions levels by 2020, and substantial further reductions (as much as 75 to 80 percent) in subsequent years.

In recent years, other northeastern states have developed state-specific plans and/or reduction targets, and New England states have formalized the NEG/ECP targets by signing them into law or establishing more stringent targets. These are summarized in Table 5.

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[9] Additionally, other states adopted measures that were not expressly aimed at climate change but clearly were driven at least in part by the issue of global warming.

TABLE
5

SUMMARY OF NORTHEASTERN STATE CLIMATE LEGISLATION/PLANS

STATE	LEGISLATION OR PLAN	YEAR SIGNED	REDUCTION TARGETS		
			2010	2020	2050
CT	Act Concerning CT Global Warming Solutions	2008		10% below 1990 levels	80% below 1990 levels
ME	Act to Provide Leadership in Addressing the Threat of Climate Change	2003	1990 levels	10% below 1990 levels	75-80% below 1990 levels
MA	Global Warming Solutions Act	2008		10-20% below 1990 levels	80% below 1990 levels
NH	NEG/ECP Climate Change Action Plan Targets				
NJ	Global Warming Response Act	2008		1990 levels	80% below 2006 levels
NY	State Energy Plan and Final Impact Statement	2002	5% below 1990 levels	10% below 1990 levels	
PA	Climate Change Roadmap	2007		25% below 2000 emissions by 2025	80% below 2007 emission levels by 2050
RI	Global Warming Solutions Act	Pending		20% below 1990 levels	80% below 1990 levels
VT	NEG/ECP Climate Change Action Plan Targets				

🟧 *Denotes non-legislative action*

In response to the expected increase in emissions attributable to the transportation sector, states in the region have adopted the California motor vehicle GHG standards, are exploring the adoption of a low carbon fuel standard, and are evaluating mechanisms to reduce vehicle miles traveled (VMT).

Overview of the Study Method

This chapter provides an overview of the method used to estimate CO_2 reductions that could be achieved by introducing advanced technologies and operational changes into new Class 8 heavy-duty[10], long haul combination trucks in the U.S. in the 2012-2017 timeframe. The core of this analysis consists of a series of modeled simulations to predict the emissions impacts of incorporating various technology combinations in new trucks. It is important to note that this study did not quantify the effect of retrofits to existing trucks and trailers, nor was an attempt made to predict the impact of technologies that may be invented and commercialized in the future. Appendix A provides a more detailed description of the specific methods and assumptions used in this analysis.

All simulation modeling for this study was performed by Southwest Research Institute (SwRI) using publicly available RAPTOR and GT-POWER software. GT-POWER was used to model the performance, fuel consumption and CO_2 emissions of the engine with a range of alternative technologies applied. RAPTOR was used to simulate the performance of the entire vehicle, using the output of the GT-POWER model as an input. RAPTOR provides detailed information on the acceleration, braking, and emissions performance of different truck designs. The modular structure of the models can accommodate a variety of vehicle configurations – including trucks, buses, cars, and motorcycles – and allows for the detailed specification of a wide range of individual vehicle components. This enables the user to investigate – at the vehicle level of detail – how modifying or replacing certain components, either individually or in combination, affects truck performance across a number of parameters, over standardized driving cycles; in terms of climbing performance; steady-state and top speed performance; maximum acceleration and traction force; and braking performance.[11]

The following sections of this chapter describe each basic step of the analysis method. In brief, these steps consist of:

1. Defining a representative "baseline" long-haul heavy-duty Class 8 truck and modeling the baseline truck, using simulation modeling.

2. Validating baseline truck model simulation results against actual performance of representative 2008 model year vehicles, and adjusting the baseline engine to meet the 2010 nitrogen oxides (NOx) emission standard.

3. Developing a list of specific technology and operational options and assessing the costs and potential CO_2-reducing benefits of each option in isolation using publicly available data.

4. Performing GT-POWER and RAPTOR model simulations for the representative engine and truck technology packages selected for this analysis to assess fuel consumption and emissions reduction impacts of the technologies.

5. Assessing the incremental and net costs of different technologies and technology combinations.

6. Assessing the impacts to the U.S. fleet of heavy-duty Class 8 long-haul trucks of widespread introduction of advanced technologies to reduce fuel consumption and CO_2 emissions.

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[10] Consistent with the classifications used in most existing state and federal regulations, Class 8 heavy-duty vehicles are defined in this study as vehicles with a GVWR more than 33,000 lbs.

[11] The range of components that can be individually specified in RAPTOR and GT-POWER includes; vehicle and trailer; engine and engine components; clutches; transmission elements; control elements; shafts (rigid or torsion-elastic); wheel/tire; electrical components; hybrid components; brakes and auxiliaries (such as water pump, air conditioning or power steering). In addition the software allows for modification of assumptions about the driver and about environmental driving conditions (such as shift points and road grade (hills)).

Selecting and Defining a Baseline Class 8 Truck

Because the focus of this study is long-haul, Class 8 tractor trailers, trucks in this category were first evaluated for major utility distinctions. The existing heavy-duty truck fleet exhibits a wide range of fuel efficiency and design features from one vehicle to another. Some of the differences in truck fuel efficiency are driven by necessity. For example, some trailer configurations such as bulk haulers or flatbeds are less amenable to aerodynamic improvement than the standard box van trailers. Operators who go off-road or who pull unusually heavy loads generally need to use overdrive transmissions that are slightly less efficient in top gear than direct drive transmissions. They do this to get an adequate gear ratio spread for their applications. Operators who run 80,000 pounds or less on highway often use overdrive transmissions as well, because an overdrive transmission will provide better overall gearing for their application. Operators who go off-road or operate frequently in low friction conditions also may need to use tires with higher traction and thus higher rolling resistance. Some operators may find aerodynamic upgrades to be cost-effective, while other operators may run into operational issues or may lack the money to pay for upgrades even if the payback interval is relatively short. Widespread introduction of wide-base single tires, which can provide a significant rolling resistance reduction, has been delayed by, among other issues, perceived downtime concerns.

A portion of the variation in fuel economy of existing heavy-duty vehicles fuel economy is driven not by variation in vehicle applications or by practical necessity, but by buyer preference. Square nose conventional tractors with external air cleaners and dual vertical exhausts mounted on the side of the cab are the traditional image of trucking. These trucks typically have very high aerodynamic drag. Many truckers, especially owner-operators and small fleets, persist in buying traditional style trucks, even though they use significantly more fuel than more aerodynamic tractor designs. They do this because driver satisfaction and retention is a big issue for truck fleets, especially smaller fleets. The recent spike in fuel prices has reduced sales of traditional style trucks, but they have not disappeared from the market.

The study team selected an older model of aerodynamic truck - the Kenworth T-600 – to be the baseline for this study. This was done in part for purposes of practical necessity and in part because this truck is representative of many trucks on the road today. The reasons for selecting this vehicle include:

- Measured drag and rolling resistance coefficients for the T-600 are available from a previous SwRI project.
- The T-600 is more aerodynamic than a traditional truck, but not competitive with the latest aerodynamic trucks. This truck can be expected to roughly match the overall trucking fleet average for aerodynamic and rolling resistance performance.
- The baseline T-600 tractor / trailer combination used tires with a rolling resistance typical of current product offerings. Dual wheels were used on every axle except the steering axle, as is typical on current trucks.

After the baseline vehicle was chosen, a baseline powertrain was selected. The requirements were to select an engine that could be modeled with reasonable accuracy at the future 2010 emissions standards, and a transmission that is typical for long-haul service. SwRI had available to them extensive test data from the SwRI Heavy-Duty Engine Benchmarking program for three 2007 model year engines: a CAT C15, a Cummins ISX, and the Volvo D13. These data allowed the calibration of a GT-POWER simulation model, which could then be used to explore a range of technology options. The engine selected was a 2007 model Volvo D13 engine for the following reasons:

- This engine has technical characteristics in common with most heavy-duty truck engines that meet 2007 emissions requirements. High pressure loop cooled exhaust gas recirculation (EGR) is used to control NOx emissions, while a diesel particulate filter (DPF) system is used to control PM.
- The Volvo exhaust emission control approach is shared with engines from Cummins, Detroit Diesel, Mack, and Mercedes. The only high volume heavy-duty truck engines that do not follow this technical approach for 2007 emissions are from Caterpillar. Because Caterpillar recently announced that it will withdraw from the heavy-duty truck market, its technical approach is unlikely to be used in future heavy-duty trucks. Thus, the Volvo D13 is representative of nearly all current heavy-duty engines.
- The Volvo D13 is not offered in the Kenworth T-600 truck, but it has very similar performance, fuel economy, and emissions characteristics to the engines that are offered.

An Eaton Fuller 10-speed manual transmission was paired with the baseline vehicle for the following reason:

The representative truck selected for this study has aerodynamic and rolling resistance characteristics that approximate the average performance of the current truck fleet. The representative truck also has a 2007 emissions engine that can be upgraded to meet 2010 emissions requirements. Finally, the representative truck has a manual transmission that has a high market share among fuel economy sensitive fleets.

- This transmission offers a very efficient direct drive top gear, and it is widely used in fleets where fuel economy is a priority. The efficiency of a heavy-duty truck transmission in top gear is important to the overall vehicle fuel economy because long-haul trucks typically spend most of their time in top gear.

The representative truck selected for this study has aerodynamic and rolling resistance characteristics that approximate the average performance of the current truck fleet. The representative truck also has a 2007 emissions engine that can be upgraded to meet 2010 emissions requirements. Finally, the representative truck has a manual transmission that has a high market share among fuel economy sensitive fleets.

Validating Simulation Modeling Results for the Representative Class 8 Long-Haul Truck

As described in the foregoing section, the specifications used to describe a representative or "average" truck for simulation purposes were based on actual 2007 vehicle characteristics. To validate model simulations of the vehicle, it was necessary to compare real world data and other data for the drivetrain and vehicle with the simulation modeling results for the baseline vehicle and the baseline engine adjusted to 2010 emissions performance.

Engine Model

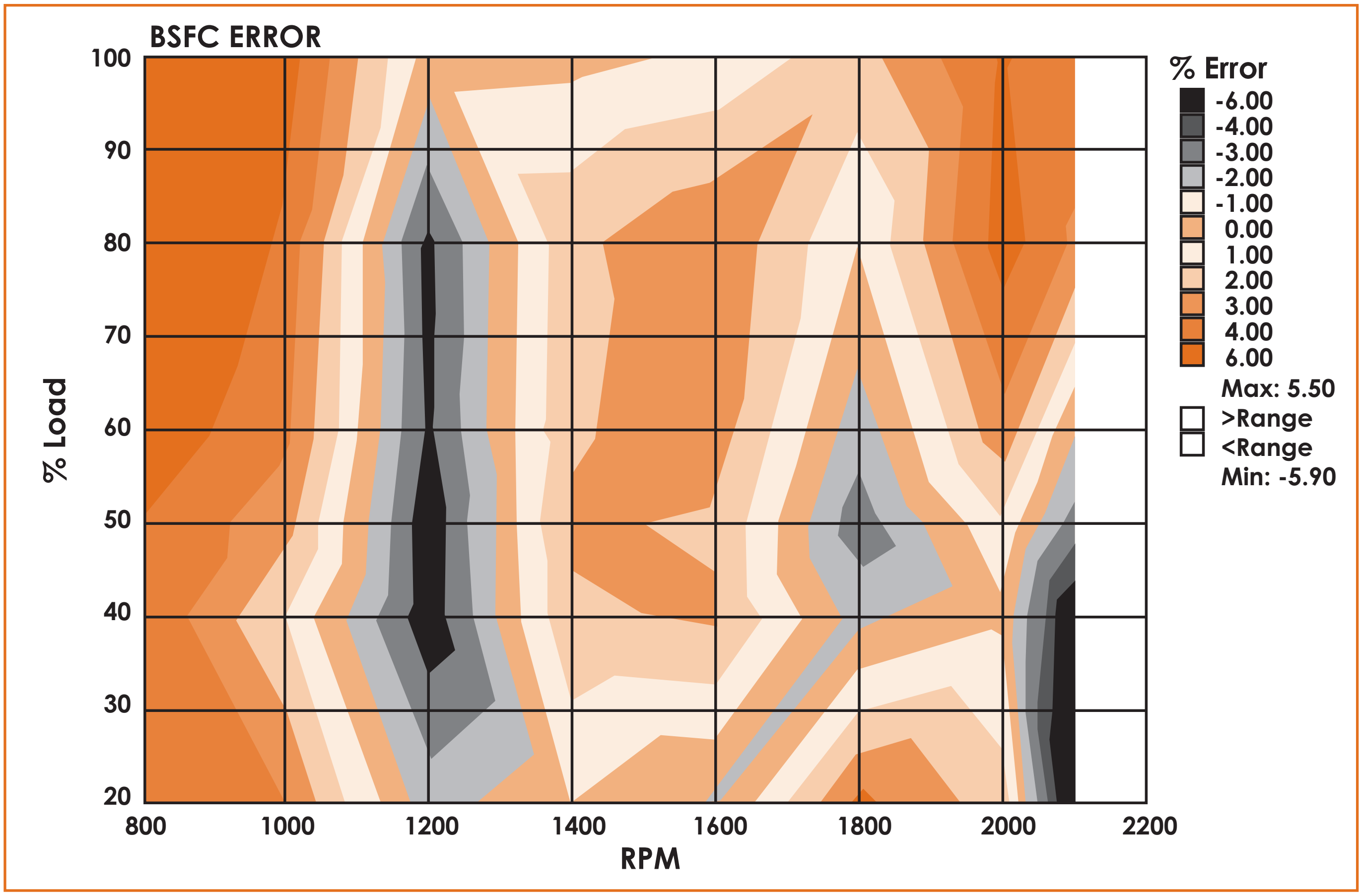
Once the baseline truck and powertrain was determined, simulation models were created to allow the evaluation of various alternative technologies. The engine simulation was done using GT-POWER, which is a commercial code widely used for engine cycle simulation. Volvo supplied the GT-POWER model used in this project, and SwRI calibrated the model using 2007 D13 data measured at SwRI in the Heavy-Duty Engine Benchmarking Program. Combustion (heat release) data from 12 engine operating conditions were evaluated and used to tune the GT-POWER model to provide an accurate estimate of actual engine performance and fuel consumption. Figure A-1 in Appendix A shows the GT-POWER model of the Volvo D13 engine in its baseline configuration.

GT-POWER provides an option for automatic control of certain parameters. The automatic control is set up to use a selected input, such as fuel quantity, to control a selected output quantity, such as engine torque. The initial model created for the baseline engine included a torque control to match the torque curve of the production engine, and an EGR control to match the EGR flow rate measured on the production engine. It is required that the model match the power and torque of the actual engine. Matching EGR rate is also important, because it means that the NOx characteristics of the simulated engine will match those of the actual engine. The variable geometry (VG) turbocharger also had a controller set to maintain the boost level and control air/fuel ratio.

In order to determine if the simulation model provides a good match to the actual engine, several parameters were evaluated. Brake specific fuel consumption (BSFC), exhaust temperature, and air/fuel ratio were selected for model validation in this study. The goal was for the simulation model to be within 4 percent of the actual engine BSFC, within 30° C of the actual exhaust temperature, and within 1 ratio of the actual air/fuel ratio. Figure 6 shows the match between the model and experimental engine data for BSFC.

> ***The goal was for the simulation model to be within 4 percent of the actual engine BSFC, within 30° C of the actual exhaust temperature, and within 1 ratio of the actual air/fuel ratio.***

FIGURE 6 BSFC COMPARISON OF SIMULATION MODEL AND ENGINE TEST DATA



The tan and light gray areas of Figure 6 show areas where the model comes within 2 percent of the test data. These colors dominate most of the area between 1,000 and 1,900 revolutions per minute (RPM), which is where the engine operates for the majority of the time. There is an area around 1,500 RPM from 40 percent to 90 percent load where the model over-predicts the BSFC by more than 2 percent, but less than 3 percent. At 1,200 RPM, the model under-predicts BSFC by more than 3 percent from 40 percent to 80 percent load. Figure 6 shows that BSFC predicted by the simulation model is within 4 percent of the actual engine data except at very low speed, high load (below 1000 RPM) and at 2000 RPM, high load. In actual operation, the engine will spend little or no time operating at these points, so the match between the engine and model was judged successful. Because the truck cruise operation is in the 1,300 to 1,500 RPM range, it is likely that the engine model will slightly over-predict fuel consumption.

The exhaust temperature predicted by the simulation was found to be always within 30° C of the actual engine test data, so the match between the engine and test data was considered successful. Typical air/fuel ratios at high load are as low as 19 or 20. It is important to maintain air/fuel ratios at or above the minimum values used on the actual engine, to control PM emissions. This is normally only an issue at lower speeds and high load. At light load, values as high as 60 can be found. For most of the operating range of the engine, less than half a ratio error in the prediction of air/fuel ratio was found between the modeled and real world data. For a small area of the operating range, a ½ to 1 ratio underestimate of air/fuel ratio was found. Only at 800 RPM and 20 percent engine load is the error greater than 2 ratios. These results meet the 1 ratio target for simulation accuracy in the heart of the operating map.

Given the results discussed in this section, the engine simulation model was determined to be accurate enough to use for the baseline 2007 engine.

Adjusting the Baseline Engine to 2010 NOx Emissions Requirements

Once the 2007 model year engine data had been validated, SwRI adjusted the GT-POWER model so that the baseline engine would meet 2010 NOx emissions limits. The model year 2007 emission limit for NOx is 1.2 grams per brake horsepower-hour (g/bhp-hr). In 2010, the limit will be lowered to 0.2 g/bhp-hr. Because heavy-duty powertrain and vehicle technologies to reduce vehicle fuel consumption and CO_2 emissions in this study were evaluated for the years 2008 and 2017, it was imperative that the baseline engine meet 2010 NOx emission standards in the modeling exercise. The Volvo D13 baseline engine uses EGR to control NOx, and a DPF to control particulate. For 2010, the engine will also use a selective catalytic reduction system (SCR) in addition to EGR to control NOx. The development of the 2010 engine is not complete, so actual test results for the 2010 engine are not available yet.

Because it is not known exactly how much of the NOx will be controlled by the EGR versus the SCR system, SwRI estimated the NOx conversion efficiency of the two components for the 2010 engine. If it is assumed that the EGR system removes most of the NOx emissions, this would result in a fuel consumption penalty compared to a 2007 engine. Conversely, a very high NOx conversion efficiency in the SCR system would allow high engine-out NOx, which would reduce fuel consumption. For the purposes of this study, SwRI made the assumption of a conversion efficiency in the 85 percent range for the SCR system, which would allow the engine to maintain 2007 levels of engine-out NOx. This assumption means that the 2010 engine is projected to have identical fuel consumption and engine-out NOx to the baseline 2007 version.

It is likely that 2010 engines will have a different engine-out NOx level than was assumed by SwRI for this study. The error caused by the SwRI estimate that 2007 engine-out levels will carry into 2010 unchanged is likely to result in an error in fuel consumption and CO_2 emissions of less than ±3 percent. Recent comments by engine manufacturers to the National Academy of Sciences committee entitled Assessment of Fuel Economy Technologies for Medium and Heavy Duty Vehicles indicate that 2010 engines are likely to have slightly lower fuel consumption than 2007 engines. SwRI did not estimate the additional CO_2 emissions that will result from the use of urea in the SCR system.

Vehicle Model

A commercial code developed by SwRI called RAPTOR was used to model the vehicle, including the transmission and driveline. This program has capabilities similar to GT-Drive and other commercially available vehicle simulation codes. Once the vehicle model was created, it was validated by comparing the predicted fuel economy on three drive cycles to actual on-road vehicle fuel economy measured

TABLE 6 COMPARISON OF VEHICLE AND MODEL RESULTS

DRIVING CYCLE	MODEL MPG	VEHICLE MPG	DIFFERENCE (%)
Hwy_65_Drive_Sch	4.78	4.83	1.0%
Line_Haul_Drive_Sch	5.69	5.57	2.2%
constant_65_sch	5.54	5.57	0.5%

using the T-600 truck (but with a different 2004 emissions engine). For this validation test, drive cycles were created to match actual driving cycles of the test truck for which data are available. The “Hwy_65_Drive_Sch” uses a 65 miles per hour (MPH) cruise speed, but the truck frequently slows to 30 MPH and then accelerates back to 65 MPH. This cycle is intended to simulate traffic congestion. The “Line_Haul_Drive_Sch” is not the schedule used in this project, but it has similar characteristics. One significant difference is lower cruising speeds in the drive cycle used for the comparison. The “constant_65_sch” is a steady state cruise schedule. In all cases shown in Table 6, the vehicle GVW was 80,000 pounds.

Note that the engine used in the vehicle testing is not the same as that used in our modeling. The vehicle has an engine that meets 2004 emissions requirements. However, the performance and fuel economy characteristics of the two engines are very similar. For the model runs, actual measured engine data for the 2007 Volvo D13 engine were provided as inputs. The results of the vehicle tests and model simulations match very well, especially considering the fact that the engines are not the same. Differences range from less than 1 percent to a maximum of 2.2 percent on the simulated line haul schedule. Because the vehicle model was created using data from the test truck, this close match is not unexpected. Table 6 provides a comparison of test truck and model results.

Next, a comparison was made between the predicted fuel economy using two different sets of input data for the vehicle model:

- Measured Volvo D13 engine data from the Heavy-Duty Diesel Benchmarking program
- Predicted Volvo D13 engine data from the GT-POWER model

Using the baseline engine and vehicle configurations at a GVW of 65,000 pounds, a comparison was made between measured engine and model results. With the measured engine data, the predicted fuel economy on the line haul cycle was 5.82 miles per gallon (MPG), while it was 5.66 MPG using the GT-POWER simulated engine. The GT-POWER model gave results 2.8 percent lower than the actual engine data when both were compared using the same vehicle model. This is within our target of predicting the actual engine performance within 3 percent over a driving cycle.

To provide confidence in the engine and vehicle simulations, two levels of comparison were completed successfully. First, the RAPTOR vehicle model was validated by comparison to actual truck test results. Second, the GT-POWER engine model was validated by comparison to actual engine test results. In both cases, the program targets for model validation were achieved.

Selecting a Drive Cycle

As mentioned previously, the target market segment of this study is line haul heavy-duty trucking, which accounts for about 70 percent of the fuel burned by heavy-duty vehicles. Line haul trucking typically involves extended time at high speeds. In addition, some time is spent in congested traffic, which introduces more variation in vehicle speed. Some time is spent getting from the loading dock to the highway and back in urban or suburban type driving. This portion of the driving cycle may have frequent stops and speed variation.

The test cycle used in this study was based on the California Heavy-Duty Diesel Truck Drive Cycle. The California cycle was created from analysis of a statistical study of line haul truck operations in California. The following changes were made to the California cycle for this study, based on input from industry experts:

- The portion of high speed driving was increased to reflect longer average travel distances
- The speeds used in the California cycle were increased by 8 percent to reflect current typical truck operating speeds on long-haul routes
- Two segments with grade were added. One segment includes positive and negative 1 percent grades, and a second segment has positive and negative 3 percent grades

Figure 7 shows the drive cycle used in the study. The total duration of the cycle is 6,830 seconds (one hour and 54 minutes), and the total distance traveled is 103.3 miles. The average speed over the cycle, including the urban/suburban portions, is 54.4 miles per hour. The first high speed segment reaches a cruising speed of 70 MPH, while the remaining high speed cruise segments are at speeds ranging from 65 to 67 MPH. The first steady speed cruise segment is with no grade. The second steady speed cruise segment has an alternating ±1 percent grade. The third steady speed cruise segment has an alternating ±3 percent grade for a portion of the segment. On portions with a positive 3 percent grade, the vehicle will not be able to maintain the desired cruise speed. The minimum speed achieved by the vehicle on the 3 percent grade will provide a measure of the performance penalty or gain from any given technology package. The final two steady speed segments are run with no grade.

Figure 8 on page 27 shows the grades and elevations on the drive cycle used for this study. The x-axis on this figure shows distance in miles, rather than time in seconds. In Figure 7, the 1 percent grade segment runs from 1,740 to 2,700 seconds, and the 3 percent grade section runs from 2,870 to 3,700 seconds. Note that this is a simulation of rolling hills, not of mountains.

It is important to note that the drive cycle chosen for this study is specific to long-haul trucks. Thus, the results described in Chapter 3 are specific to long-haul trucks and cannot necessarily be extrapolated to other heavy-duty trucks operating on different drive cycles.

FIGURE 7 HEAVY TRUCK LINE-HAUL DRIVE CYCLE

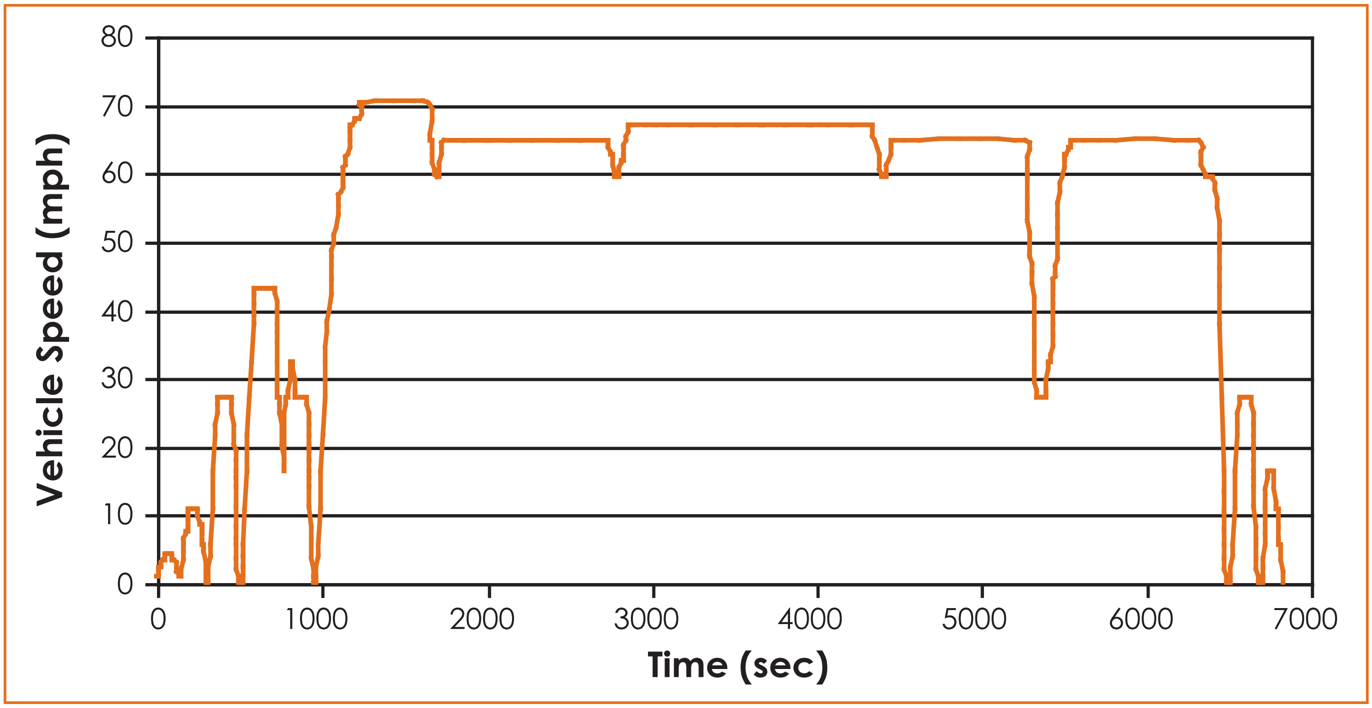


FIGURE 8 GRADES ON HEAVY TRUCK LINE-HAUL DRIVE CYCLE

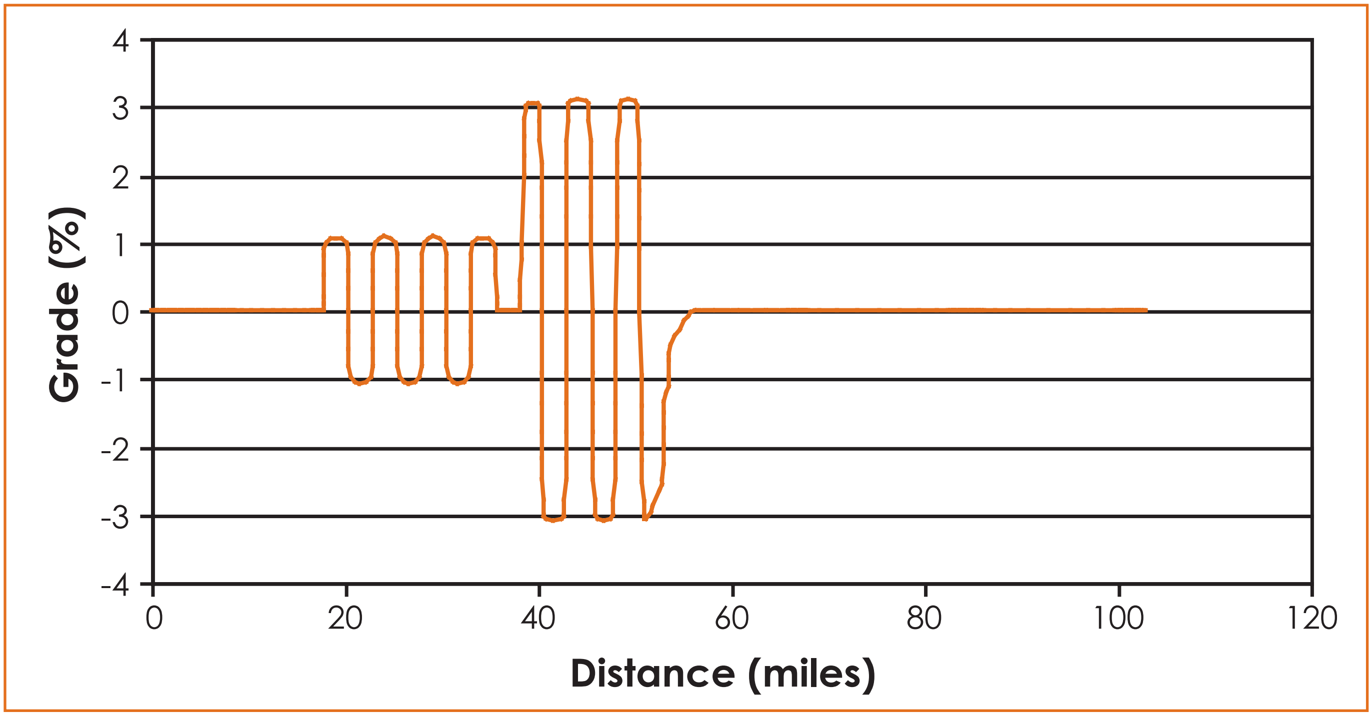


TABLE 7 VEHICLE TECHNOLOGIES EVALUATED FOR POSSIBLE INCLUSION IN THIS STUDY

ENGINE	POWERTRAIN	AERODYNAMICS
Improved SCR Efficiency	Automated Manual Transmission	Fully aerodynamic mirrors
Engine Friction Reduction	Moderate Hybrid Systems	Cab side extenders
Mechanical Turbocompound	Aggressive Hybrid Systems	Integrated sleeper cab roof fairings
Electric Turbocompound		Aerodynamic front bumper
Dual Stage Turbocharging	**OTHER TECHNOLOGIES**	Full fuel tank fairings
EGR Pump	Mass Reduction	Trailer side skirt fairings
Variable Valve Actuation (VVA)	Component Friction Improvements	Trailer gap fairing
Advanced VVA	Reduced Rolling Resistance	Rear-mounted trailer fairing
Alternative Combustion Modes	Auxiliary Power Unit	Undercarriage Flow Device
Insulated Exhaust Ports		Advanced tractor-trailer gap seal
Bottoming Cycle	**OPERATIONAL CHANGES**	Advanced rear-mounted trailer fairing
Accessory electrification	Lower Road Speed	
	Increased Vehicle Size and Weight	

Identifying Discrete Vehicle Technology Options for Evaluation

A total of 32 technologies were identified and considered for inclusion in this project. Table 7 lists the individual vehicle technologies considered in this study for purposes of evaluating future Class 8 heavy-duty truck fuel consumption and CO_2 emissions reduction potential. A complete description of each of the technologies – including an explanation of how each option might reduce CO_2 emissions – is provided in Appendix A.

Downselection of Technologies Included in this Analysis

As a first step toward identifying technology options for inclusion in this study, the potential CO_2 emissions impact of each of the options listed in Table 7 were evaluated. The purpose of the evaluation was to identify promising technologies and then to identify a select group of technologies to be included in a set of “maximum reduction” technology combination simulations conducted later in the analysis. Technology analysis varied, including both literature-based and model-based methods.

An overview of each technology and the approach used to incorporate it into the analysis follows:

Improved SCR Conversion Efficiency

Exhaust after-treatment systems capable of converting a high percentage of NOx into N_2 and O_2 may yield higher powertrain efficiency in the future. This improvement would be made possible by permitting different balances between engine efficiency and after-treatment efficiency, if the durability of such systems is proven by the considerable work now going on within the industry.

Depending on how much conversion efficiency can be achieved from an advanced SCR system, an improvement of up to 3 percent could be achieved in fuel consumption and CO_2 emissions. Since it is not clear what increase in SCR system performance will prove possible over the next few years, and there are no published data that provide good guidance on this topic, SwRI did not make projections based on improved SCR performance. Therefore, the model of the 2010 engine matches the efficiency and CO_2 emissions of the 2007 engine exactly.

Engine Friction Reduction

Development of engine main and rod bearings is under way to allow the use of lower viscosity engine oils. The lower viscosity oil will in turn reduce engine friction in the bearings and between the piston, rings, and liner. About a 10 percent reduction in engine friction is expected if the current standard 15W40 engine lube oil can be replaced by a 5W30 grade. A more expensive synthetic oil is expected to be required in order to allow the use of a lower viscosity. For this study, we made the assumption that a 10 percent reduction in friction could be achieved, which results in a 1 percent improvement in fuel efficiency and CO_2 emissions. This effect was judged to be small enough to leave out of the rest of the study.

Improved Air Handling Efficiency

Almost all turbocharged heavy-duty diesel engines sold in North America today use high pressure loop EGR for control of engine-out NOx levels. To get EGR to flow from the exhaust manifold to the intake manifold, the pressure in the exhaust manifold must be higher than the pressure in the intake manifold, whereas the opposite condition is the result of a higher efficiency engine/turbocharger system. To achieve the “negative delta-p” required to cause EGR flow, turbocharger efficiency is intentionally sacrificed. Some potential ways of avoiding this and achieving improved air handling efficiency are to use high efficiency turbocharging in combination with: mechanical or electric turbocompounding, an EGR pump, dual stage turbocharging with an EGR pump, or variable valve actuation. This technology was evaluated as part of the two turbocompound packages.

Mechanical Turbocompound

A power turbine is added to the exhaust system after the normal turbocharger. The backpressure created by the power turbine allows the use of a very efficient conventional turbo, while still providing the negative delta-p required to support EGR flow and harvesting useful work from the exhaust stream. The power turbine is geared to put power back into the crankshaft through a fluid coupling that allows control of turbine speed and isolates the power turbine from engine crankshaft torsional vibration.

Electric Turbocompound

This is the same concept as the mechanical turbocompound, except the power is fed into an electrical machine. Electric turbocompound is ideal as a power source for a hybrid system, and will in fact require a hybrid system or some type of electric propulsion system to utilize the power generated by the turbine. Independent control of engine speed and turbine speed makes electric turbocompounding slightly more efficient than mechanical turbocompounding.

Dual Stage Turbocharging with Intercooling

Achieving the high pressures required by modern engines can be done more efficiently with two turbos, where each achieves half of the required pressure ratio, and intercooling is used between the two turbos and before the intake manifold. This approach requires an EGR pump, turbocompound system, or other device to facilitate EGR flow. Packaging two turbocharger stages with a turbocompound power turbine was judged to be very difficult from a cost and mechanical feasibility standpoint, so this approach was not evaluated. This technology has a potential benefit of 1 to 2 percent.

EGR Pump

An EGR pump can facilitate EGR flow and help control the flow rate to achieve the desired level of EGR. This device makes EGR flow independent of the engine's delta-p, which allows the use of high efficiency air handling systems. Energy used by an EGR pump partially cancels the efficiency gain from the high efficiency turbocharger we pair it with. Based on simple spreadsheet calculations, the EGR pump proved less attractive than turbocompound as a way of providing the negative delta-p required to drive EGR flow. This technology was not included in the analysis.

Variable Valve Actuation

In gasoline engines, variable valve actuation (VVA) can have a huge impact on engine performance and fuel economy. VVA can be used to improve engine breathing over wide engine speed ranges, thus increasing power and/or reducing the pumping losses caused by throttling the intake. In heavy-duty diesel engines, the potential benefits of VVA are much more limited, in part due to their narrower range of operating speeds as compared to gasoline engines. VVA allows flexibility to operate a turbocharger at a more efficient point on the compressor map, but with consideration to maintain adequate SCR temperature at low loads to prevent an increase in NOx emissions. VVA can also be used to improve the power output of a turbo-compound system by leaving more energy (temperature/pressure) in the exhaust stream. Variable valve actuation was extensively modeled in GT-POWER, both as a stand-alone feature and in combination with turbocompounding and the bottoming cycle. SwRI results show that the ability of VVA to improve diesel engine efficiency as a stand-alone feature is rather limited, which agrees with past results from several engine makers.

Electric turbocompound is ideal as a power source for a hybrid system, and will in fact require a hybrid system or some type of electric propulsion system to utilize the power generated by the turbine. Independent control of engine speed and turbine speed makes electric turbocompounding slightly more efficient than mechanical turbocompounding.

Advanced VVA:

There are examples in the literature where dramatic improvements are claimed from modified engine operating cycles that VVA can enable, such as the Sturman "Digital Engine" combustion cycle. This cycle is claimed to be revolutionary in its ability to inject air during a combustion event in ways that are impossible in conventional engine arrangements. According to Sturman, this ability opens up significant possibilities for efficiency improvement and in-cylinder emissions control. Unfortunately, the available literature does not provide enough details to allow SwRI to attempt to duplicate the claimed results for this study.

Alternative Combustion Modes: LTC / HCCI / PCCI

Low temperature combustion (LTC), homogeneous charge compression ignition (HCCI), and premixed charge compression ignition (PCCI) are all "alternative" combustion modes that can be used in place of standard diesel combustion. All of these modes have been developed in an effort to reduce NOx output, and in the case of HCCI, Particulate matter (PM) output as well. If NOx is not an issue, these alternative combustion modes generally suffer from lower thermal efficiency than conventional diesel combustion. However, conventional diesel combustion suffers substantial thermal efficiency degradation at low engine-out NOx levels, so these alternative modes can become attractive. The performance of these alternative combustion modes is duty cycle dependent: most of the potential is at low load. Typically, alternative combustion modes can be used up to 30 percent or 40 percent load. Therefore, alternative combustion modes will have little impact on the fuel economy or CO_2 emissions of an engine that operates most of the time at higher loads, such as in a long-haul truck application. These modes do not offer a fuel consumption or CO_2 benefit over standard diesel combustion combined with SCR, so the decision was made not to pursue alternative combustion modes for this project.

Engine Thermal Management Improvements

The goal of thermal management features is to retain energy in the gas flow through the engine rather than allow heat to be lost along the way. Examples include insulated exhaust ports and a bottoming cycle, discussed below.

Insulated Exhaust Ports

Increased exhaust temperature was calculated for an engine outfitted with ports insulated using ceramic coatings or inserts with air gaps. The retained energy can then be used in an energy recovery device, such as a turbocompound system or a bottoming cycle. The energy potential of insulated ports and is better at high load, but there can also be a benefit from higher temperature into an SCR system for improved NOx conversion efficiency. In practice, the potential from features such as insulated exhaust ports is small.

> ***The great advantage of a bottoming cycle is that it uses "free" energy – energy that is otherwise thrown away by the primary engine. The great disadvantage of a bottoming cycle is that its efficiency is limited by the amount (flow rate) and quality (temperature) of waste heat sources, further disadvantaged by variability in heat sources linked to varied driving conditions.***

Bottoming Cycle

A bottoming cycle is a heat engine that uses waste heat from the primary engine, in this case the heavy-duty diesel, to produce additional work. There are many concepts available for use in a bottoming cycle, including steam turbines. Heat sources for a bottoming cycle include exhaust gas flow, EGR flow, charge air flow, and engine coolant. The great advantage of a bottoming cycle is that it uses "free" energy – energy that is otherwise thrown away by the primary engine. The great disadvantage of a bottoming cycle is that its efficiency is limited by the amount (flow rate) and quality (temperature) of waste heat sources, further disadvantaged by variability in heat sources linked to varied driving conditions. Bottoming cycles have been used for many years in stationary power plants, yet so far, they have not found application in vehicles because of cost, weight, packaging, reliability, and performance challenges.

After studying the available literature, SwRI decided to model a steam turbine bottoming cycle using water as the working fluid. Water has well understood properties and a boiling temperature favorable for bottoming cycle applications. Disadvantages include risk of freezing, difficulty in packaging, surviving on-road vibration, and more, all requiring careful engineering design consideration to develop a successful system. A sophisticated spreadsheet simulation of the bottoming cycle was created in order to evaluate alternative designs, taking into account many parameters and assumptions, and calculating temperatures, pressures and flow rates through the system.

In the evaluation performed by SwRI, by far the best performance was obtained by heating the bottoming cycle fluid first with the exhaust gas stream, and then adding additional heat from the EGR stream. This approach provided much better results than using either of the two sources alone. Only about 25 to 30 percent of the exhaust flow is devoted to EGR, but it is taken from the exhaust manifold before the turbocharger, therefore offering the highest quality (temperature) of the available waste-heat streams.

The amount of energy available from a bottoming cycle is strongly dependent on engine speed and load. At high speed and load, the highest temperatures and exhaust flow rates are achieved, which allows a high bottoming cycle power. At average loads such as 1400 RPM and 40 percent load, the modeled bottoming cycle still contributes 7.5 percent of total engine crankshaft power, which translates into a 7.5 percent reduction in fuel consumption and CO_2 emissions.

Transmission System Technologies

Automated Manual Transmission

Most heavy-duty trucks use manual transmissions with 8 to 18 ratios available. The most common transmissions for line haul applications have 10 ratios with an overdrive top gear. Torque-converter automatic transmissions, similar to those used in passenger cars, are used in some stop/go truck applications but are more expensive do not have an efficiency advantage in line-haul applications. Automated manual transmissions have been available on the market for over 10 years now and are increasing in market share. Automated manuals have a computer to decide when to shift and use pneumatic or hydraulic mechanisms to actuate the clutch and hidden shift levers. An automated manual can shift as quickly as the best driver, and the shift schedule can be tailored to match the characteristics of the engine and vehicle. This reduces variability of fuel consumption and CO_2 emissions between drivers, with all drivers achieving results closer to those of the best drivers.

An Eaton 10 speed manual transmission was selected as the baseline transmission for the project and was simulated with a model driver using good shifting practices. The shifting practices chosen for the automated manual transmission were identical, meaning that the automated manual showed no CO_2/fuel economy benefit. Therefore, the automated manual transmission was not included in this analysis. In the real-world, there would be a fuel economy improvement proportional to the number of non-fuel-conscious drivers in a fleet.

Moderate Hybrid Systems

These systems are similar in concept to the mild hybrids used in light-duty applications using an integrated starter/generator, often mounted between the engine flywheel and the transmission. Engine start/stop capability is included, along with limited duration auxiliary power unit (APU) capability using battery power, electrified accessories, launch assist, and regenerative braking to recharge the battery. The battery size is modest to control cost and weight. A moderate hybrid system was not modeled for this project. The Steering Committee agreed that a more powerful "aggressive hybrid" offered much more potential fuel savings for heavy-duty trucks.

Aggressive Hybrid Systems

These systems are similar in concept to the full hybrids used in light-duty applications. Both a parallel-hybrid and a series-hybrid approach were considered in this study.

The first approach has a 50kW motor/generator on the transmission with a battery, all-electric engine and vehicle accessories, and APU-capability using the battery. The second hybrid approach modeled for this study was a series hybrid in combination with a 2-speed transmission. At very low speeds, a 10kWh battery pack drives the wheels through a 200kW electric motor without starting the engine. At medium speeds, the engine drives a generator that drives the wheels using a 200 kW electric motor. The special 2-speed transmission is used to directly connect engine to the drive wheels only at highway speeds.

The parallel hybrid was chosen for use in this study. The series hybrid model displayed large energy conversion losses making this system unattractive. The series hybrid approach allows the engine to operate at more efficient speed/load points, but this is not enough to overcome the energy conversion losses in the electric machines. As a result, the series hybrid was not able to provide an advantage over the fuel efficiency of the baseline manual transmission and was not considered in this study. There may be ways of operating the series hybrid that would provide better results, but we were not able to get enough detail from any company developing a series hybrid system to accurately model their approach.

Vehicle Technologies

Accessory Electrification

The use of a hybrid system or electric turbocompound provides a large source of electrical energy that can be used to drive accessories that are engine-driven on today's vehicles. Given the availability of significant electric power, the following accessories can be converted to electric drive: electric power steering (EPS), electric water pump (EWP) electric a/c compressor, and an electric air compressor. If over 30 kW of electric power is available, the engine

> ***Given the availability of significant electric power, the following accessories can be converted to electric drive: electric power steering (EPS), electric water pump (EWP) electric a/c compressor, and an electric air compressor. If over 30 kW of electric power is available, the engine cooling fan can also be converted to electric drive, though in line haul applications the efficiency savings from an electric cooling fan is normally not required at higher vehicle speeds.***

cooling fan can also be converted to electric drive, though in line haul applications the efficiency savings from an electric cooling fan is normally not required at higher vehicle speeds. Fan-on time tends to be very low except during low speed vehicle operation, since ram air provides adequate cooling under most higher speed conditions.

If electric power is not available, there are still some technologies that can be applied to reduce the parasitic power consumption of accessories. Increased component efficiency is one approach, and clutches can be used to disengage the alternator and air compressor when they are not required. Air compressors that are rotating but not creating pressure absorb about half the power of a pumping compressor, and compressors normally only pump a small percentage of the time in long-haul trucks.

For this study, the accessory power demand of a baseline truck was modeled as a steady state power draw of 5 kW, and 3 kW for more electrical accessories in individual vehicle configurations that included electric turbocompounding and/or hybridization. This 2 kW savings versus average engine power of 100 to 200kW over a drive cycle nets roughly 1-2% savings compared to a baseline vehicle.

Component Friction Improvements

Engine friction reduction is described in Appendix A. Lower viscosity lubricants, and lubricants whose viscosities are less temperature sensitive, can also be applied in transmissions, differentials, and axles. In many cases, these components need to be designed to be compatible with low friction lubricants. The benefits of friction reduction on these components are sensitive to ambient temperature with larger benefits found in cold weather. Due to the complexity of modeling friction reductions, realistic reduction estimates were included in the overall rolling resistance values that are used in Package 2, Package 3, and all subsequent packages, which use the Package 3 values. Package 2 assumes no change in component friction, while Package 3 assumes a 10 percent reduction in component friction.

Aerodynamic Drag Reduction

There are many technical features that are available or under development to reduce the coefficient of drag (Cd) of a heavy-duty truck. Because reliable data are not universally available from independent sources on the effects of individual features and because modeling the effects of individual features was beyond the scope of this project, we modeled the effect of changes in overall Cd from “off-the-shelf” and “emerging” technologies on the fuel economy and CO_2 emissions of the truck.

A long list of aerodynamic features initially discussed was used as a starting point to down-select technologies for the study. That list included: reduced tractor to trailer gap, trailer side skirts and undercarriage skirts, a boat tail, boat tail plates, integrated tractor roof fairings, a tractor “eyebrow,” frontal area reduction (not implemented, in order to keep carrying capacity constant), trailer edge rounding, vortex generators, guide vanes, active and passive pneumatics, aerodynamic mirrors, replacement of mirrors with cameras, a trailer underbody wedge, fuel tank fairings, bumper fairings, and hidden vertical exhaust stacks.

Aerodynamic improvements considered for this study were broken into two groups, as shown in Table 8.

TABLE 8

AERODYNAMIC IMPROVEMENTS CONSIDERED

“OFF-THE-SHELF” IMPROVEMENTS	
Fully aerodynamic mirrors	Mirrors shaped and positioned to minimize drag.
Cab side extenders	Designed to reduce the tractor-trailer gap.
Integrated sleeper cab roof fairings	Large fairings to match the roof height of a truck to the height of the trailer.
Aerodynamic front bumper	For smoother airflow around the hood and wheels.
Full fuel tank fairings	To smooth airflow over fuel and air tanks.
Trailer side skirt fairings	To deflect air away from the trailer undercarriage.
Trailer gap fairing	Mounted to the trailer to reduce the tractor-trailer gap.
Rear-mounted trailer fairing	Sometimes called a 'boat tail,' used to reduce drag at the rear of the trailer.

“EMERGING” IMPROVEMENTS	
Undercarriage Flow Device (UFD)	To further deflect air away from the trailer's undercarriage.
Advanced tractor-trailer gap seal	A device that creates a nearly-complete closure of the tractor-trailer gap. This will require redesign of the tractor and trailer shape.

The baseline Kenworth T-600 truck with a standard 53 foot van trailer is known to have a Cd of 0.63, a value that can be expected to roughly match the overall trucking fleet average. From the baseline, two packages of aerodynamic improvements were considered.

The off-the-shelf improvements were incorporated into a group known as Package 2, representing a full implementation of technologies currently recommended by EPA Smart Way. This package assumed a drag coefficient of 0.5. A second, more aggressive aerodynamic package called Package 3 looked at a feasible drag coefficient for 2017. After much discussion in the Steering Committee, a drag coefficient of 0.4 was selected, based on available data regarding emerging aerodynamic improvements. To reach a value of 0.4, vehicle design changes that go well beyond those listed above, and which have some effect on the operation of the truck are likely to be required. Since the technology is not mature at this time, the impact of these operational changes has not yet been determined. This means that some risk is inherent in the assumption that a Cd of 0.4 is achievable within the time frame of this study.

Mass Reduction

Reduced mass can benefit fuel efficiency and CO_2 emissions in two ways. If a truck is running at its gross vehicle weight limit with high density freight, more freight can be carried on each trip, increasing the trucks ton-miles per gallon. If the truck is carrying lower density freight and is below the GVW limit, the total vehicle mass is decreased, reducing rolling resistance and the power required to accelerate or climb grades.

Weight reduction can be achieved by making components with lighter materials (high strength steel, aluminum, composites) or by eliminating components from the truck. A common component-elimination example is to use wide-base single tires and aluminum rims to replace traditional dual tires and rims, eliminating 8 steel rims and 8 tires. Many of the features being added to modern trucks to benefit fuel economy, such as additional aerodynamic features or idle reduction systems, have the effect of increasing truck weight.

Reduced Rolling Resistance

Lowering the rolling resistance of tires through improved design and inflation reduces the power required to move the truck down the road, directly reducing fuel consumption and GHG emissions. A well designed wide-base single tire has lower rolling resistance than traditional dual tires and manufacturers also offer low rolling resistance versions of dual tires. Automatic tire inflation and tire monitoring systems also lower the rolling resistance by helping drivers operate their tires at optimum pressure. Actual vehicle testing yielded baseline rolling resistance data, while improved values used in the technology packages were provided by EPA SmartWay and Michelin. An important consideration with lower rolling resistance is that traction and braking performance often suffer as the rolling resistance is reduced. A balance must be achieved that provides the lowest practical rolling resistance without too great of an effect on vehicle performance or safety.

Lowering the rolling resistance of tires through improved design and inflation reduces the power required to move the truck down the road, directly reducing fuel consumption and GHG emissions. A well designed wide-base single tire has lower rolling resistance than traditional dual tires and manufacturers also offer low rolling resistance versions of dual tires.

Lower Road Speed

Since aerodynamic drag is a function of speed squared, reducing speed can improve vehicle fuel economy and CO_2 emissions. Limits to this approach include delivery time requirements for certain cargo or an increase in the number of trucks on the road to deliver a given amount of freight. Any possible increase in the number of trucks caused by lower speeds could be eliminated by a proportional increase in truck size and weight. To model the impact of speed alone, a speed limit of 65, 60 and 55 MPH was imposed on the chosen drive cycle.

Increased Vehicle Size and/or Weight

Trucks that travel at maximum weight or with a maximum volume of cargo could deliver more freight if heavier or larger longer trailer combinations, respectively, were allowed. A truck is said to be “cubed-out” when it is full of low density freight, while a truck at the GVW limit is said to be “grossed out” when it is full of high density freight. Maximum operating efficiency is achieved if a trucking company is able to load the truck until one or both of the limits are reached. Increase in the permitted size and weight of trucks could reduce fuel consumption on a ton-mile basis and lead to lower CO_2 emissions for the fleet provided that concerns including infrastructure are addressed. This study considered a 3-axle 53’ trailer and a variety of Long Combination Vehicles (LCVs) but settled on one LCV known as a Rocky Mountain Double (RMD) that consists of a standard 45-48’ trailer towing a second 28’ foot trailer with a maximum GWVR of 120,000lb. Modeling accounted for these changes by adjusting Cd and rolling resistance to represent larger, heavier vehicles. Real and publicly perceived safety considerations of larger and heavier trucks could be addressed by mandating driver training, vehicle performance characteristics such as braking performance and crash compatibility, and by requiring technologies such as stability control, crash avoidance, and more.

Idle Reduction

Line haul truck engines use a significant amount of fuel meeting overnight “hotel loads” for drivers. These hotel loads include heating, cooling, and electricity to power appliances (televisions, computers, etc). A typical truck uses hotel loads that range from 3 to 5 kW (U.S. DOE 2000). Trucks frequently idle their engines throughout the evening to meet these loads. Because truck engines are sized for much higher on-highway power requirements, the engine operates very inefficiently to provide these small amounts of power. EPA (SmartWay 2009) estimates that an idling engine consumes 0.8 to 0.9 gallons of diesel per hour. The amount of time that a truck spends idling is estimated to run as high as 2,400 hours per year (nominally 8 hours per day, 300 days per year) (SmartWay, 2009). Sodolsky (2002) estimates the average idle time for long haul trucks to be 1,800 hours per year. These estimates suggest that a typical line haul truck without idle reduction technology uses 1,500 to 1,600 gallons per year; total on-road fuel use for a truck that travels 120,000 miles at 6 MPG is 20,000 gallons, so overnight idling can consume 7 to 8 percent of the truck’s fuel.

There are several approaches for powering hotel loads more efficiently. These include shore power systems, which plug in to an off-board electricity source; direct fire heaters, which burn diesel fuel directly to meet heating loads; automatic engine idle control systems, which intelligently power the engine on and off throughout the evening; battery powered systems, which use energy stored in a battery pack charged by the engine; and auxiliary power units, which are small, highly efficient diesel generators. These idle reduction technologies are all currently available either through third party vendors or as add-on options to trucks directly through manufacturers.

Our analysis focused on the potential for achieving idle reduction using an APU, included in the SmartWay technology (package 2); and a battery-based system, included as part of the hybrid package (package 4). We did not evaluate shore power systems, as this represents an infrastructure challenge that lies outside the scope of the study. We selected an APU rather than a battery based system as part of the SmartWay package because these systems are capable of providing hotel loads for longer periods; battery based systems require that the engine be powered on frequently (a few minutes per hour) to recharge the battery.

The hybrid package uses a battery-based system because all of the tertiary systems are already included in standard hybrid vehicle, so idle reduction is realized for “free.” Both of these systems are estimated to reduce fuel use to 0.2 gallons per hour (SmartWay 2009), which reduces fuel use by approximately 6 percent on a line-haul truck.

In addition to estimating the emission reduction potential of each of the individual technology options described above and listed in Table 7, rough cost estimates were developed for each option to gauge the relative cost-effectiveness of employing one CO_2 reduction technology versus another. In most cases, costs available in the literature were reported as retail costs. In two cases, discussed in more detail on page 43 of this chapter, factory component hardware costs were converted to retail costs using a markup factor of 2.0 by TIAX.

Overall, the study encompassed technologies that are already in production for the U.S., European, or Japanese truck markets, or that are known to be under development for production in these markets. These technologies were identified by SwRI, by other members of the NESCCAF study team, or by the Research Steering Committee formed to provide advice during this project. SwRI performed the fuel consumption and CO_2 analysis, while TIAX assembled functional definitions of each of the CO_2 reduction technologies as they were modeled by SwRI, gathered industry information on specific technologies using interviews and technical papers, and performed a cost and impact study using adoption-rate estimates. The results of TIAX’s analysis were reported in the form of a matrix of the truck-level difference in hardware costs (relative to a baseline truck) for any given package of technologies. The cost matrix is summarized in Appendix B.

Future Developments in Heavy-Duty Truck Technology

As mentioned above, SwRI did not consider fuel consumption and CO_2 reduction technologies unless they are currently in production or for which a design specification is available in the literature. As such, the study findings do not represent the total available potential to reduce heavy-duty vehicle fuel consumption and CO_2 emissions – the results only estimate what can be done given known technologies. Going forward, more advanced technologies to improve engine, vehicle, and transmission technologies could and will likely be developed that would further reduce truck fuel consumption and CO_2 emissions beyond the 2017 timeframe. Engine manufacturers and others are currently working on advanced approaches to improve truck efficiency. Some of these technologies could include:

- Improvements in thermal efficiency. The 21st Century Truck Program has established a target of reaching a 55 percent thermal efficiency for heavy-duty vehicles. An efficiency similar to that level was not evaluated because a technical path to achieve this goal has yet to be identified or demonstrated

- Further reductions in engine friction

- Advanced variable valve actuation that is used to create a new type of engine cycle (Sturman Digital Engine)

- Alternative combustion modes (HCCI, PCCI, LTC, others to be invented)

- Advanced bottoming cycles and exhaust thermal-to-power schemes that extend beyond the steam bottoming cycle concept modeled in this study

Modeling technologies such as those described in the list above was beyond the scope of this project for two reasons: first, some of the technologies require very sophisticated and expensive modeling, and second, in several cases it is not clear from the literature exactly what to model. Additional strategies are also available to reduce fuel consumption and GHG's from transporting freight that were outside the scope of this analysis including intermodal shipping, improved logistics to avoid congestion and reduce empty hauls, driver training and driver aid technologies (real-time fuel economy monitors, GPS systems for anticipating road grade changes), improved efficiency for refrigerated cargo, amongst others.

Assembling Technology Packages for Model Simulation

Using the most promising individual technologies that emerged from the initial screening evaluation described above, in combination with cost estimates for the individual technologies, a series of technology packages was assembled for modeling. Generally, these packages were designed to span a wide range of CO_2 reduction potential so they necessarily reflect a wide range of impacts and costs.

Package 2 represents a suite of technologies recommended by the EPA Smart-Way program and available for purchase today, including aerodynamic improvements, low rolling resistance tires, and an APU. Package 2 goes one step beyond Smart-Way by including the rolling resistance benefits of the best currently available wide-base single tires. Package 3 represents a further improvement of aerodynamics and tires, based on estimates of the capability of emerging technologies.

Most of the remaining packages have been modeled in comparison to the baseline Package 1 and Package 3. Packages 4 through 8 and Package 11 were each modeled to determine their ability to reduce fuel consumption of an otherwise baseline truck. These powertrain-focused options were evaluated separately to provide a clearer understanding to the team about how they might be combined in the final "maximum reduction" packages.

Packages 9 and 10 are unique, in that they involve operational changes to trucks and do not require new technologies. Introducing these changes broadly might, however, require regulatory changes. The effect of speed on fuel economy is well understood and a variety of types of Long Combination Vehicles that carry more freight are already in use in most states in the US and in Canada.

Packages 12-14 use differing combination of technologies and operational changes to demonstrate various paths to achieve a maximum reduction in CO_2 using the technologies included in the study available for incorporation into trucks prior to 2017.

A full GT-POWER and RAPTOR simulation was then performed for each technology package, using the performance constraints identified for 2017 models. For all packages except for Package 9 (the longer / heavier vehicle combinations), engine performance (power and torque) remained the same as the 2007 baseline vehicle. Engine power was increased in Package 9 to accommodate the higher vehicle weight. The specific packages evaluated, along with model simulation results for each package, are presented in Chapter 3.

TABLE 9 **DESCRIPTION OF TECHNOLOGIES SIMULATED BY SWRI**

PACKAGE	PACKAGE NAME	DETAILED PACKAGE DESCRIPTION
1	Baseline	Volvo D13 (2010 emissions), Kenworth T600, 10-speed manual transmission
BUILDING BLOCK TECHNOLOGIES		
2	SmartWay 2007 (SW1)	Additional aero streamlining sufficient to reduce the coefficient of drag from 0.63 to 0.5 to the cab and the trailer. Fully aerodynamic mirrors, cab side extenders, integrated sleeper cab roof fairings, aerodynamic bumper, and full fuel tank fairings. Trailer streamlining includes a side skirt fairing, and either a trailer gap fairing or a rear-mounted trailer fairing such as a boat tail. RR of 0.0055. Wide-base singles and aluminum wheels. Idle reduction, improved transmission and axle lubricants
3	Advanced SmartWay (SW2)	Package #2 plus advanced aero and rolling resistance package. Includes continued streamlining of the cab/trailer combination, a reshaped trailer, boat tail, full skirting of cab and trailer, tractor-trailer gap fairing, and very low rolling resistance tires
4	Parallel hybrid-electric powertrain (HEV)	Parallel hybrid system
5	Mechanical Turbocompound	Mechanical turbocompound plus package #7
6	Electrical Turbocompound	Electrical turbocompound plus package #7
7	Variable Valve Actuation (VVA)	Variable valve actuation
8	Bottoming Cycle	Bottoming cycle
11	Advanced EGR	Advanced exhaust gas recirculation
OPERATIONAL MEASURES		
9	Rocky Mountain Double Trailers (RMD)	Longer/heavier trailer (Rocky Mountain doubles – 48’ and 28’ trailers)
10	60 mph speed limit	Slower road speed (60 mph)
MAXIMUM REDUCTION COMBINATION PACKAGES		
12	Maximum Reduction Combo 1	Standard 53’ trailer, hybrid, bottoming cycle, advanced aero and rolling resistance package, 60mph speed limit (packages #3, #4, #8, #10)
13	Maximum Reduction Combo 2	Longer heavier trailer, bottoming cycle, hybrid, electric turbocompound, VVA, advanced aero and rolling resistance package, 60 mph speed limit (packages #3, #4, #6, #7, #9, #10)
14	Maximum Reduction Combo 3	Longer heavier trailer, hybrid, bottoming cycle, advanced aero and rolling resistance package, 60 mph speed limit (packages #3,#4,#8,#9, #10)

An important benefit of simulating the performance of technology packages, rather than individual technologies, is that it eliminates the possibility that CO_2 reductions will be “double counted.” The emissions benefits associated with various options do not necessarily add when these improvements are combined in a single vehicle, particularly to the extent that many technologies target the same sources of mechanical or thermodynamic inefficiency. The simulation modeling conducted for this analysis avoids this problem. At the core of each simulation is an engine map that defines CO_2 emissions over a full range of engine speed and load points. Each map reflects the contribution of all engine technologies incorporated in the vehicle and therefore accounts for their composite impact on CO_2 emissions. Engine maps were completely replaced for each engine technology package simulated in this analysis; they were not added or otherwise manipulated. In the case of technologies that do not directly affect the engine map but rather the point on the map at which a vehicle is operating (e.g., rolling resistance or aerodynamic drag), the simulation model ascribes benefits to those technologies in accordance with their cumulative effect on engine operation. Thus, at any given point in time, the vehicle is simulated as operating at one speed/load point as determined by the *combination* of technologies present; in turn, the specific CO_2 emissions rate for that point in time is simply read from the underlying engine map.

The following example briefly illustrates how this process works. As described above, combinations of technologies are modeled as a complete vehicle system. Take, for example, a technology package consisting of a combination of improved aerodynamic drag and reduced vehicle speed. These improvements will reduce the power demand on the engine. However, when modeled in combination, the package provides a reduction in fuel consumption that is somewhat less than the sum of the individual technology benefits. The reason for this is that the relative benefit of aerodynamic drag improvements changes with speed, since aerodynamic drag is proportional to the square of speed.

In our example, one could measure or simulate at 65 MPH the improvement in fuel consumption caused by moving from a baseline aerodynamic package to a new aerodynamic package. Next, one could measure or simulate the reduction in fuel consumption caused by slowing the baseline truck from 65 MPH to 60 MPH. Unfortunately, the two improvements cannot be simply added together to determine the benefit caused by both improving aerodynamics and lowering vehicle speed. A more aerodynamic truck will have a lower drag force, and therefore it will not benefit from lower speed to the same extent as a higher drag truck. There are two correct paths to determine the benefit of combining these two technologies, and one path that gives the wrong answer:

1. Correct: first simulate the benefit of improved aerodynamics at 65 MPH, and then calculate the benefit of lower speed, using the new, lower coefficient of drag (Cd) value. These two improvements can be added together.

2. Correct: first calculate the benefit of lowering speed from 65 to 60 MPH, and then determine the benefit of improved aerodynamics at 60 MPH. These two benefits can be added together.

3. Incorrect: calculate the benefit of improved aerodynamics at 65 MPH and calculate the benefit of lower speed using the baseline Cd. These two benefits are not fully additive.

Note that changes in drag coefficient and speed may result in a change in required engine power that is different from the fuel economy benefit that is realized. For example, a given set of changes might reduce the power requirement by 30 percent. If all things remain equal, a reduction in power required should translate directly into a 30 percent fuel savings. However, if the engine then has to operate at a less efficient point on its map, the overall fuel savings might be less, for example only 28 percent. Conversely, if the changes in vehicle power demand put the engine at a more efficient point on its operating map, the fuel savings will be larger than the reduction in power demand. The simulation technique used in this project accounts for these situations.

Some technologies tend to interfere with each other's performance. This interference may be so large that one would not consider combining the two technologies. An example of this is a combination of low temperature EGR and a bottoming cycle or a turbocompound system. Low temperature EGR by itself reduces fuel consumption, but if it is combined with a system that extracts energy from the exhaust, the two technologies work against each other. Low temperature EGR reduces the exhaust stream temperature, which will lower the performance of a turbocompound system or a bottoming cycle. Thus, the benefits of low temperature EGR and either turbocompound or a bottoming cycle cannot be added together. Similarly, turbocompound and a bottoming cycle cannot be combined without substantially degrading the performance of one of these systems. Because both systems work to extract energy from the exhaust, they cannot be added together to provide a benefit even close to the sum of the two individual benefits.

Method of Estimating Cost of Technology Packages

For each of the technology combinations listed in Table 9, TIAX developed net cost estimates from direct published quotes and pricing guidelines such as those published by the EPA SmartWay program. Net hardware costs in this context include system and component costs, as well as applicable credits in instances where the use of a particular technology would reduce other component or system costs. For example, the entire cost of lightweight tires is not added to the cost of a truck because the lightweight tire purchase is partially offset by the avoided cost of standard tires.

When more than one value was found, the estimated cost was calculated by averaging all values. Key reference sources for most of the cost estimations are listed in Appendix C. Input from industry experts was also incorporated, particularly when the technologies were not currently available for purchase. Cost assessments were based on the assumption of reasonable volume production for the Class 8 line haul truck industry and corresponding market penetration.

> ***Once costs for individual technologies were developed, TIAX integrated these values to arrive at cost estimates for the technology packages modeled by SwRI. Total package costs were calculated based on the assumption that for each tractor equipped with new technologies, three trailers would need to be equipped.***

For certain pre-commercial technologies (such as bottoming cycle), the estimated costs were developed from a typical bill of materials assuming design and development costs would be fully amortized. Once costs for individual technologies were developed, TIAX integrated these values to arrive at cost estimates for the technology packages modeled by SwRI. Total package costs were calculated based on the assumption that for each tractor equipped with new technologies, three trailers would need to be equipped. This was based on the industry average ratio of existing in-use trailers to tractors. Because the packages included technologies affecting different aspects of the vehicle (engine, transmission, aerodynamics, etc.), in most cases the costs were additive. However, there were some cases (e.g., hybridization combined with electric-turbo-compounding) for which double-counting had to be avoided to arrive at an estimated system cost. TIAX addressed these situations by developing a bill of materials for each technology package, and from this bill of materials duplicative components were removed. All of the technology packages were compared to the 2007 baseline (Package 1).

As described above, rough cost estimates were developed for each option to gauge the relative cost-effectiveness of employing one CO_2 reduction technology versus another. This task was performed using available information on incremental system and component hardware costs. TIAX obtained incremental system and component hardware costs as retail costs. In the case of two technologies – bottoming cycle and hybridization – costs were calculated as incremental factory manufacturing cost to truck and engine manufacturers. For these two technologies, the impact on the retail price of the trucks from a consumer perspective was then estimated by applying a factor of 2.0 representing “Retail Price Equivalent” (RPE). The basis for this factor is a series of U.S. Department of Energy reports published on hybrid electric and automotive fuel cell system manufacturing cost. Although these reports are based on the light-duty automotive sector, we assume that roughly the same market dynamics apply to the heavy-duty vehicle manufacturing sector (i.e., many of the same Tier One suppliers serve both light-duty and heavy-duty original equipment manufacturers (OEMs), and have high-volume manufacturing and relatively low margins). Therefore, the 2.0 factor is a reasonable factor for estimating RPE for heavy-duty vehicle technologies. The ratio of retail price to ex-factory cost was taken at 2.0 assuming that for these line haul packages, first tier suppliers would provide most components to the OEM truck builder. A lower ratio would be appropriate only if all the technology components were manufactured from raw materials by the OEM.

The retail price equivalent includes:

- Actual cost of materials, parts and assembly labor, including facilities, factory tooling (amortized), equipment maintenance, depreciation cost of operating capital and utilities, and other process costs

- Factory overhead or mark-up of the OEM and/or Tier One supplier includes items such as warranty, research and development, engineering, depreciation, legal, marketing and sales, corporate overhead, retirement and health benefits, accounting, shipping and distribution, corporate taxes, and dealer support

- Dealer discount or mark-up

- Profit

TIAX's cost estimates attempt to capture all costs to the manufacturer of incorporating new technologies, and include an estimate of cost impact at the consumer level as reflected in the purchase price of a new vehicle.

All costs are presented in 2007 U.S. dollars and assume the subject technologies will be manufactured in a highly competitive environment using flexible and lean manufacturing methods. Costs are estimated for the year 2012 and beyond assuming that each manufacturer will produce between 2,000 and 10,000 units per year, thereby achieving full economies of scale. Importantly, TIAX did not assume future cost reductions due to currently unknown advances in either technology design or manufacturing – future costs reflect fully learned, high-volume production of current technology designs. To the extent that basic science advances in design or manufacturing do occur, future costs may be lower than estimated. To the extent that development may require additional features or improvements to achieve the expected performance with adequate reliability and durability, future costs may be higher than estimated.

Method of Cost-Benefit Analysis

As described above, for each of the technology packages an incremental and retail price equivalent cost was determined and is presented in the cost results section of Chapter 3. Using the incremental vehicle costs and operations & maintenance (O&M) costs, the net cost of ownership was calculated for each of the technology packages. This analysis takes into account the savings realized through reduced fuel use over two time periods: (1) a 15-year time horizon; and (2) a three-year time horizon.[12] The 15-year vehicle life is a good proxy for determining societal benefit from adopting a new technology, and hence may be used to justify regulation. However, experience suggests that truck operator use a far shorter time horizon in making their vehicle purchase decisions. The basic elements of these calculations are described below. A more detailed description of the cost-benefit analysis is provided in Appendix C.

The TIAX analysis weighs the fuel savings against capital costs and any change in the yearly maintenance cost, such as impacts on brake maintenance, major overhaul intervals and other operation and maintenance costs. Future costs and benefits are discounted at a rate of 7 percent per year. The 7 percent figure has been used in regulations such as the EPA's Tier 2 [1999] and Heavy-Duty Vehicle Regulations [1997]. Cost of ownership is defined as follows:

$$\text{Cost of ownership} = (\text{Capital Cost}) - \Sigma(\text{Fuel saved} - \text{O\&M})/(1+r)^t$$

Where r is the discount rate (7 percent), t is the age of the vehicle, and the fuel savings and O&M costs are expressed in dollars per year, and are summed (Σ) over either a three-year or a fifteen-year time horizon. A negative cost of ownership implies that a given technology saves the buyer money.

The fuel savings accrued over the life of the vehicle, and hence ownership costs, are very sensitive to a truck's annual mileage, which varies as a function of vehicle age. This age dependence was estimated using data from the

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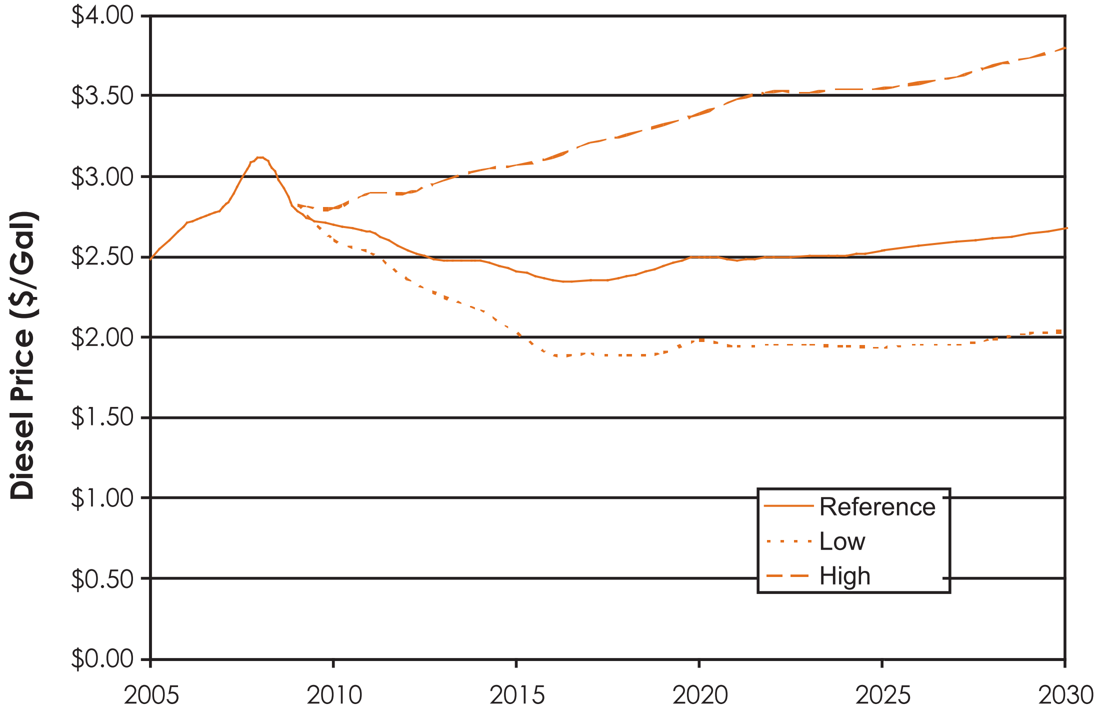
[12] The 15-year vehicle life is a good proxy for determining societal benefit from adopting a new technology. However, experience suggests that truck operator use a far shorter time horizon in making their vehicle purchase decisions . Several industry sources have suggested payback periods of 18 to 24 months to justify an investment in fuel saving technology. There may be extreme cases where fleets run tractors for a 15-year period, however, this would be extremely rare. Over the road operators typically run 4 years and then sell or trade the vehicle. Because of this an owner of a heavy-duty long haul truck will not realize a cost benefit from introduction of technologies that have a payback period longer than 2 years, even though over the life of the vehicle the technologies could be cost effective. Thus, without regulation or subsidies, many of the technologies evaluated would not likely be introduced into the market.

2002 Vehicle Inventory and Use Survey [VIUS 2002], a wide-ranging survey of the commercial trucking industry; additional confirmation was provided by discussions with industry stakeholders. Over the first three to four years of the vehicle life, trucks operate in long-haul service, which is characterized by upwards of 100,000 miles traveled per year, primarily, long-range trips (a radius greater than several hundred miles), and travel primarily over interstate highways at highway speeds. This type of duty-cycle typically dominates the first five to seven years of a tractor's life. As trucks age, they tend to migrate into local and regional applications, and a growing fraction get retired from service altogether. Regional operators tend to drive much shorter distances (on the order of 50,000 miles per year); operate within a confined region; and travel a significant number of miles in urban or exurban areas at lower speeds with more frequent stops. The median age of trucks in regional operation is on the order of 18 to 20 years. In sum, the long-haul portion of a truck's service life accounts for 60 percent to 70 percent of the total tractor-trailer fuel use [VIUS 2002].

The cost of ownership calculations account for this age dependence by treating mileage as a function of age. In the case of calculations over a 3-year time horizon, mileage is assumed to remain constant at 120,000 miles per year. Over a 15-year time horizon, the annual mileage for a typical truck on long-haul duty cycles declines dramatically

FIGURE 9 2008 EIA LONG-TERM ENERGY OUTLOOK DIESEL PRICE SCENARIOS



to less than 20,000 miles per year[13]. Our cost of ownership analysis focuses only on the long-haul portion of a truck's service life. This means that fuel savings accrued during regional operation are not accounted for. These unaccounted for savings from regional service may be significant for certain technologies that were considered, such as hybrids; but fairly small for others, such as aerodynamic improvements or 60 MPH speed governors. In addition, the long trailer or double trailer configurations that were considered are not feasible for regional haulers. A more detailed discussion of this issue is presented in Appendix D.

Fuel price scenarios were a critical element of the analysis of fuel-savings benefits, and we relied on DOE Energy Information Administration (EIA) forecasts from their 2008 long-term energy outlook, shown in Figure 9 [EIA 2008]. As additional forecasts are released by EIA these can be readily used to update the analysis.

Fleet-Wide Emissions Benefit Analysis Methodology

The last step in the heavy-duty CO_2 analysis was to estimate the amount of fuel and CO_2 reduced through widespread adoption of heavy-duty technologies into the U.S. fleet of heavy-duty Class 8 long-haul trucks. This work is described below.

Fleet Characterization

To project the fleet-wide effect of the technology packages described above, TIAX developed a spreadsheet-based heavy-duty fleet model. The fleet model uses estimates of new truck sales, scrap rates, vehicle miles traveled, and fuel economy to develop a bottom-up estimate of fleet-wide characteristics, such as fleet fuel use, fleet VMT, and truck population. The model uses historical data to estimate the size, composition, duty cycle, and turnover of the long-haul truck fleet, and an estimated fleet growth rate to extrapolate these data into the future. Because many of the technology packages under consideration, such as moderate and aggressive improvements to aerodynamics, apply specifically to "box" or "van" type trailers, the fleet model calculates benefits only for those tractor-trailer ("combination") trucks that primarily tow van trailers. Based on data from the 2002 Vehicle Inventory and Use Survey [VIUS 2002], we estimate that these types of trailers account for 60 percent of the combination truck population. In addition, miles accrued on a regional duty-cycle were not included. A more detailed description of the data sources and assumptions used to develop this fleet model is included in Appendix D.

Annual mileage assumptions are based on appropriate averages for tractor-trailers as a function of vehicle age, including the effects of vehicle age on annual mileage, the migration to regional service, and the retirement rate of older trucks. When the combined impacts of declining VMT, increasing vehicle retirements, and discounted future cash flow are considered, fuel savings beyond 15 years are negligible, so the calculations assume a 15 year truck lifetime.

Fleet Model Validation

In order to validate the fleet model, TIAX compared the bottom-up fleet model estimates for fuel use with actual historical data. Figure 10 illustrates how the modeled fuel consumption in millions of gallons per year for all Class 8

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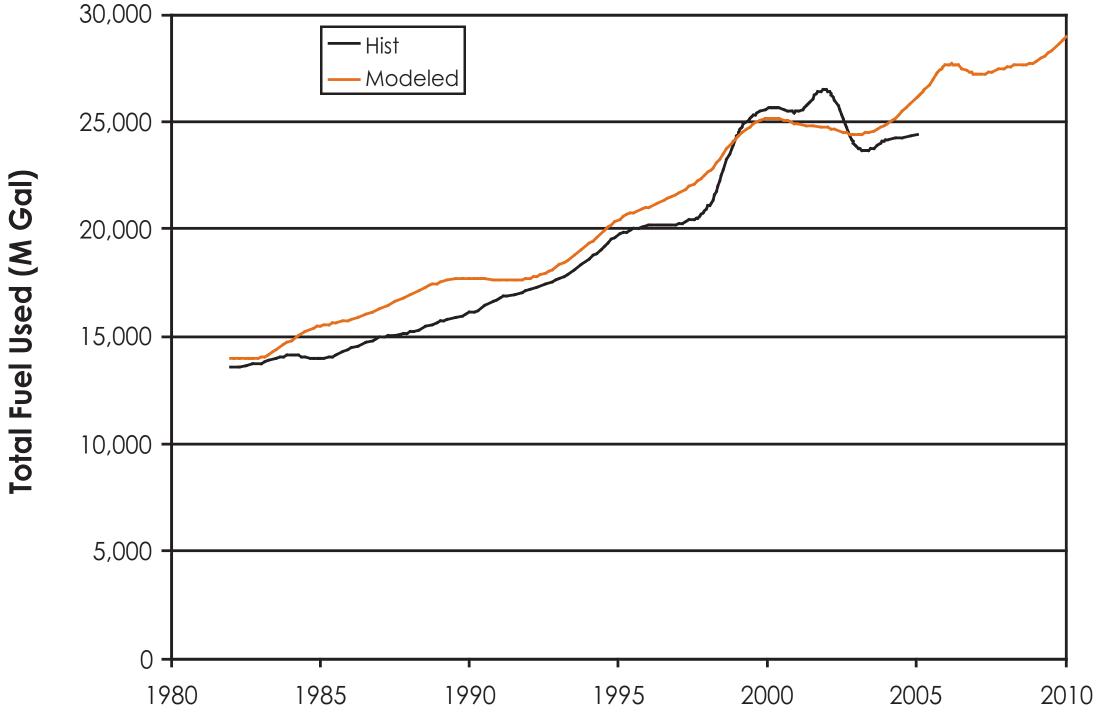
[13] This mileage estimate represents long-haul miles for a typical truck. Included in this "average" data is the fact that some trucks are scrapped, and that most miles are driven on regional routes. Analysis of a regional duty-cycle was not conducted for this study.

combination trucks compares with historical data from the Federal Highway Administration [TEDB 2007]. As shown, the modeled data match fairly well with the historical data.[14] Given that the focus of this study was on the effect of technology introduction on the future fleet, the bottom-up model is a reasonable foundation on which to estimate the impact of technology penetration on a fleet-wide basis.

Technology Adoption Methodology

The next step in the fleet assessment was to estimate the adoption rate of specific technologies into the U.S. fleet. The TIAX fleet model estimates rates of adoption as a function of an individual technology's cost, benefit, and year of introduction. Within the model, each individual technology is allowed to compete based on net present value (NPV) against other similar technologies for market share within the fleet. Because it is impractical to individually model every combination of technologies that could be adopted, it was necessary to disaggregate the results of simulation modeling results generated by SwRI and make reasonable judgments about what combinations of technologies would plausibly be adopted by the fleet. For example, the fleet model is structured to allow only a single waste heat recovery technology (e.g., bottoming cycle,

FIGURE
10 **HISTORICAL VS. MODELED FUEL USE IN U.S. COMBINATION CLASS 8 TRUCKS**



Source: TEDB 2007

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[14] The primary source of inconsistency between the modeled and actual data comes from differences between historical and modeled estimates of the truck population. Historical data have inherent inaccuracies, particularly with regard to truck sales and scrappage, and as a result, truck populations fluctuate from year to year to a greater extent than is predicted by the data, primarily due to macroeconomic factors such as economic growth.

TABLE 10 **SCENARIO SUMMARY**

SCENARIO A – MAXIMUM TECHNOLOGY ADOPTION SCENARIO	SCENARIO B – MARKET DRIVEN
Net-positive NPV technologies are fully adopted	3-year payback is used to estimate market-based technology adoption
EIA Ref & High fuel price cases	EIA Ref & High fuel price cases
7-year ramp for new technologies	10-year ramp for new technologies

These scenarios and the assumptions used to develop them are described in more detail in Appendix D.

turbo-compounding, or advanced EGR) to be adopted into a vehicle at a time. This approach is described in greater detail in Appendix D.

Two different technology adoption scenarios were modeled for this analysis. The two scenarios differ in the assumed rate of adoption. These were compared against a reference case scenario in which the fuel economy and CO_2 emissions of the fleet remains constant, but the fleet grows at a constant rate. The first scenario ("Scenario A") assumes maximum penetration of fuel consumption and CO_2 reducing technologies into the heavy-duty long-haul fleet. Under this scenario, the most aggressive technologies that have a negative cost of ownership over a fifteen-year time horizon are fully adopted, subject to technology availability and assumed production capacity technologies. The second technology adoption scenario ("Scenario B") uses a rational buyer model in which the rate of adoption for a given technology is calculated as a function of time to payback.

Both technology introduction scenarios assume that it takes several years for new technologies to ramp up to full production and fully penetrate new vehicle sales. This phase-in period is based on EIA projections for the introduction of incremental vehicle technology options in the light-duty sector [EIA 2008], which typically require five to 10 years to fully penetrate new vehicle sales. The model also assumes that technology costs decline from the time of technology introduction until full deployment. For mature technologies, such as moderate aerodynamic improvements (Package 2), a faster phase-in period with no cost reduction is assumed. In the case of Rocky Mountain doubles, implementation will require buy-in from many stakeholders, regulatory changes in a number of states, and some infrastructure changes. In addition, they are not feasible in urban areas and may not offer benefits for less-than-truckload (LTL) carriers. Due to these complexities, we have capped the maximum market penetration at 60 percent of the long-haul tractor-trailer fleet, or approximately 40 percent of the entire tractor-trailer fleet.

The next chapter provides results for the fuel consumption and CO_2 emissions reduction analysis, cost analysis, cost-benefit analysis, and fleet-wide CO_2 and fuel consumption reduction analysis.

Overview

The methods described in Chapter 2 and detailed in Appendices A through C were used to predict the CO_2 emissions and fuel consumption impacts and costs associated with deploying a variety of automotive technologies on future heavy-duty long-haul trucks. In this report, fuel consumption results, CO_2 emissions, and costs are presented for one representative long-haul vehicle.

A total of 32 engine, vehicle, drivetrain, load reducing technologies, and truck configuration or speed modifications were evaluated in this analysis to quantify associated CO_2 reduction potential. Currently available heavy-duty engine technologies such as aerodynamic drag improvements and improved tires were evaluated as well as more advanced technologies such as bottoming cycle and variable valve actuation. Turbocompounding and hybridization were also considered. The emissions and fuel consumption benefits of individual technologies and packages or combinations of these technologies were analyzed. The study relies on a systems analysis approach that avoids the “double counting” that could occur by simply combining the emission reduction benefits of individual technologies. In some cases, benefits of individual technologies are not additive. Examples of this issue are presented in the method overview to illustrate the impact of a systems analysis approach on emission benefit projections.

This chapter first discusses the CO_2 reduction potential of individual technologies. Vehicle results are presented in miles per gallon and ton mile per gallon (ton MPG) units, but all percent changes are presented in terms of percent change in total fuel consumed (gallons per mile) and percent change in total CO_2 emissions. In many cases, MPG and percent savings in fuel consumption are plotted on the same graph, with MPG on the left hand y-axis, and percent reduction in fuel consumption and CO_2 emissions presented on the right hand y-axis. The overall CO_2 impact, retail price equivalent, and net cost estimates are then presented for each of the technology packages evaluated. The technologies evaluated in this study are described in Appendix A. Finally, an analysis of the potential CO_2 and fuel consumption reductions that could be achieved in the U.S. fleet of heavy-duty long-haul vehicles with introduction of technologies to reduce fuel consumption and emissions is presented. Appendix D describes in detail the method used to estimate the fleet-wide fuel consumption and CO_2 emissions reductions associated with the introduction of heavy-duty vehicle technologies.

Emission and Fuel Consumption Reduction Results

As described in Chapter 2, the emission benefit analysis conducted for this study involved several steps. The first step was a literature survey and engineering assessment to identify potential CO_2 reduction technologies and assess their likely emission reduction capabilities. These included both stand-alone technologies and those appropriate for inclusion with other technologies in combination packages. Second, an actual vehicle model from the U.S. fleet was selected to represent a Class 8 long-haul truck. Third, SwRI’s RAPTOR and commercially available GT-POWER software were used to assess the CO_2 and fuel consumption impacts of individual or combinations of technologies for the Class 8 long-haul truck. A systems analysis was subsequently conducted for the selected technology packages. The results of these analyses are presented in the following sections.

CO_2 Emission and Fuel Consumption Reduction Potential for Individual Technologies

Individual technologies were first evaluated to aid in the selection of options for inclusion in technology packages or combinations which were then subjected to more in-depth evaluation using GT-POWER and RAPTOR simulation code (as described in the method section). This initial evaluation was designed to provide approximate CO_2 reduction estimates for use solely in the context of selecting technologies for further investigation. Because this first part of the study served a preliminary screening function, no technologies were evaluated using full model simulations. All technologies were evaluated using data from published literature.

From the published literature, individual technologies were found to produce a broad range of projected CO_2 reductions. The analysis indicates that evolutionary engine and drivetrain technologies generally provide reductions ranging from 1 to 10 percent. The technologies offering the most significant CO_2 reductions are aerodynamic drag improvements (10 percent to 26 percent), bottoming cycle (up to 10 percent with the configuration evaluated), trailer weight and size increases (up to 30 percent), and reduced road speed (up to 10 percent). Other technologies showing significant reduction potential over a long-haul cycle include mechanical and electrical turbocompounding and hybridization.

The only GHG considered in this study was CO_2. Some evaluation was done of the potential to reduce hydrofluorocarbons (HFCs) from air conditioning systems and also to reduce CO_2 emissions associated with the additional load of running the air conditioning system. However, these approaches were not analyzed in the simulation modeling given the small relative contribution of HFC leakage, and given the fact that CO_2 emissions from powering air conditioning represent a very small share of heavy-duty vehicle CO_2 emissions from fuel consumption. For the same reason, approaches to reduce N2O or other tailpipe GHG emissions from long-haul trucks were not evaluated. Finally, approaches to reducing carbon black from long-haul trucks were not evaluated as part of this study.

Modeled CO_2 Emission and Fuel Consumption Reduction Potential for Individual Technologies and Technology Combinations

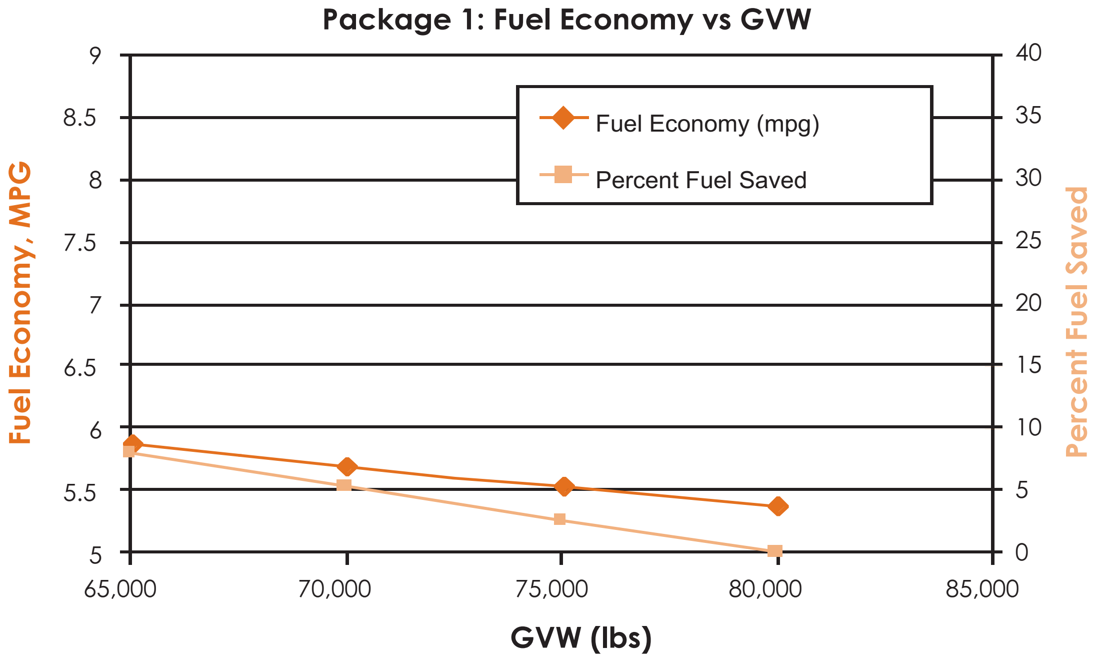
The following sections describe the results of the simulation modeling conducted by SwRI.

Package 1 – Baseline Vehicle and Weight Reduction Evaluation

Figure 11 shows the fuel economy of the baseline vehicle in MPG. The baseline vehicle on the highway duty cycle described in Chapter 2 achieved a fuel economy of 5.4 MPG. In addition to evaluating the baseline vehicle fuel economy in this simulation, the potential to reduce fuel consumption and CO_2 emissions by reducing weight from the baseline weight of 80,000 pounds was evaluated. For the purpose of this calculation, the weight reduction could come either from carrying lighter freight or from a reduction in the empty weight of the truck. If the vehicle mass is reduced to 65,000 pounds, the fuel economy improves to 5.9 MPG. The fuel savings and CO_2 reduction on the baseline vehicle amount to about 0.5% per 1,000 pounds of mass reduction. This result suggests that efforts to reduce the empty vehicle mass will have only a modest benefit on fuel economy, at least on a long haul route.

FIGURE

11 BASELINE VEHICLE FUEL ECONOMY AND SENSITIVITY TO VEHICLE MASS



Package 2 – 2007 SmartWay Aerodynamic Improvement Plus Wide Base Single Tires

Figure 12 shows the fuel economy of the truck with tractor and trailer aerodynamic improvements that comply with the 2007 EPA SmartWay program. The rolling resistance has been reduced to represent the improvement offered by the best currently available wide base single tires. Figure 12 also shows the sensitivity of the results to changes in aerodynamic drag. If the value of the coefficient of drag (Cd) = 0.6298 at the far right of the plot is taken, this result shows the fuel savings from the rolling resistance reduction alone. All results shown in this figure are for a vehicle mass of 80,000 pounds.

The results presented in Figure 12 show that the reduction in rolling resistance coefficient from 0.0068 to 0.0055 provides a fuel savings and CO_2 gas reduction of 6 percent, while the reduction in the coefficient of drag from 0.6298 to 0.5 provides an additional 8 percent fuel savings. The combined benefit due to aerodynamics and rolling resistance improvements of Package 2 is a 14 percent fuel savings and CO_2 reduction. This package represents the best currently available aerodynamic and rolling resistance technology. This package also includes a diesel powered APU to provide power for heating, cooling, and electrical accessories while the truck is shut off (also called “hotel load”). The benefits of reducing the idling of the truck engine were calculated separately, and are shown in Table 19.

FIGURE 12 RESULTS FROM MODERATE DRAG AND ROLLING RESISTANCE REDUCTION

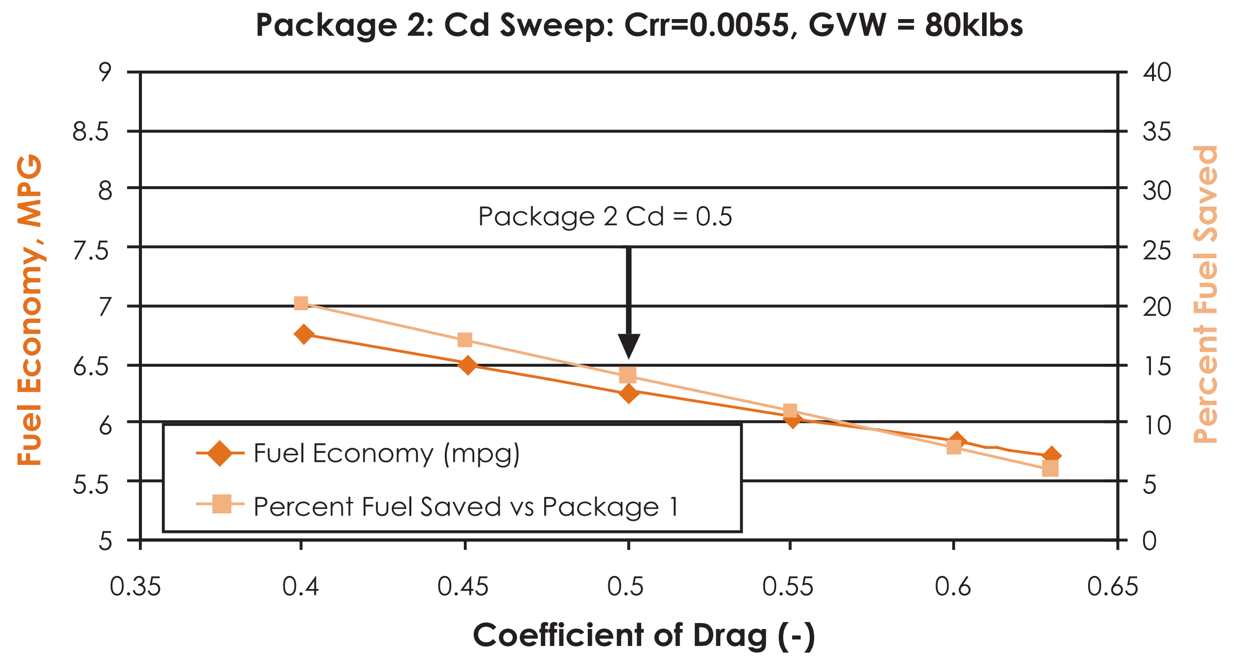
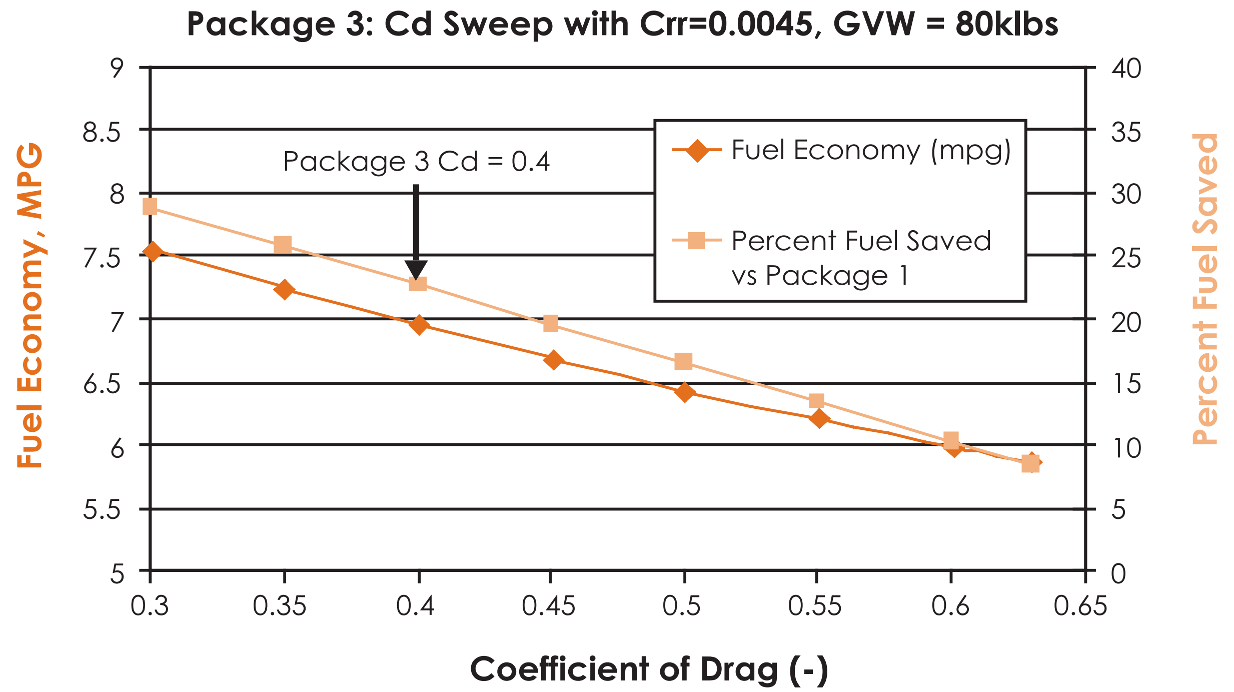


FIGURE 13 RESULTS FROM ADVANCED DRAG AND ROLLING RESISTANCE REDUCTION



Package 3 – Advanced Aerodynamic Drag and Rolling Resistance Improvements

The next set of technologies evaluated included advanced technologies to improve aerodynamic drag such as sealing the gap between the cab and the trailer and significantly improved tires with lower rolling resistance.

Package 3 includes a reduction in the aerodynamic drag coefficient to 0.4 from the original value of 0.63 (Package 1) and 0.5 (Package 2). Interviews with engineers responsible for aerodynamic design of trucks indicate that a reduction in drag coefficient to 0.4 will not be possible by adding new features to current designs of trucks and trailers. A complete redesign of the truck/trailer combination vehicle will probably be required, and this is likely to have significant impacts on the operational characteristics of the vehicle. The coefficient of rolling resistance is reduced to 0.0045 from the original value of 0.0068 and the Package 2 value of 0.0055. Figure 13 shows the results in terms of MPG and percent fuel savings for an 80,000 pound truck.

The results presented in Figure 13 show that the reduction in rolling resistance coefficient from 0.0068 to 0.0045 provides a fuel savings and CO_2 reduction of 10.6 percent, while the reduction in aerodynamic drag coefficient from 0.63 to 0.4 provides an additional 14.1 percent fuel savings. The overall benefit of Package 3 is a 24.7 percent fuel savings and CO_2 reduction compared to the baseline truck.

It is interesting to note that a long/heavy combination vehicle with Package 3 characteristics and a GCW of 140,000 pounds provides nearly identical fuel consumption and GHG emissions to a Package 1 (baseline) vehicle at 80,000 pounds GCW. In other words, a turnpike double combination vehicle with Package 3 aerodynamic and rolling resistance features can deliver nearly twice the freight of a baseline Package 1 vehicle at approximately equal fuel consumption.

This package also includes a diesel powered APU which reduces idling. The emissions and fuel consumption reductions associated with reduced idling for the package are shown in Table 19.

Package 4 – Hybrid Electric System

Two hybrid systems were evaluated in combination with Package 3, the aggressive aero and rolling resistance improvements. Each version of the hybrid drivetrain also includes electrification of engine accessories, which is assumed to reduce total engine-driven accessory load from 5 kW to 3 kW. The first hybrid system to be evaluated was a series hybrid. Despite several iterations in the modeling effort, favorable fuel consumption results were not achieved. There is a commercial series hybrid system under development, but the control strategy being developed for this system was not available for evaluation during the time of this study.

Results are presented here for the second hybrid system evaluated - a parallel hybrid similar in concept to those used in many passenger cars. A 50 kW motor/generator was installed along with a battery storage system. At first, the motor/generator was coupled to the engine flywheel. Later, the motor/generator was moved to the transmission input, on the other side of the clutch. This allowed the engine to be disconnected from the driveline during regenerative braking, increasing the energy that can be recaptured. Putting the electric motor on the transmission side of the clutch also allows the truck to move at low speeds on electric power alone.

TABLE 11 **PARALLEL HYBRID SYSTEM MODELING RESULTS**

VEHICLE MASS	BASELINE MPG (PKG. 3)	HYBRID MPG	% REDUCTION IN FUEL CONSUMPTION & CO_2 EMISSIONS
65,000 lbs.	7.95	8.46	**6.0%**
80,000 lbs.	7.18	7.61	**5.6%**
140,000 lbs.	**5.20**	**5.50**	**5.5%**

TABLE 12 **MECHANICAL TURBOCOMPOUND SYSTEM RESULTS**

VEHICLE MASS	BASELINE MPG (PKG. 3)	MECHANICAL TURBO-COMPOUND MPG	% REDUCTION IN FUEL CONSUMPTION & CO_2 EMISSIONS
65,000 lbs.	7.95	8.15	**2.4%**
80,000 lbs.	7.18	7.36	**2.4%**
140,000 lbs.	**5.20**	**5.35**	**2.9%**

TABLE 13 **ELECTRICAL TURBOCOMPOUND SYSTEM RESULTS**

VEHICLE MASS	BASELINE MPG (PKG. 3)	ELECTRICAL TURBO-COMPOUND MPG	% REDUCTION IN FUEL CONSUMPTION & CO_2 EMISSIONS
65,000 lbs.	7.95	8.30	**4.2%**
80,000 lbs.	7.18	7.49	**4.1%**
140,000 lbs.	**5.20**	**5.43**	**4.2%**

Initially, a 10 kW-hr battery pack was used with the parallel hybrid system. Later, a 4 kW-hr battery pack was simulated in order to reduce the system cost and weight. The fuel economy penalty for the smaller battery pack was small, so the smaller 4 kW-hr battery pack was chosen for the final configuration. The results for the final parallel hybrid system are shown in Table 11.

If the hybrid system is applied to the baseline Package 1 vehicle, the savings will be 5.5 percent. In addition to the improvement in fuel economy during the long-haul drive cycle, a hybrid can be used to handle hotel loads such as heating, cooling, and electricity when the vehicle is stationary. Instead of idling all night, the engine can be run for a few minutes each hour to charge the battery pack. This hotel load reduction nearly doubles the fuel consumption benefit of hybridizing a tractor-trailer, increasing its fuel consumption benefit to 10 percent. An APU is not included in Package 4, since the battery storage of power takes care of idle reduction.

Package 5 – Mechanical Turbocompound

A mechanical turbocompound system was added to the GT-POWER engine model in this study. The vehicle model includes Package 3, the aggressive aero and rolling resistance package. Variable valve actuation was added to help provide more exhaust energy to the power turbine within the constraints of maintaining the efficiency of the base engine. The results are summarized in Table 12.

The performance of a turbocompound system is sensitive to engine load, so better results are achieved with heaver truck combinations. If mechanical turbocompound is applied to the 80,000 pound baseline Package 1 vehicle, the reduction in fuel consumption and GHG emissions will be 2.9 percent.

Package 6 – Electric Turbocompound

An electrical turbocompound system was added to the GT-POWER engine model in this study. The vehicle model includes Package 3, the aggressive aero and rolling resistance package. Electric turbocompound also includes electrification of engine accessories, which is assumed to reduce the total accessory load from 5 kW to 3 kW. Variable valve actuation was added to help provide more exhaust energy to the power turbine within the constraints of maintaining the efficiency of the base engine. The results are summarized in Table 13.

Most of the difference in performance between the mechanical and electrical turbocompound is due to the conversion of accessories from mechanical to electric drive. Another factor is that the electric generator allows the power turbine to run at a speed independent of the engine crankshaft speed, which slightly improves the efficiency of the turbocompound system itself. If electric turbocompound is applied to the baseline Package 1 vehicle, the fuel and CO_2 savings will be 4.2 percent.

Package 7 – Variable Valve Actuation

VVA was explored in the GT-POWER engine model within the constraints of maintaining the baseline diesel combustion cycle. Maintaining both baseline EGR flow rates and high load air/fuel ratios was also a requirement, in order to maintain baseline NOx and PM emissions. Within these constraints, only about a 1 percent reduction in fuel consumption could be obtained with VVA, regardless of the performance of the baseline vehicle. One percent reductions were found both against a Package 1 baseline, as well as against a Package 3 baseline. This result is consistent with results achieved by diesel engine manufacturers who have evaluated VVA. Alternative engine cycles were not evaluated because there is not enough information available in the literature to allow modeling of the alternative cycles.

Package 8 – Bottoming Cycle

This technology is described in Appendix A along with a detailed description of the modeling approach used in this study. The GT-POWER model of the engine was combined with a spreadsheet-based bottoming cycle model to create an engine fuel map. In the vehicle model, the bottoming cycle fuel map was combined with the aggressive aero and rolling resistance improvements of Package 3. In addition, the bottoming cycle includes electric accessories, since the bottoming cycle expander is connected to a generator. As in other packages using electrically powered accessories, it was assumed that the accessory power demand on the engine is reduced from an average of 5 kW to 3 kW.

Because the bottoming cycle relies on EGR and exhaust heat, anything that reduces exhaust temperature will reduce the performance of the bottoming cycle. Therefore, features such as turbocompound, VVA, and low temperature EGR should not be combined with a bottoming cycle. These features were all evaluated in combination with a bottoming cycle, and they all provided reduced bottoming cycle performance. The performance of the bottoming cycle with an otherwise standard engine is summarized in Table 14.

The bottoming cycle provides a significant improvement in fuel consumption and CO_2 emissions, and the sensitivity to vehicle load is small. However, see Appendix A regarding difficulties that are expected in developing a bottoming cycle for heavy truck applications. Also, the bottoming cycle will probably have to be combined with a hybrid system in order to address the fact that the bottoming cycle does not have acceptable transient response (see Appendix A). For the cost / benefit analysis performed later, a reduced scope bottoming cycle was used. The maximum power of the system was limited from 57 kW down to 30 kW, and more conservative assumptions were made for the condenser outlet pressure and temperature. With these more conservative assumptions, the fuel savings on the drive cycle dropped from 10 percent to 8 percent. The more conservative bottoming cycle was not put into the vehicle model for a complete evaluation, and thus the 8 percent figure is an approximation based on spreadsheet analysis of the bottoming cycle performance.

Package 9 – Longer / Heavier Vehicle Combinations

If trucks are able to carry a higher volume or heavier weight of freight, there is potential to carry the same total

TABLE 14 BOTTOMING CYCLE SYSTEM RESULTS

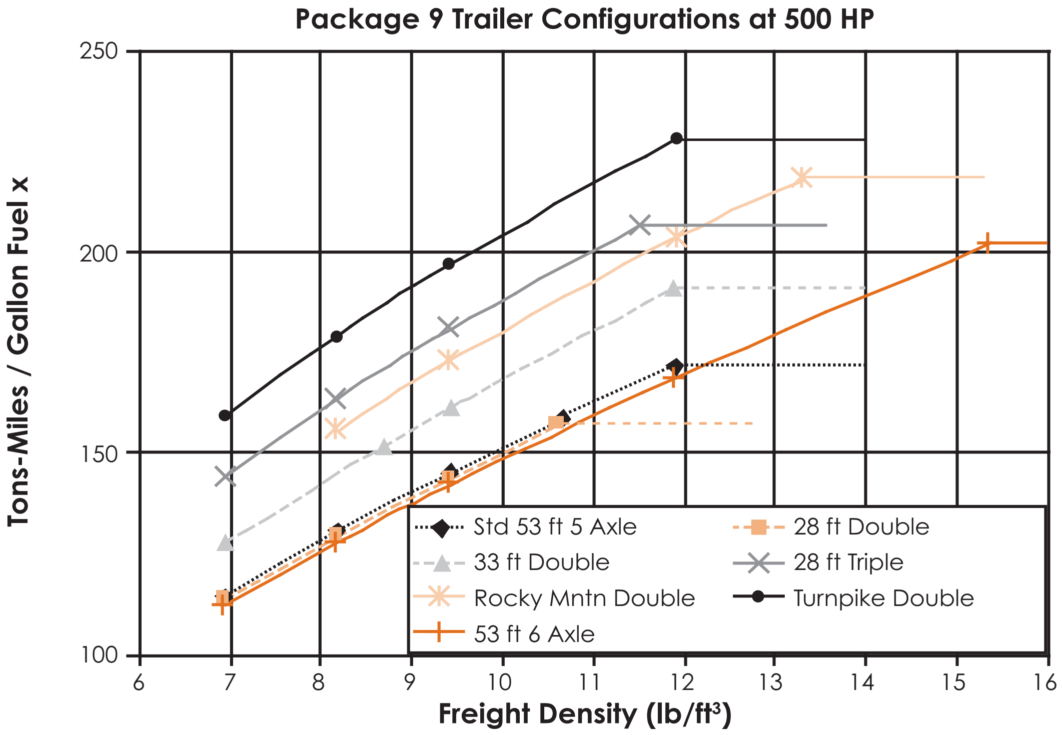
VEHICLE MASS	BASELINE MPG (PKG. 3)	BOTTOMING CYCLE MPG	% REDUCTION IN FUEL CONSUMPTION & CO_2 EMISSIONS
65,000 lbs.	7.95	8.83	**9.9%**
80,000 lbs.	7.18	8.01	**10.3%**
140,000 lbs.	**5.20**	**5.84**	**10.3%**

TABLE 15 SUMMARY OF LONGER / HEAVIER VEHICLES EVALUATED

VEHICLE CONFIGURATION	EMPTY WEIGHT (LB)	MAX. GCW (LB)	FREIGHT VOLUME (FT^3)	VOLUME INCREASE (%)	MAX. FREIGHT (LB)	LOAD INCREASE (%)
Baseline 53' trailer	32,000	80,000	4040	N/A	48,000	**N/A**
53 Foot Three Axle Trailer	35,000	97,000	4040	0	62,000	**29.2%**
28 Foot Doubles	35,500	80,000	4200	4%	44,500	**-7.3%**
33 Foot Doubles	37,000	97,000	4950	22.5%	60,000	**25%**
Rocky Mountain Doubles	43,500	120,000	5750	42.3%	76,500	**59%**
28 Foot Triples	47,500	120,000	6300	56%	72,500	**51%**
Turnpike Doubles	**50,000**	**137,000**	**7300**	**81%**	**87,000**	**81%**

FIGURE

14 **EFFICIENCIES FOR LONGER/HEAVIER VEHICLES EVALUATED**



amount of freight using less fuel. There is also a potential of reducing the number of trucks required to move a given amount of freight. This offers the potential for congestion reduction in locations where truck traffic makes up a substantial portion of overall traffic.

This study evaluated a number of existing truck combinations that are used in some areas of the United States today. This approach allowed for a direct comparison with the efficiency of existing vehicle combinations. The range of vehicle combinations modeled is presented in Table 15. All of the combinations listed in the table use a standard tandem axle tractor. The Rocky Mountain double is a combination of a 48 foot trailer with a second 28 foot trailer. A turnpike double is a combination of two 48 foot trailers. In the summer of 2009, the Canadian province of Ontario started a one year pilot program to evaluate the safety and performance of combination vehicles consisting of one tractor with two 53 foot trailers. This 53 foot double is larger than any vehicle evaluated in this study.

Some of the trailer configurations shown in Table 15 provide significant increases in either freight volume, maximum freight load, or both. Each configuration was evaluated on the long-haul vehicle cycle described in Chapter 2 with a range of freight densities (and thus a range in GCW). Results are presented in terms of ton-miles per gallon in Figure 14 for varying freight densities. On the sloped portion of each curve, the vehicle load is volume limited. In other words, the trailer is completely full, without reaching the maximum allowed vehicle weight. The fuel efficiency of each truck combination increases with increasing freight density, since more tons of freight fit into the truck as freight density increases. Adding weight to the truck causes MPG to go down, but the ton-MPG values increase. This is a paradox when considering truck operations. A more heavily loaded or longer/heavier truck will get worse fuel economy (lower MPG) and a higher fuel consumption (gallons per mile), but it will be more efficient (higher ton-miles per gallon, or lower gallons per ton-mile). This is because a larger/heavier or more fully loaded truck can do more work for a given amount of fuel.

The flat part of each curve in Figure 14 represents the situation where the vehicle is at maximum GCW. As the freight density increases beyond the point where maximum GCW is reached, the truck weight remains constant, but it is no longer possible to completely fill the trailer. Figure 14 shows that there is significant potential to increase truck efficiency by going to longer / heavier vehicle combinations with all of the configurations evaluated.

The reductions in fuel consumption and CO_2 for longer/heavier vehicles run over the duty cycle selected for this study as compared with the baseline vehicle are summarized in Table 16. The combination that shows the greatest benefit on the cycle was the turnpike double, which provides a 25 to 28 percent reduction in fuel consumption and CO_2 emissions, depending on freight density. Rocky Mountain doubles and 28 foot triples both achieved the second best reduction, with a range of 17 to 21 percent improvement. The triples are more favorable for low density freight, while the Rocky Mountain doubles are better with high density freight. The widely used 28 foot double combination is slightly worse than the standard 53 foot trailer baseline. It appears that operational convenience for the shipper is the only reason to use this configuration. Adding an extra axle to a standard size 53 foot trailer provides a slight penalty with low density freight, but for high density freight there is a 15.3 percent benefit.

One issue that results from increases in vehicle weight or size is a reduction in the vehicle power/weight ratio. As

TABLE 16 CO_2 AND FUEL CONSUMPTION REDUCTIONS FOR LONGER / HEAVIER VEHICLES

VEHICLE CONFIGURATION	TON-MPG @ 6.93 LB/FT^3 DENSITY	% REDUCTION IN FUEL AND CO_2	TON-MPG @ MAX. GCW	% REDUCTION IN FUEL AND CO_2
Baseline 53' trailer	115	N/A	172	**N/A**
53 Foot Three Axle Trailer	113	-1.7%	203	**15.3%**
28 Foot Doubles	114	-0.9%	158	**-8.1%**
33 Foot Doubles	128	10%	192	**10%**
Rocky Mountain Doubles	138	16%	218	**21%**
28 Foot Triples	145	21%	207	**17%**
Turnpike Doubles	**160**	**28%**	**229**	**25%**

TABLE
17 RESULTS FOR LONGER/HEAVIER TRUCKS WITH HIGHER ENGINE POWER

VEHICLE CONFIGURATION	BASELINE ENGINE POWER (HP)	HIGHER ENGINE POWER (HP)	% FUEL AND CO_2 PENALTY FOR HIGHER POWER	
			6.93 LB/FT^3	HI DENSITY
53 Foot Three Axle Trailer	500	600	3.6%	3.8%
Turnpike Doubles	500	700	6.7%	4.8%

the power/weight ratio declines, the vehicle can suffer from a decrease in acceleration capability, and the speed that can be maintained on hills will decline. This could result in trucks becoming more of an impediment to light vehicle traffic, particularly where there are limited opportunities for cars to pass slower trucks. One way to deal with this issue is to increase engine power to make up for some or all of the loss in power/weight ratio.

A concern with higher engine power is the potential to reduce the fuel savings achieved by the longer / heavier vehicle combination. To address this concern, SwRI modeled two vehicle configurations with higher engine power. The two selected configurations were the three axle 53 foot trailer and the turnpike doubles. For the three axle 50 foot trailer, the maximum GCW is 97,000 pounds, a 21 percent increase over the standard 80,000 pounds. The GT-POWER engine model was scaled up to 600 horsepower (HP), 20 percent more than the standard model, to match the higher GCW.

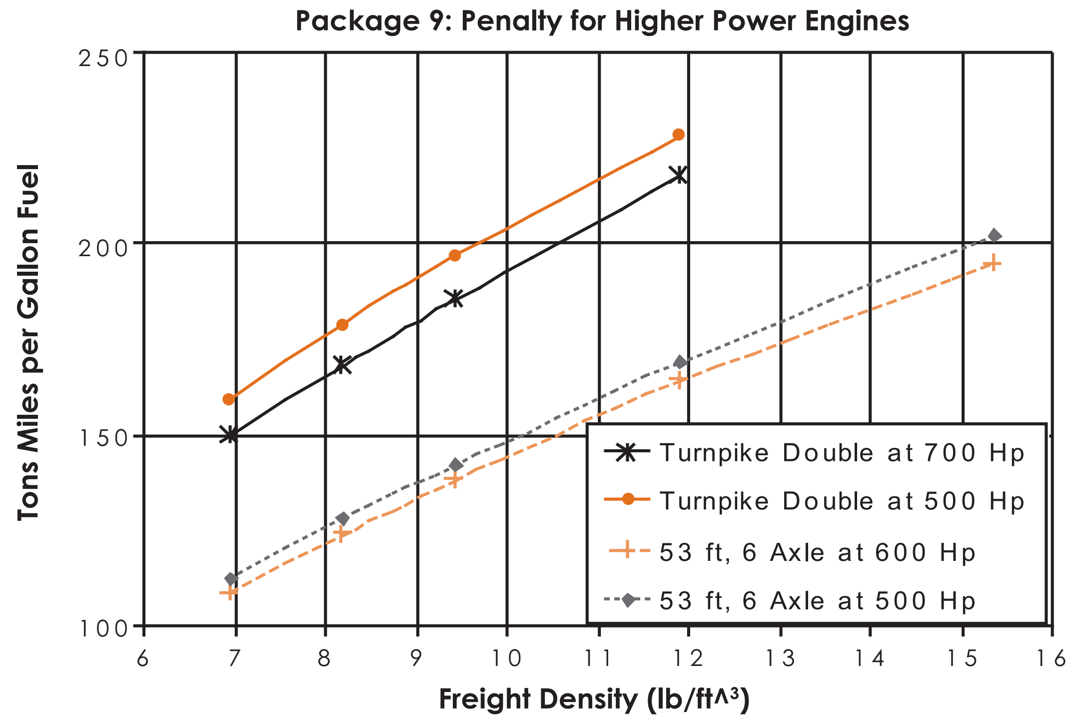
For the turnpike doubles vehicle combination, the maximum GCW is 137,000 pounds, a 71 percent increase over the standard GCW of 80,000 pounds. It is not practical to increase engine power to this extent, so the GT-POWER engine model was scaled up to 700 HP, a 40 percent increase. This power level will still suffer some acceleration and hill climbing performance penalty compared to the baseline truck. Table 17 shows the effect of increased power on the efficiency of the two truck combinations.

Increasing engine power to limit vehicle performance losses does increase fuel consumption, but the penalty is much smaller than the benefit in overall fuel consumption that can be achieved with larger / heavier vehicle combinations. Even if power/weight ratios are held constant to maintain vehicle performance, the longer/heavier vehicles do save fuel and reduce CO_2 emissions. The results in Table 17 can also be used to evaluate the potential savings of engine downsizing. A downsizing of 20 percent results in less than a 4 percent fuel savings, and even a 40 percent downsizing only saves 5 to 6 percent.

The fuel consumption and CO_2 emissions increases that result from moving to higher horsepower engines are depicted graphically in Figure 15. In Figure 15 the results for the longer/heavier trucks with the baseline engine are shown in the solid orange and dotted gray lines. The results for the longer/heavier trucks with the higher horsepower engines are shown in the solid gray and dotted orange lines. The graph in Figure 15 shows the penalty in ton miles of freight moved per gallon of fuel that results from

FIGURE 15

RESULTS FOR LONGER / HEAVIER TRUCKS WITH INCREASED ENGINE POWER AT DIFFERING FREIGHT DENSITIES



the use of higher horsepower engines in these two trucks. In this analysis, several simulations using the longer/heavier truck settings were run over the drive cycle with several different assumptions about freight densities.

All of the results reported in this section for longer/heavier combination vehicles include Package 3 rolling and aerodynamic features as a baseline. If long/heavy combinations are built using baseline Package 1 technology, the fuel economy (MPG) and ton-miles per gallon numbers will be lower, and fuel consumption will be higher. However, the basic relationships regarding percent fuel and CO_2 saved for each variation compared to the baseline will be almost identical. All of the longer heavier truck configurations assume the use of additional safety features in the cost analysis, including anti lock disk brakes, vision assists, and stability controls.

Package 10 – Lower Road Speed

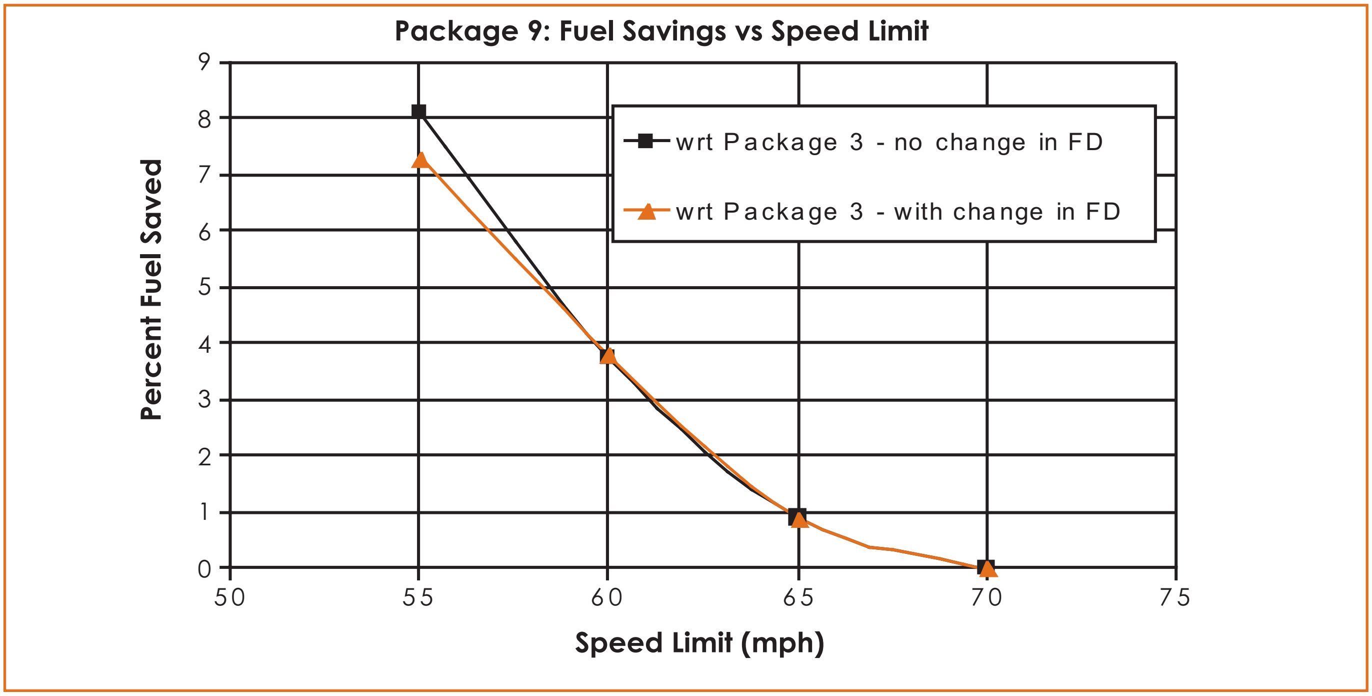
Road speed reduction is a well known method for improving vehicle fuel economy. In this study, the standard engine model was combined with the vehicle model of Package 3, the aggressive aero and rolling resistance improvements. The drive cycle was modified by imposing a range of speed limits onto the cycle: no limit, 65 MPH, 60 MPH, and 55 MPH. As the cruise road speed is reduced, the vehicle specification normally will be changed to match. The rear axle ratio will be increased numerically to provide higher engine RPM at a given road speed. This is done to maintain the ability to climb a grade without the need for downshifting.

The study looked at two scenarios for lower road speed. In the first scenario, the road speeds were reduced, but no vehicle changes were made to compensate. In the second scenario, the final drive ratio (rear axle ratio) was modified to match the reduction in road speed for the 60 and 55 MPH routes. This is done to maintain the match between engine and road speeds. Figure 16 summarizes the results for the two vehicle scenarios.

On the driving cycle evaluated, this package yielded only a 1 percent benefit for reducing road speed to 65 MPH. This is because the drive cycle includes only a small portion at speeds above 65 MPH. The step down from 65 to 60 MPH provides an additional improvement of almost 3 percent. This step influences all of the cruise portions of the drive cycle. There is no evident penalty for matching the final drive ratio to maintain engine RPM at 60 MPH. At 55 MPH, fuel consumption improves by an additional 3.6 to 4.4 percent from 60 MPH. The overall fuel savings caused by reducing maximum route speed from 70 MPH to 55 MPH is 7.3 to 8.1 percent, depending on whether or not the final drive ratio is adjusted. The improvement would be larger if the baseline vehicle route included more time at 70 miles per hour.

Overall, a benefit of about 0.7 percent per MPH speed reduction is seen. This is less than the 1 percent per MPH figure often quoted in the literature. There are two reasons

FIGURE 16 IMPACT OF LOWER ROAD SPEED ON FUEL CONSUMPTION



that may explain the discrepancy. The figures quoted in the literature are normally for steady state operation on level ground. The drive cycle used in this study included some suburban type driving at speeds below 55 MPH, as well as some driving on grades. The differences in drive cycle will tend to reduce the benefit of lower road speed. In addition, the vehicle model used for this study included aggressive aerodynamic and rolling resistance reductions, which also tends to reduce the benefit of lower road speed. If the same analysis was performed on a Package 1 baseline vehicle, the benefit is expected to be closer to 0.9 percent per MPH speed reduction.

One issue must be dealt with in considering lower road speed limits for trucks. As the speed limit goes down, the travel time will increase. If the lower speed only applies to a small portion of the route, the increase in travel time will be minimal. This is the case for situations where traffic or road conditions often limit the truck's speed to a value below the road speed limit. Vehicles in this situation will also experience little savings in fuel. However, on long-haul routes where traffic density is relatively low, a reduction in cruise speed will translate directly into increased trip time. These vehicles will experience a significant fuel consumption and CO_2 reduction. To some extent, this will also mean that more trucks are required to deliver a given amount of freight over a given distance per day. Overly aggressive road speed limits will increase truck traffic density and will impede traffic flow in areas where passing is difficult.

The drive cycle used in this study included some suburban type driving at speeds below 55 MPH, as well as some driving on grades. The differences in drive cycle will tend to reduce the benefit of lower road speed. In addition, the vehicle model used for this study included aggressive aerodynamic and rolling resistance reductions, which also tends to reduce the benefit of lower road speed.

Package 11 – Advanced EGR Cooling

By reducing the temperature of the EGR stream, lower NOx can be achieved. If NOx is held constant, the timing can be advanced to improve engine's brake specific fuel consumption in g/kW-hr. In this study, an auxiliary EGR cooler was added to the GT-POWER engine model to drop the EGR stream temperature by about 60° C from the standard engine values. For example, at 1400 RPM and 60 percent load, the EGR temperature coming out of the EGR cooler was reduced from 167° C down to 104° C. In a vehicle, this would be accomplished with a secondary EGR-to-air heat exchanger at the front of the vehicle. There are some significant practical concerns about condensation that need to be resolved in order to use this approach in vehicle applications. It is important not to have condensation coming into the turbocharger compressor inlet, in order to avoid corrosion of the compressor wheel.

According to the GT-POWER engine model, fuel consumption and CO_2 emissions can be reduced by 1 to 1.2 percent using advanced EGR. The performance advantage is largest for lightly loaded trucks, since the brake specific fuel consumption benefit is largest at light loads.

Because low temperature EGR going into the cylinder also reduces the temperature of the exhaust coming out of the cylinder, low temperature EGR does not work well with systems that extract energy from the exhaust, such as turbocompound or a bottoming cycle.

Maximum Reduction Combinations

To determine the potential benefit of combining several vehicle and engine technologies, additional simulation runs were made using selected combinations of technologies evaluated in Packages 1 through 11. Three combinations were selected for the maximum reduction packages. One combination was built to evaluate the maximum benefit that could be obtained within the constraint of current vehicle size and weight limits. This becomes Package 12. The second configuration added a longer / heavier vehicle combination to Package 12 and substituted electric turbocompound for the bottoming cycle to reduce cost and technical risk. This is Package 13. Finally, a version was created to represent a maximum technology version of Package 13. This is Package 14, which also includes the bottoming cycle and the longer / heavier vehicle combination.

Several of the technologies evaluated did not provide enough benefit to be included in the maximum technology combinations. The Package 2 aerodynamic and rolling resistance improvements were left out in favor of the more advanced Package 3, which is expected to be available by 2017. Mechanical turbocompound (Package 5) was left out in favor of the higher performing electric turbocompound. Advanced EGR (Package 11) was not used, because it reduced the energy available for the exhaust energy recovery systems.

VVA was used in combination with turbocompound, but not with the bottoming cycle. This is due to the tendency to reduce exhaust temperature available to the bottoming cycle system. VVA is used with the turbocompound system, where it can be tuned to help the overall system performance. From Package 10 (reduced road speed) a 60 mph speed was chosen. The 60 MPH speed was selected to minimize the potential increase in traffic density that a low road speed could cause, as well as to minimize the disruption to normal traffic flow that slow-moving trucks would cause. In addition, the 60 MPH speed would not require such a large re-gearing of the trucks as would be necessary with the 55 MPH option. These three combination packages, along with the modeling results are provided below.

Package 12 – Standard Trailer Maximum Technology Combination

Package 12 includes the following technologies in a standard 80,000 pound GCW, standard 53 foot trailer vehicle combination:

- Aggressive aero and rolling resistance reduction, without the APU (idle reduction is achieved using the hybrid system) (Package 3)
- Parallel electric hybrid drivetrain with electrified accessories (Package 4)
- Bottoming cycle (Package 8)
- 60 MPH road speed governor (Package 10)

This configuration represents the maximum improvement in fuel consumption and CO_2 emissions that is technically feasible within the 2017 timeframe of the study for a standard 53 foot, 80,000 pound GCW truck. This conclusion was based on conversations with experts in industry, Steering Committee members, and experts at national laboratories.

Package 13 – Longer/Heavier Truck Lower Cost Maximum Technology Combination

Package 13 includes a Rocky Mountain double vehicle configuration. The Rocky Mountain double is a combination of one 48 foot trailer with one 28 foot trailer. This approach is more conservative than the use of turnpike doubles (two 48 foot trailers), but the safety and political implications of going to such a large vehicle combination could be a considerable challenge. Package 13 includes:

- Aggressive aero and rolling resistance reduction, without the APU (idle reduction is achieved using the hybrid system) (Package 3)
- Parallel electric hybrid drivetrain with electrified accessories (Package 4)
- Turbocompound (Package 6)
- VVA (Package 7)
- Rocky Mountain doubles (Package 9)
- 60 MPH road speed governor (Package 10)

This configuration represents the maximum improvement in fuel consumption and CO_2 emissions in the 2017 timeframe at a lower cost and technical risk than package 14.

Package 14 – Longer/Heavier Truck Higher Cost Maximum Technology Combination

This configuration is a modification of Package 13. The bottoming cycle is regarded as having a high technical risk, higher cost, and having other difficult issues to overcome before a production feasible system could be made available. Package 14 replaces the electric turbocompound system and VVA modeled in package 13 with a bottoming cycle. Otherwise, Package 14 matches 13:

- Aggressive aero and rolling resistance reduction, without the APU (idle reduction is achieved using the hybrid system) (Package 3)
- Parallel electric hybrid drivetrain with electrified accessories (Package 4)
- Bottoming cycle (Package 8)
- Rocky Mountain doubles (Package 9)
- 60 MPH road speed governor (Package 10)

This configuration represents the maximum improvement in fuel consumption and CO_2 emissions that can be achieved with reasonable technical risk within the 2017 time frame of the study. This package is basically a long/heavy version of Package 12.

TABLE

18 MAXIMUM TECHNOLOGY COMBINATION MODELING RESULTS

TECHNOLOGY PACKAGE	FUEL SAVINGS / CO_2 REDUCTION	
	GROSSED OUT DENSITY > 13.3 LB/FT³	CUBED OUT DENSITY = 8.17 LB/FT³
12 – 53 foot trailer, bottoming cycle	36.9%	**38.6%**
13 – Turnpike doubles, electric turbocompound	46.9%	**44.2%**
14 – Turnpike doubles, bottoming cycle	50%	47.5%

Maximum Technology Combination Results

Fuel and CO_2 savings have been calculated for vehicles operating at several freight densities. First, calculations were run at a freight density of 8.17 lb/ft^3. This density results in a GCW of 65,000 pounds in a standard 53 foot tractor/trailer combination vehicle. The results were also calculated for freight density greater than 13.3 lb/ft^3, which will result in all vehicles evaluated running at their maximum legal GCW. The low density calculation is typical of “cubed out” applications (the trailer is completely full with low density freight, and the vehicle is under the GCW limit), while the high density calculation represents “grossed out’ applications (the trailer is not filled, but the truck is at the GCW limit). The results are summarized in Table 18.

Package 14 provides the best results of all the simulated packages. Package 14 includes both the longer / heavier vehicle combination and a bottoming cycle. According to the simulation results, a maximum of 50 percent reduction in fuel consumption and CO_2 emissions is possible. Package 13, which substitutes a less technically risky turbocompound system for the bottoming cycle, also provides impressive results, only 3.1 to 3.3 points less than Package 14. Package 12 offers less potential benefit, but the overall savings are still over 36 percent compared to the baseline vehicle. These results make it clear that by combining several fuel saving technologies, a dramatic improvement in vehicle fuel efficiency is possible.

Estimate of Fuel Consumption and Emissions Reduced from Idling Reduction

The potential reductions in CO_2 and fuel consumption that result from the use of idling reduction technologies were not estimated as part of the simulation modeling, since the drive cycle used in the simulation modeling did not include an idle segment. Idling reduction benefits were calculated outside of the simulation model. Total gallons of fuel used on road per year per truck was estimated to be 20,000 gallons of fuel, a typical value for a long haul truck that travels 120,000 miles per year. Next, the idle fuel consumption rate in gallons per hour was multiplied by an assumed 1,800 hours of idling per year per truck. For the purposes of this analysis, the total fuel consumption per truck per year was calculated by summing the fuel consumed annually during idling and driving. The reduction in fuel consumption attributable to idling reduction technologies

TABLE 19 FUEL CONSUMPTION AND CO_2 REDUCTIONS FROM IDLE REDUCTION TECHNOLOGIES

PACKAGE #	DESCRIPTION	% FUEL CONSUMPTION AND CO_2 REDUCTION COMPARED TO PACKAGE 1	% FUEL CONSUMPTION AND CO_2 REDUCTION COMPARED TO PACKAGE 1 - WITH IDLING REDUCTION
2	SmartWay	14%	17.8%
3	Advanced SmartWay	24.7%	27.9%
4	Hybrid	5.5%	10%
12	Maximum reduction combination 1	36.9% grossed out 38.6% cubed out	38.6% grossed out 40.2% cubed out
13	Maximum reduction combination 2	46.9% grossed out 44.2% cubed out	48.7% grossed out 46.2% cubed out
14	Maximum reduction combination 3	50% grossed out 47.5% cubed out	50.6% grossed out 48.3% cubed out

was estimated by assuming all of the 1,800 hours of engine idling would be replaced by a more efficient auxiliary power unit or, in the case of the hybrid, a battery that is periodically recharged by the engine. The results of this analysis are shown in Table 19. The table shows results only for those technology packages that include idle reduction technology such as a diesel APU or a hybrid system. These are packages 2, 3, 4, 12, 13, and 14.

The next sections describe the results of the package cost and cost benefit analyses conducted by TIAX using the SwRI modeled results for the different technology combinations. In addition, results from the TIAX fleet model analysis estimating the amount of fuel use and CO_2 emissions that could be avoided with introduction of heavy-duty efficiency improving technologies is provided.

Cost Analysis

As described in Chapter 2, TIAX estimated costs for each of the technology packages modeled by SwRI. Appendix B provides detailed costs for components in each of the technology packages and Appendix C presents a detailed explanation of how these costs were developed. Table 20 presents a summary of these costs.

TABLE 20 SUMMARY OF COSTS ESTIMATED FOR EACH OF THE TECHNOLOGY PACKAGES

PACKAGE	PACKAGE NAME	DESCRIPTION	CAPITAL COST		INTRO YEAR	O&M	COMMENTS
			INITIAL	FLOOR		($/MI)	
1	Baseline	–	–	–	–	–	–
2	SmartWay	Improved aero & tires, idle reduction, and advanced lubricants	$22,930	$22,930	2009	($0.004)	Cost information from EPA's SmartWay website. Costs are based on three trailers and one tractor and include an APU.
3	Advanced SmartWay	Generation 2 aero & tires	$66,530	$44,730	2015	($0.004)	Estimates based on feedback from experts and TIAX cost estimates
4	HEV	Parallel hybrid	$35,000	$23,000	2012	($0.006)	Based on component-level estimates with assumed RPE of 2.0, and early-stage demonstration vehicles.
5	Mech. Turbo (MTC)	Includes VVA	$5,300	$2,650	2010	($0.003)	Based on industry experience with small turbines
6	Elec. Turbo (ETC)	Includes accessory electrificaiton & VVA	$13,100	$6,550	2012	($0.007)	Component-level estimates similar to those used for the HEV and mechanical turbocompounding.
7	VVA	Var. valve actuation	$600	$300	2009	$0.000	$50 incremental cost per cylinder
8	Bottoming Cycle (BC)	Steam cycle, ~30 kW	$30,200	$15,100	2015	($0.003)	TIAX bottom-up estimate based on prospective bill-of-materials and assumed RPE of 2.0.
9	Rocky Mt Double	48' trailer + 28' trailer	$25,000	$17,500	2015	($0.002)	TIAX estimate based on assumed engine, safety, and brake upgrades, and increased number of trailers.
10	60 MPH	60 MPH speed limit	$0	$0	2010	$0.000	Assumes no additional cost
11	Adv. EGR	Low-temp EGR system	$1,500	$750	2010	$0.000	Estimated cost of added cooling and pumps.
12	Max Tech, Std. trailer	SW2 + 60 MPH + HEV + BC	$117,330	$71,630	2015	($0.013)	Sum of individual packages
13	Low Cost Tech. Combination	SW2 + 60 MPH + HEV + ETC + RMD	$124,830	$80,380	2015	($0.012)	Sum of individual packages
14	Max Tech, Long trailer	SW2 + 60 MPH + HEV + BC + RMD	$142,330	$89,130	2015	($0.015)	Sum of individual packages

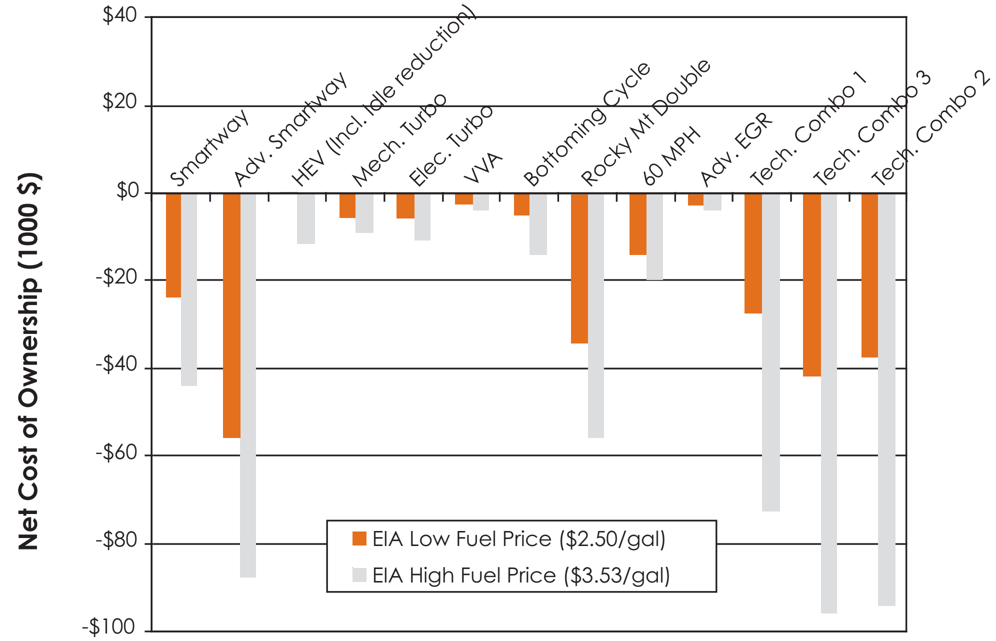
Cost Benefit Analysis

As described in Chapter 2, TIAX calculated the net cost of ownership over a 3 year and a 15 year time horizon. They assumed two fuel costs: 1) $2.50 per gallon of diesel fuel; and 2) $3.53 per gallon of diesel fuel. TIAX used a 7 percent discount rate for the analysis. Figure 17 summarizes the results of the cost benefit analysis for the 15 year ownership case assuming a $2.50 per gallon price of diesel fuel and a $3.53 per gallon price of diesel fuel. Negative numbers indicate a cost savings for the vehicle owner. As can be seen from Figure 17, at both $2.50 per gallon of diesel fuel and at $3.53 per gallon of diesel fuel, for 12 of the 13 technology packages, owners will recoup the entire incremental vehicle purchase price in fuel savings; the exception is the hybrid package when evaluated at $2.50 per gallon, which has a slightly positive lifetime cost of ownership.

The technology packages that provide the greatest savings over the 15 year period are Advanced SmartWay, Rocky Mountain double, and the three maximum technology combination packages shown at the far right of the graph.

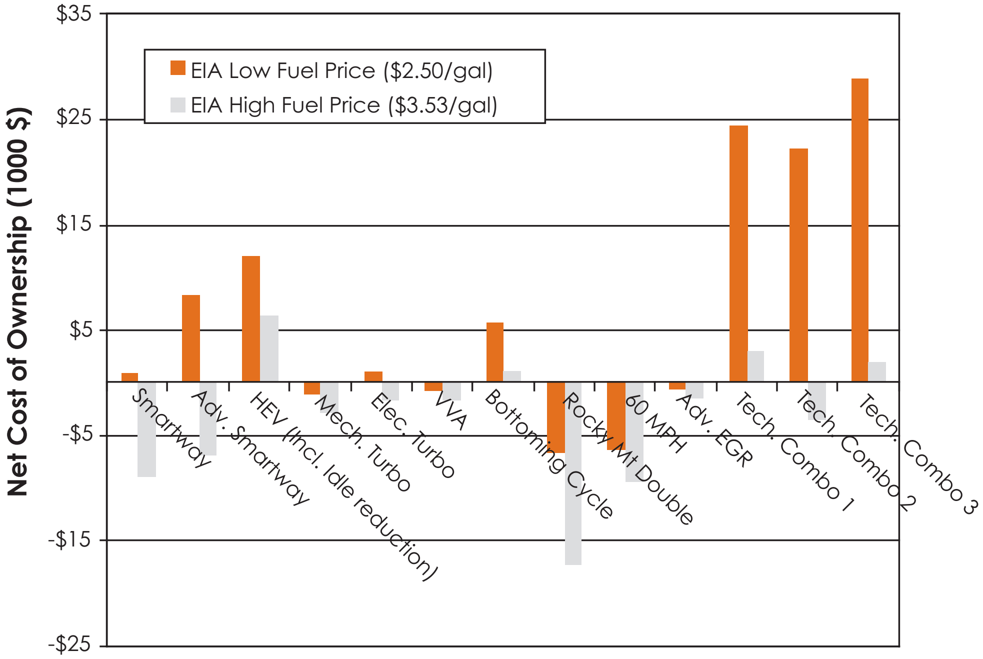
Figure 18 summarizes the results for the 3 year ownership scenario assuming both a cost of $2.50 per gallon of diesel and $3.53 per gallon of diesel. As can be seen from Figure 18, the net cost of ownership is much higher than in the 15 year case, since the vehicle owner recoups only the amount of money saved from lower fuel consumption over a period of 3 years instead of a 15 year period. Over a period of 3 years at $2.50 a gallon, 5 technology packages pay for themselves. The remaining 8 do not. The five include: mechanical turbocompounding, variable valve actuation, Rocky Mountain doubles, 60 MPH speed, and advanced EGR. In the 3 year net cost of ownership case at a diesel price of $3.53 per gallon, 9 technology packages are cost effective and 4 are not.

FIGURE 17 15 YEAR NET COST OF OWNERSHIP FOR TECHNOLOGY PACKAGES



FIGURE

18 3 YEAR NET COST OF OWNERSHIP FOR TECHNOLOGY PACKAGES



A more detailed discussion of these results is included in Appendix C.

Figure 19 depicts the relative benefits and costs of each of the evaluated technology packages for the 3 year and 15 year ownership period at $2.50 per gallon of diesel fuel. As this figure suggests, for both ownership scenarios, the technology packages span a broad range of reduction potential and costs. For example, in the three year cost of ownership scenario, packages providing CO_2 reductions from 2.5 percent to 28 percent encompass a net cost range from approximately negative $10,000 (i.e., net consumer savings) to positive $10,000. Clearly, a least-cost solution would favor the technology packages in the lower end of this cost range. Nevertheless, for purposes of this study, we have assumed a technology supply curve[1] that includes all of the evaluated technology packages. This allows for the fact that least-cost technologies may not be viable for some segments of the market and that vehicle manufacturers may therefore choose not to implement specific CO_2 reduction solutions across the entire vehicle class. For example, because approaches such as longer and heavier trailers or technologies such as turbocompounding may be limited to a subset of heavy-duty vehicles, a supply curve constructed solely on the basis of least-cost solutions may understate the actual cost of class-wide CO_2 reduction solutions. Including all of the evaluated technology packages in the development of the supply curve provides a more robust indication of likely class-wide impacts.

The diamonds in Figure 19 represent the CO_2 reduction supply curve for long-haul trucks assuming a

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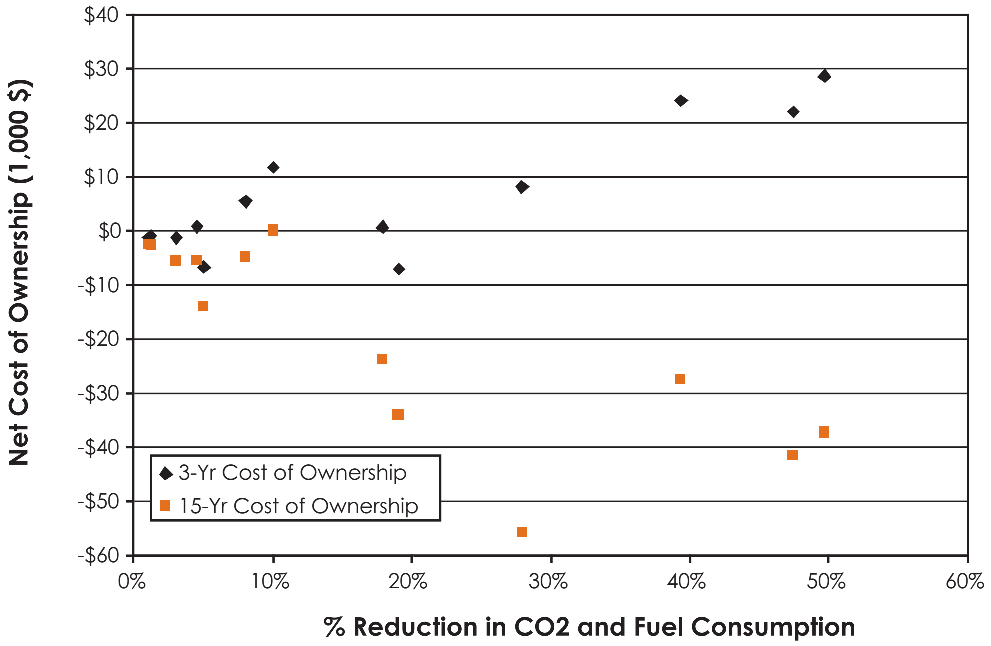
[1] A supply curve indicates the relationship between CO_2 emissions reduction potential and cost.

FIGURE 19 NET VEHICLE COSTS ASSUMING 3 AND 15 YEARS OF OWNERSHIP



3 year ownership period from the time of initial purchase. The net cost is equal to the additional purchase price of the truck minus the fuel cost savings over three years, discounted at 7 percent. Each point represents the net cost of ownership for a different technology or technology combination. Presumably, a rational fleet operator would adopt technologies that offer net negative ownership. As indicated, at least one technology provides CO_2 and fuel consumption reductions of about 20 percent are obtainable for a net negative cost (i.e., three year fuel savings exceed incremental technology costs). The figure also includes a second set of cost of ownership calculations to show the results of a sensitivity analysis in which the assumed time of ownership is 15 years rather than three. With the longer vehicle life (shown as squares in Figure 17), most technology packages reflect negative net costs. The package which fails to pay back over 15 years is the parallel hybrid system. The hybrid system can only be made to pay back in combination with other more cost-effective or with higher fuel costs; for example, it may interact synergistically with electrified waste-heat recovery systems, such as electric turbocompounding. The economics of the hybrid system are hampered both by the duty cycle used in the study, which offers only modest benefits; and battery replacement, which is assumed to be required every six years[2].

In the 15 year ownership scenario, estimated lifetime cost savings can be as high as $56,000 for a vehicle achieving approximately a 28 percent reduction in CO_2 and fuel consumption. Assuming a three year ownership scenario, costs are estimated to be $10,000 for the same level of emission reduction.

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[2] At this point, battery replacement intervals and strategy are highly speculative as there is not any operational data by which to judge.

Fleet-Wide Fuel Consumption and CO_2 Emissions Benefit Analysis

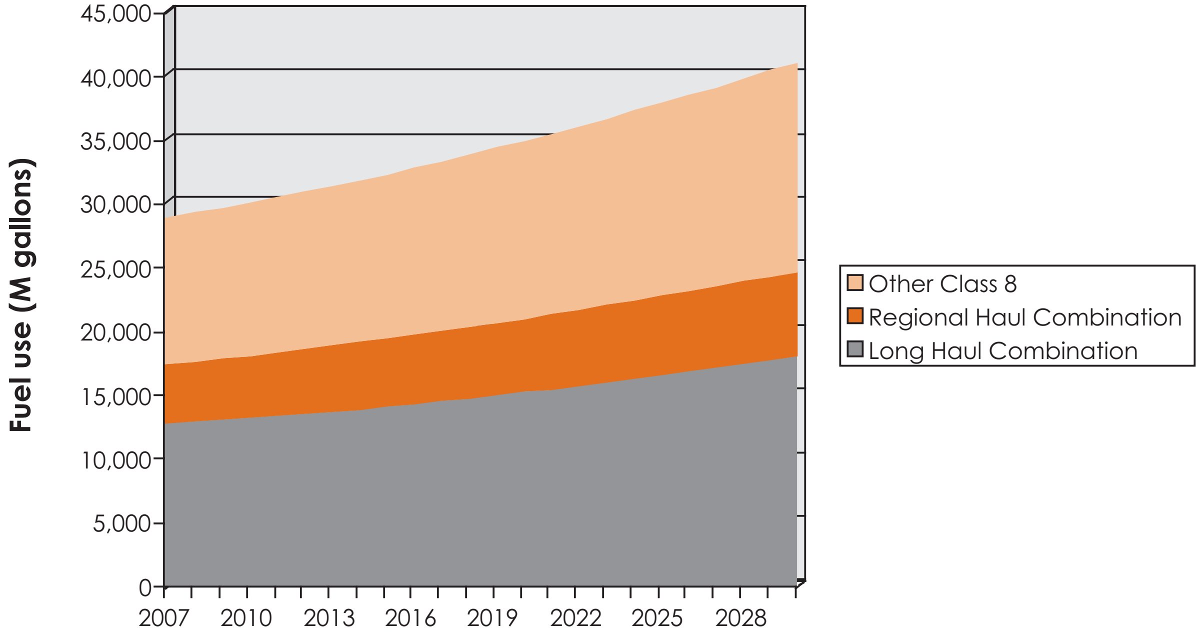
The last step in the study was to estimate the potential to reduce CO_2 emissions and fuel consumption in the U.S. heavy-duty long haul fleet from the introduction of existing and emerging technologies. A detailed discussion of these results, as well as fuel price sensitivity analysis, is included in Appendix D. TIAX conducted this analysis using a propriety fleet model. In the fleet model, technologies are adopted as they become cost effective.

The analysis includes that portion of the fuel consumed by long haul tractors hauling dry box van trailers. A breakdown of fuel use in different types of Class 8 trucks is shown in Figure 20 to illustrate the fraction of Class 8 fuel consumed in long haul tractor trailer trucks. As can be seen from the figure, approximately 45 percent of total Class 8 truck fuel is consumed in the long haul box trailer fleet segment – shown in the gray wedge. The TIAX fleet model focuses on this fleet segment because many of the technologies modeled by SwRI would not offer the same benefits over a regional duty cycle, and many aerodynamic devices cannot be implemented on irregularly shaped trailer bodies.

The red wedge shows the amount of fuel consumed annually by regional and local heavy-duty trucks hauling combination trucks. The yellow wedge represents the combined fuel use of all remaining combination trucks, such as flatbed or lowboy trailers.

In the next section, the TIAX analysis of potential CO_2 and fuel consumption reductions that could be realized with

FIGURE 20 BREAKDOWN OF FUEL CONSUMED IN CLASS 8 TRUCKS



introduction of efficiency improving technologies into the U.S. fleet of long haul combination vehicles is presented. Results for the analysis are shown for a 15 year payback case, a 3 year payback case, and a maximum technology penetration case.

Fleet Wide Analysis Assuming 15 Year Payback Requirement

Figure 21 depicts the total potential fuel and CO_2 emissions savings in the U.S. heavy-duty long-haul box trailer fleet, assuming penetration of technologies modeled by SwRI in this study. The analysis estimates the technology adoption that could occur over a 20 year timeframe, assuming that all technologies which offer a 15 year payback are fully adopted by the fleet. Each wedge in the graphic represents a different technology modeled by SwRI and the benefit associated with adoption of that technology into the U.S. heavy-duty long-haul fleet. The analysis does not assume that any existing vehicles are retrofitted with technologies, with the exception of a 60 MPH speed limit.[3] As such, the figure could underestimate the total potential emissions and fuel use avoided from heavy-duty technologies evaluated in this study.

In this scenario, by 2022, 30 percent of total U.S. heavy-duty long-haul combination truck CO_2 and fuel consumption could be avoided. By 2030, the fuel savings grows to 39 percent of the total for this fleet segment.

Fleet Wide Analysis Assuming 3 Year Payback Requirement

The second fleet-wide analysis evaluated the fuel consumption and CO_2 emission reductions that would be achieved using the assumptions described for Scenario B in Chapter 2. In this scenario, technologies are adopted by an increasing fraction of the fleet as the time to payback decreases; if the time to payback is three years, 50 percent of the fleet will adopt a technology. Figure 22 graphically presents the results of this scenario. In this case, fuel use and CO_2 emissions from the long-haul truck fleet are reduced by 11 percent, or by 1.8 billion gallons, by 2022 and by 3 billion gallons by 2030. In contrast to the 15 year payback scenario, the year-by-year fuel reductions projected in the 3 year payback case slow the growth in total fleet fuel use, but do not appreciably reduce consumption below present-day levels.

In both the scenarios described above, fleet fuel use begins to grow again starting in 2022 to 2024 due to the lack of new technology after 2017. This is due to the constraints of this study that required a design specification for technologies evaluated.

Fleet Wide Analysis Assuming Maximum Technology Case

In the maximum technology case, TIAX used a diesel price of $4.40 per gallon and a 15 year payback requirement. At this diesel price, all of the technologies evaluated by SwRI were adopted by the fleet model, resulting in CO_2 and fuel consumption reductions even greater than the 15 year payback case. In this case, 44 percent of U.S. long haul combination truck fuel use and CO_2 emissions were reduced in 2030. The higher fuel price allowed for the hybrid technology to be adopted into the fleet model.

Impact on Regional Heavy-Duty Trucks and Alternative Tractor-Trailer Configurations

As discussed in Chapter 2, our analysis focused on long-haul combination trucks. The fuel used by Class 8 long haul trucks represents a subset of total, lifetime Class 8

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[3] Speed governors are already widely deployed, but are typically fixed to a higher speed limit.

FIGURE 21

15 YEAR PAYBACK REQUIREMENT FLEET ANALYSIS

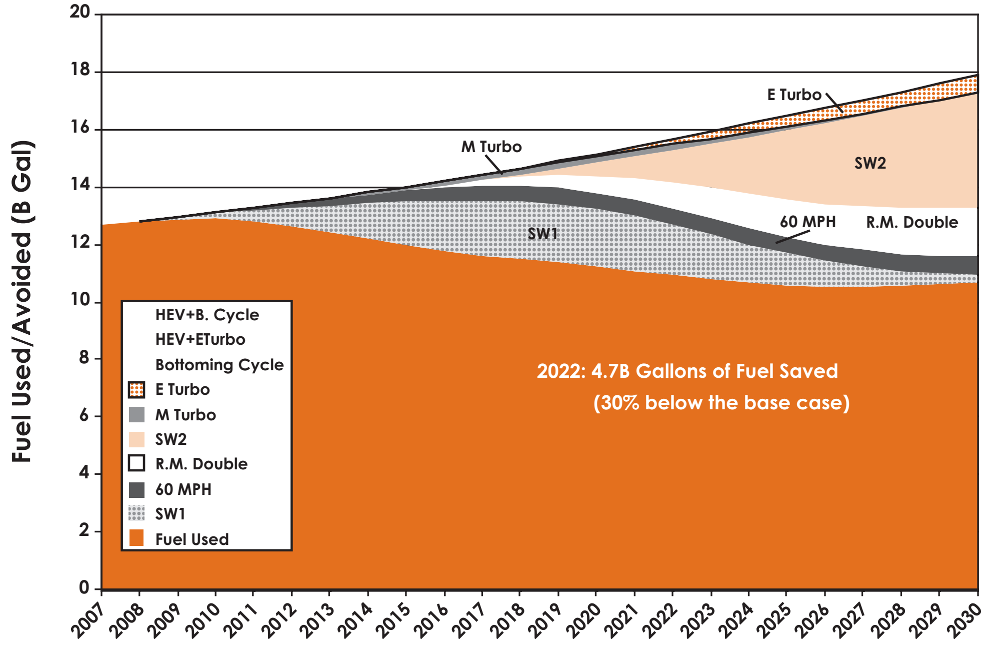
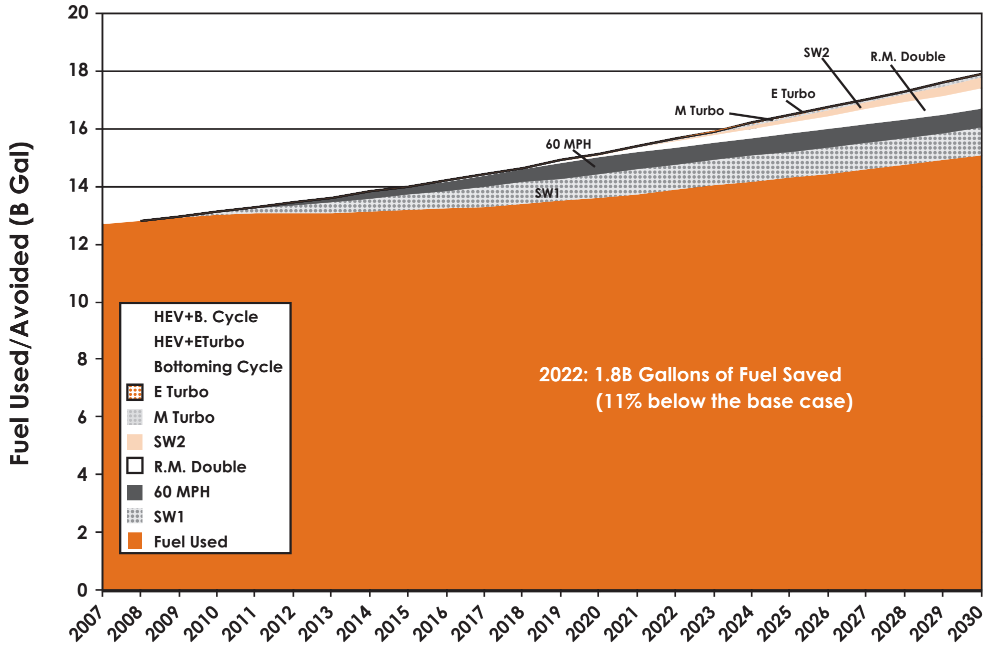


FIGURE 22

3 YEAR PAYBACK REQUIREMENT FLEET ANALYSIS



combination truck fuel usage since long-haul trucks are typically sold into regional service after several years. As such, our analysis does not attempt to account for fuel savings benefits that accrue once the same truck migrates from long-haul operation to regional service. Nor does it attempt to account for technology adoption in the approximately 40 percent of the Class-8 heavy-duty fleet that does not pull van-type trailers (e.g., tankers, flat beds, etc). These two fleet segments can leverage many of the approaches that have been analyzed for long-haul trucking, but also present unique challenges that are expected to reduce the potential benefits.

The main challenges with transferring technologies from the long-haul trucking fleet to trucks operating in regional service include: different duty cycles and the greater variety of trailers in the regional fleet. For example, in the case of the non-van trailer segment of the fleet, the non-uniformity of the trailer would prevent full implementation of the aerodynamic improvements specified in Packages 2 and 3. As such, the projected benefits of the improved aerodynamic packages would be lower in these applications than in a long-haul truck. However, some other technologies that were examined in this study could likely offer very similar benefits as with the long-haul truck.

Because regional service trucks frequently operate on a more stop and go type cycle than do long-haul trucks, some of the most cost-effective benefits for long-haul trucks – such as aerodynamic and rolling resistance improvements – will not achieve the same benefit over a regional duty cycle. While the tires-and-wheels benefits would carry over to other duty cycles, aerodynamic benefits will be reduced under lower speed operation. On the other hand, given the frequent periods of inefficient low-load operation, in-use idling, and frequent braking, hybrids are likely to perform significantly better in regional service than in long-haul operation.

Approaches for addressing these challenges in the regional fleet could include: (1) developing regional-haul specific retrofit packages, such as limited aero, or a start-stop idle reduction mode; and (2) implementing regional haul-specific fuel consumption packages in the approximately 20 percent of new tractor sales that enter the regional fleet directly.

Conclusions

The results of the analysis suggest that existing and emerging automotive technologies can achieve substantial and cost-effective reductions in heavy-duty vehicle CO_2 emissions and fuel consumption in the 2012 to 2017 timeframe. Specifically, CO_2 and fuel consumption emissions from heavy-duty vehicles can be reduced up to 20 percent with technologies such as mechanical turbocompounding

> ***The results of the analysis suggest that existing and emerging automotive technologies can achieve substantial and cost-effective reductions in heavy-duty vehicle CO_2 emissions and fuel consumption in the 2012 to 2017 timeframe.***

and moderate aerodynamic drag and rolling resistance improvements. CO_2 and fuel consumption can be reduced up to 50 percent in the 2017 timeframe using more advanced technologies. Policy changes to require reduced road speed or allow for increased weight or length vehicles were not evaluated as part of this study but would likely be required to reach the 50 percent reduction level. Assuming a three year vehicle ownership period and a diesel fuel price of $2.50 per gallon, this study found that five of the technology packages capable of achieving these reductions would result in net cost savings to the vehicle owner, taking into account both incremental technology costs and fuel savings over the three year period, and three others achieve cost savings over a four year period. The analysis shows that some of the technology combinations that provide the greatest reductions would not be adopted into the fleet assuming a three year payback requirement. This indicates that given the short payback period demanded by the trucking industry, most of these technologies will not be adopted into the U.S. fleet absent regulation or incentives.

With a longer vehicle ownership period of 15 years, net savings are between $30,000 and $42,000 for owners of vehicles achieving CO_2 and fuel consumption reductions in the 40 to 50 percent range. Aggressive introduction of the technologies and strategies modeled in this study into the U.S. heavy-duty long haul fleet between now and 2030 would lead to an estimated eight billion gallons of diesel fuel saved annually beginning in 2030, with lesser reductions being achieved as soon as 2012. The 8 billion gallons of fuel saved annually represents approximately 44 percent of the total projected business as usual fuel consumption and CO_2 emitted by the heavy-duty long haul fleet. Cumulative fuel savings between now and 2030 would equal approximately 90 billion gallons of diesel fuel. Approximately 97 million metric tons of CO_2 emissions could be reduced beginning in 2030. Cumulative CO_2 emissions avoided between now and 2030 would equal 1.1 billion metric tons.

APPENDIX A: Description of Heavy-Duty Technologies and Modeling Approach

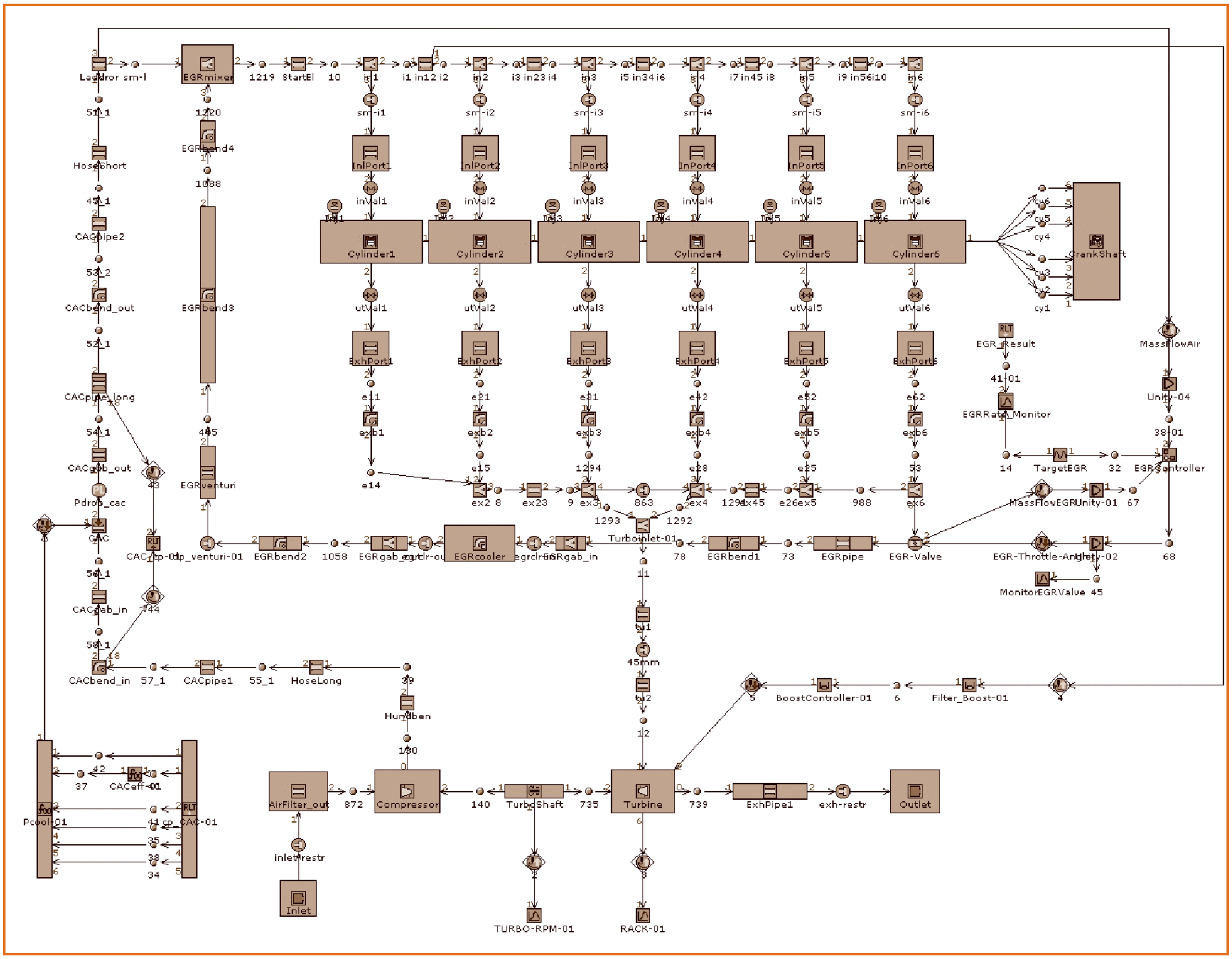
TABLE A-1 TECHNOLOGIES AND OPERATIONAL MEASURED CONSIDERED

	EFFICIENCY MEASURE:	DESCRIPTION AND CO_2/FUEL SAVINGS METHOD	INCLUDED IN PACKAGES
ENGINE TECHNOLOGIES			
1	Improved SCR Conversion Efficiency	After treatment improvements that allow increased engine efficiency in EPA 2010-compliant engines.	NO
2	Engine Friction Reduction	Improved engine bearings to allow lower viscosity oil, reducing energy lost to friction.	2, 3, 12, 13,14
3	Mechanical Turbocompound	An extra turbine in the exhaust harvests waste energy and delivers it to the crankshaft.	5
4	Electric Turbocompound	An extra turbine in the exhaust harvests waste energy and generates electricity to power accessories or propel the vehicle.	6, 13
5	Dual Stage Turbocharging	Twin-turbocharging with charge-air cooling for increased efficiency. EGR pump required to meet emissions.	NO
6	EGR Pump	Mechanical pump that moves exhaust into the intake manifold. Required in high-efficiency turbocharger or dual-stage turbocharger applications to meet emissions.	NO
7	Variable Valve Actuation (VVA)	Advanced control of engine valves to improve efficiency, power, and emissions.	5, 6, 7, 13
8	Advanced VVA	Advanced control of engine valves, used to create new combustion cycles such as in the Sturman Digital Engine. Insufficient data available.	NO
9	Alternative Combustion Modes	Low temperature combustion (LTC), homogeneous charge compression ignition (HCCI), and premixed charge compression ignition (PCCI) to reduce emissions at certain operating points.	NO
10	Insulated Exhaust Ports	To increase exhaust temperature for improved energy recovery in a turbocompound system or a bottoming cycle.	5, 6, 8, 12, 13, 14
11	Bottoming Cycle	An additional thermal cycle, such as a steam turbine, added to harness waste energy from hot engine exhaust.	8, 12, 14
TRANSMISSION SYSTEM AND ELECTRIFICATION TECHNOLOGIES			
12	Automated Manual Transmission	A manual transmission clutched and shifted by a computer for maximum efficiency and reduced driver variability.	NO
13	Moderate Hybrid Systems	A heavy-duty hybrid with moderate power level and moderate energy storage - a stop start system.	NO
14	Aggressive Hybrid Systems	A heavy-duty hybrid with significant power and energy storage capability, studied in both parallel and series architectures.	4, 12, 14
15	Accessory electrification	Powering water pumps and air compressors with electricity instead of using traditional belts or gears.	4, 6, 12, 13, 14
16	Component Friction Improvements	Use of lower viscosity lubricants in the transmission, differentials, and axles.	2, 3, 12, 13, 14

TABLE A-1 **TECHNOLOGIES AND OPERATIONAL MEASURED CONSIDERED (continued)**

	EFFICIENCY MEASURE:	DESCRIPTION AND CO_2/FUEL SAVINGS METHOD	INCLUDED IN PACKAGES
AERODYNAMIC DRAG AND ROLLING RESISTANCE REDUCTION TECHNOLOGIES			
17	Fully aerodynamic mirrors	Mirrors shaped and positioned to minimize drag.	2, 3, 12, 13, 14
18	Cab side extenders	Designed to reduce the tractor-trailer gap.	2, 3, 12, 13, 14
19	Integrated sleeper cab roof fairings	Large fairings to match the roof height of a truck to the height of the trailer.	2, 3, 12, 13, 14
20	Aerodynamic front bumper	For smoother airflow around the hood and wheels.	2, 3, 12, 13, 14
21	Full fuel tank fairings	To smooth airflow over fuel and air tanks.	2, 3, 12, 13
22	Trailer side skirt fairings	To deflect air away from the trailer undercarriage.	2, 3, 12, 13, 14
23	Trailer gap fairing	Mounted to the trailer to reduce the tractor-trailer gap.	3, 12, 13, 14
24	Rear-mounted trailer fairing	Sometimes called a 'boat tail,' used to reduce drag at the rear of the trailer.	3, 12,13, 14
25	Undercarriage Flow Device (UFD)	To further deflect air away from the trailer's undercarriage.	3, 12, 13, 14
26	Advanced tractor-trailer gap seal	A device that creates a nearly-complete closure of the tractor-trailer gap.	3, 12, 13, 14
27	Advanced rear-mounted trailer fairing	To significantly reduce drag at the rear of the trailer.	3, 12, 13, 14
28	Mass Reduction	Lightweight materials and component elimination to increase payload capacity and reduce the power required to accelerate or climb hills.	1
29	Reduced Rolling Resistance	Lowering the rolling resistance of tires through improved design and inflation to reduce the power required to move the truck.	2, 3, 12, 13, 14
OPERATIONAL MEASURES			
30	Lower Road Speed	Reducing speed improves vehicle fuel economy and CO_2 emissions.	10, 12, 13, 14
31	Increased Vehicle Size and/or Weight	Changes to weight limits, number of trailers, and truck design to increase cargo capacity while preserving road safety and infrastructure.	9, 13, 14
IDLE REDUCTION TECHNOLOGIES			
32	Auxiliary Power Unit (APU) or hybrid system that provides power while the engine is off	Provides the driver with overnight cabin heat or cooling and with electricity without idling the main diesel engine	2, 3, 4, 12, 13, 14

FIGURE
A-1
GT-POWER MODEL OF THE VOLVO D13 ENGINE



Engine System Technologies and Modeling

The engine system was modeled using a commercial one dimensional computational fluid dynamics code called GT-POWER. This code is widely used in the engine industry to predict engine performance characteristics. As described in Chapter 2, the Volvo D13 engine was chosen for use in this study. Chapter 2 also describes the validation work that was done to calibrate the model with measured engine data, and to demonstrate that the model provides an adequate simulation of the actual 2007 model Volvo D13. See Figure A-1 above for a layout of the GT-POWER model of the baseline Volvo D13 engine.

Improved SCR Conversion Efficiency

SCR systems typically have a NOx conversion efficiency of 75 to 90 percent, which means that 75 to 90 percent of the NOx in the exhaust is successfully reduced to N_2 and O_2. There is considerable work going on in the industry to improve conversion efficiency and improve the durability of SCR systems so that conversion efficiency is maintained over the life of the system. For a given NOx emissions standard, higher conversion efficiency in the SCR system will allow a higher engine-out NOx level. As the permitted engine-out NOx level increases, better fuel economy and lower CO_2 emissions can be achieved.

Modeling Approach:

For the 2010 version of the D13, Volvo plans to add SCR to the existing emissions control hardware, which consists of a diesel particulate filter for PM control and EGR for NOx control. SwRI assumed that the 2010 version of the engine will maintain the current engine-out NOx level, which will require an SCR efficiency of about 82 percent. By retaining the current engine-out NOx, the engine also retains its current fuel consumption and CO_2 emission levels. It may prove possible to improve the performance of the SCR system, so that engine-out NOx levels can be increased. Other design and calibration tweaks may lead to small efficiency gains. Depending on how much conversion efficiency can be achieved from the SCR system, an improvement of up to 3 percent could be achieved in fuel consumption and CO_2 emissions. Since it is not clear what increase in SCR system performance will prove possible over the next few years, and there are no published data that provide good guidance on this topic, SwRI did not make projections based on improved SCR performance. Therefore, our model of the 2010 engine matches the efficiency and CO_2 emissions of the 2007 engine exactly.

Engine Friction Reduction

Development of engine main and rod bearings is under way to allow the use of lower viscosity engine oils. The lower viscosity oil will in turn reduce engine friction in the bearings and between the piston, rings, and liner. About a 10 percent reduction in engine friction is expected if the current standard 15W40 engine lube oil can be replaced by a 5W30 grade. This change has already been made in Europe, where $9/gallon fuel pays for the savings in a single oil change interval. In order to go to the lower viscosity oil, synthetic is required. This roughly doubles the cost of an oil change. A potential issue should be noted here: if the increased cost of low viscosity oil does not pay for itself in fuel savings within the oil change interval, operators may go back to using higher viscosity oil. Given the need to maintain the production of higher viscosity oils for older engines, it is likely that several grades of oil will be available on the market for many years.

Modeling Approach:

There is no straightforward way of modeling engine friction reduction. Sophisticated bearing analysis can be used to predict friction in bearings, and other analyses can be used to predict friction between pistons and liners, in the valve train, and in other engine components. For this study, we made the assumption that a 10 percent reduction in friction could be achieved, and then did some simple calculations to predict the benefit. At a typical cruise condition, engine friction consumes around 10 percent of the crankshaft output power. A 10 percent reduction in this friction will thus provide a 1 percent improvement in fuel efficiency and CO_2 emissions. This effect was judged to be small enough to leave out of the rest of the study.

Improved Air Handling Efficiency

Almost all heavy-duty diesel engines sold in North America today use high pressure loop EGR for control of engine-out NOx levels. Engines from Caterpillar are the sole exception, and these engines are being withdrawn from the truck market at the end of 2009. To get EGR to flow from the exhaust manifold to the intake manifold, the pressure in the exhaust manifold must be higher than the pressure in the intake manifold. When the exhaust manifold pressure is higher than the intake manifold pressure, this is called having a negative Δp, where Δp refers to the difference in pressure between the intake and exhaust manifolds. High efficiency turbos naturally produce a positive Δp over much of the operating range, so turbocharger efficiency is intentionally compromised in order to facilitate EGR flow. If it is possible to produce EGR flow without reducing turbo efficiency, the overall engine efficiency will increase. Some potential ways of achieving improved air handling efficiency are listed below.

Modeling Approach:
Both mechanical and electrical turbocompound options were modeled and optimized using GT-POWER.

Mechanical Turbocompound

A power turbine is added to the exhaust system behind the normal turbocharger. The backpressure created by the power turbine allows the use of a very efficient conventional turbo, while still providing the negative Δp required to support EGR flow. This improves the air handling efficiency. The power turbine is geared to put power back into the crankshaft. A fluid coupling is normally used to isolate the power turbine from engine crankshaft torsional vibration. The fluid coupling also allows for some variation in the ratio of crankshaft speed to power turbine speed.

The basic effect of the power turbine is to add exhaust restriction, which enables EGR flow. This causes the engine pumping loss to increase to overcome the restriction imposed by the power turbine. However, unlike a simple exhaust restriction, the power turbine can recover energy from the exhaust, which more than compensates for the pumping loss created by the added restriction.

Modeling Approach:
A power turbine was added to the engine. It was geared to the engine through a fluid coupling to prevent damage to the gears from torsional vibration. Several scenarios were simulated:

- Variable geometry primary and power turbines
- Fixed geometry (higher efficiency) primary and power turbines
- A range of power turbine flow capacities
- Variable valve actuation

The basic strategy used in the modeling study was to achieve as large as possible fuel efficiency improvement at part load cruise conditions. As a result, the maximum power from the turbocompound was somewhat less than that found in some production applications, where increased engine power is often an important goal. On the baseline engine, a variable geometry turbocharger is required to control EGR flow. With the turbocompound, this proved unnecessary. Fixed geometry turbines proved to be the most efficient approach, with the added advantage of lower cost and complexity. A relatively small power turbine flow capacity was selected, in order to improve performance under part-load conditions.

Variable valve actuation (VVA) can be used to provide more exhaust energy to the turbos (higher exhaust temperature) under part load conditions, with little penalty to base engine efficiency. Because this approach proved effective, the results reported in Chapter 3 include the use of VVA. Overall, the best results were obtained with fixed geometry primary and power turbines, a relatively small power turbine flow capacity, and VVA.

In the course of developing the turbocompound model, it was important to retain the engine-out NOx and PM performance of the baseline engine. Therefore, care was taken to maintain air/fuel ratios and EGR flow at values very close to the baseline engine. Many iterations of the model were run to achieve the desired results.

Electric Turbocompound

This is the same concept as the mechanical turbocompound, except the power is fed into an electrical machine. Electric turbocompound is ideal as a power source for a hybrid system, and will in fact require a hybrid system or at least an electric motor connected to the driveline, since the power generated will be more than the accessories can consume under at least some operating conditions.

Modeling Approach:
The electric turbocompound benefits from the use of an electrical generator connected to the power turbine. This eliminates the need to have the power turbine and engine speeds match at a fixed ratio. As a result, the electric turbocompound is slightly more efficient. In addition, the electrification of accessories was combined with electric turbocompound. This reduced the assumed accessory load from 5 kW to 3 kW, providing a significant efficiency benefit.

The GT-POWER engine model started with the mechanical turbocompound results, and then the system was re-optimized for the conversion to electrical turbocompound configuration. Once again, considerable care was taken to maintain air/fuel ratios and EGR flow, to avoid any increase in NOx or PM emissions.

There is one aspect where the electric turbocompound is less efficient than the mechanical system. Because there are losses in generating and in using electricity, a smaller portion of the shaft power from the power turbine actually appears at the wheels of the vehicle.

Dual Stage Turbocharging with Intercooling

Modern engines require high pressure ratios. The pressure ratio is the ratio between intake manifold pressure and ambient pressure, and values up to 4 are common in production engines. One negative effect of high pressure ratio is that it limits the efficiency of a turbocharger. Using two turbos in series with intercooling between the two turbos and aftercooling between the second turbo and the intake manifold would allow higher turbocharger efficiency. This approach requires an EGR pump, turbocompound system, or other device to facilitate EGR flow. The combination of two engine turbochargers with an EGR pump or turbocompound results in serious cost, complexity, and packaging issues. This is a lot of hardware to fit on the engine.

Modeling Approach:
This technology approach was not modeled in GT-POWER. Based on simple spreadsheet calculations, it appears that the efficiency of an engine can be improved by about 2 percent by the use of dual stage turbocharging with intercooling. However some, if not all, of this improvement would be lost in powering an EGR pump. Packaging two

turbocharger stages with a turbocompound power turbine was judged to be very difficult from a cost and packaging standpoint, so this approach was not evaluated.

High Efficiency Turbocharging

This is the same concept as dual stage turbocharging, but within the limits of a single stage turbocharger. Because an efficient turbocharger produces a positive Δp, this approach will require an EGR pump, turbocompound system, or other device to facilitate EGR flow.

Modeling Approach:

This is the same concept as dual stage turbocharging, but within the limits of a single stage turbocharger. This technology approach was not modeled as a stand-alone technology in GT-POWER. Based on simple calculations, it appears that the efficiency of the engine can be improved by about 1 percent by the use of high efficiency single stage turbocharging. This benefit would be lost when an EGR pump is added to provide adequate EGR flow. However, this approach is attractive in combination with turbocompound, where an EGR pump is not needed. A high efficiency single stage turbocharger was used with both mechanical and electric turbocompound versions as described in previous sections.

EGR Pump

An EGR pump can facilitate EGR flow and help control the flow rate to achieve the desired level of EGR. This device makes EGR flow independent of the engine's Δp, which allows the use of high efficiency air handling systems. Unfortunately, an EGR pump consumes power, which at least partially cancels the efficiency gain from the improved air handling system. Also, an EGR pump adds cost, weight, and complexity to the engine package.

Modeling Approach:

An EGR pump was not modeled using GT-POWER. Based on simple spreadsheet calculations, the EGR pump proved less attractive than turbocompound as a way of providing the negative Δp required to drive EGR flow.

Variable Valve Actuation

In gasoline engines, variable valve actuation can have a huge impact on engine performance and fuel economy. VVA can be used to improve engine breathing, and thus power, and/or to reduce the pumping losses caused by throttling the intake. In heavy-duty diesel engines, the potential benefits of VVA are much more limited. This is partly due to the much narrower operating speed range of heavy-duty diesel engines. VVA allows flexibility to operate the turbochargers at a more efficient point on the compressor map. This may allow the use of a more efficient turbo with a narrower map. VVA would only be used at appropriate speed/load conditions. When applying VVA to a heavy-duty diesel, the designer needs to consider how to maintain adequate SCR temperature at low loads to prevent an increase in NOx emissions. VVA can also be used to improve the power output of a turbocompound system by leaving more energy (temperature) in the exhaust stream.

Modeling Approach:

Variable valve actuation was extensively modeled in GT-POWER, both as a stand-alone feature and in combination with turbocompounding and the bottoming cycle. SwRI modeled VVA as a way of optimizing the standard diesel combustion cycle. The ability of VVA to improve diesel engine efficiency as a stand-alone feature is rather limited. This is not surprising; several engine makers have evaluated VVA with the conventional diesel cycle and found little benefit. There are examples in the literature where dramatic improvements are claimed from modified engine operating cycles that VVA can enable. The Sturman "Digital Engine" is one example. Unfortunately, the available literature does not provide enough detail to allow SwRI to attempt to duplicate the claimed results.

Low Temperature Combustion / HCCI / PCCI

Low temperature combustion (LTC), homogeneous charge compression ignition (HCCI), and premixed charge compression ignition (PCCI) are all "alternative" combustion modes that can be used in place of standard diesel combustion. All of these modes have been developed in an effort to reduce NOx output, and in the case of HCCI, PM output as well. If NOx is not an issue, these alternative combustion modes generally suffer from lower thermal efficiency than conventional diesel combustion. However, conventional diesel combustion suffers substantial thermal efficiency degradation at low engine-out NOx levels, so these alternative modes can become attractive. The performance of these alternative combustion modes is duty cycle dependent: most of the potential is at low load. Typically, alternative combustion modes can be used up to 30 percent or 40 percent load. Therefore, alternative combustion modes will have little impact on the fuel economy or CO_2 emissions of an engine that operates most of the time at higher loads, such as in a long haul truck application. PCCI does not require hardware changes unlike HCCI. Hardware changes required for HCCI include additional injector(s). Control changes include careful control of injection timing and precise control of EGR flow and air/fuel ratio in the cylinder.

Modeling Approach:

These "alternative" combustion modes are intended to provide reduced engine-out NOx. They can reduce the need for aftertreatment systems, and this is the main reason for considering alternative combustion modes. These modes do not offer a fuel consumption or CO_2 benefit over standard diesel combustion combined with SCR, so the decision was made not to pursue these modes for this project. Another issue is that it is extremely difficult to accurately model these combustion modes, and a full three dimensional computational fluid dynamics model is required.

Engine Thermal Management Improvements

The goal of thermal management features is to retain energy in the gas flow through the engine rather than allow heat to be lost to the engine coolant, to air under the hood, or to other loss paths. This approach is only of value if the retained energy is going to be used in some way, or if it is necessary to reduce underhood temperatures to protect certain components from heat related damage.

In the 1980s, there was a lot of research in the engine industry on the subject of "adiabatic engines." The term adiabatic refers to a thermodynamic process such as compression or expansion in the cylinder that takes place without any heat transfer between the working gas and the combustion chamber walls. The idea behind the adiabatic engine concept was that by insulating the combustion chamber, the engine would reject less heat and have a higher efficiency. Unfortunately, it turned out that heat rejection to the coolant was not reduced as much as expected, and efficiency actually fell. Heat transfer between the working gas in the cylinder and the ceramic coated cylinder walls actually increased. The energy diverted from the cooling system went out the exhaust. This experience makes it clear that attempts to implement simple thermodynamic concepts in an engine can have unintended consequences.

Modeling Approach:
Insulated ports and a bottoming cycle were modeled as described below.

Insulated Ports and Manifolds

Ceramic coatings or inserts with air gaps are used to increase exhaust temperature. The retained energy can then be used in an energy recovery device, such as a turbocompound system or a bottoming cycle. The energy potential of insulated ports and manifolds is better at high load, but there can also be a benefit from higher temperature into an SCR system for improved NOx conversion efficiency.

Modeling Approach:
Insulated ports were modeled in GT-POWER. The heat transfer coefficient for the port walls can be adjusted in the model to predict the performance of insulated ports. Insulated manifolds were not simulated in this project. The heat loss of manifolds to the air outside the engine is expected to be significantly lower than the heat loss of the ports to the cooling water jacket in the cylinder head. The benefits of insulated ports proved to be small.

Bottoming Cycle

A bottoming cycle is a heat engine that uses waste heat from the primary engine (the heavy-duty diesel) to produce additional work. There are many concepts available for use in a bottoming cycle, including steam turbines. For the steam turbine approach, many different working fluids can be considered. Potential sources of waste heat include:

- The exhaust gas flow
- EGR flow
- Charge air flow
- Engine coolant

The great advantage of a bottoming cycle is that it uses “free” energy – energy that is going to be thrown away by the primary engine. The great disadvantage of a bottoming cycle is that its efficiency is limited by the poor quality (low temperature) of most waste heat. In addition, the amount of waste heat available also varies greatly with the engine’s operating condition. Bottoming cycles have been used for many years in stationary power plants. So far, they have not found application in vehicles because of cost, weight, packaging, reliability, and performance issues.

Another issue that must be dealt with in using a bottoming cycle is finding a way to deal with the very poor transient response of the bottoming cycle. When there is a sudden increase in demand for engine power, it will take considerable time for the bottoming cycle to see the resulting waste heat increase and increase its own power output accordingly. Also, if there is a sudden decrease in engine power demand (the driver takes his foot off the throttle), the bottoming cycle will continue to make power for some time because of waste heat already in the system.

One way to deal with the transient response issue is to combine the bottoming cycle with a hybrid electric drive system. Electricity produced by the bottoming cycle can be used directly to supplement engine power when desired. If the bottoming cycle cannot produce power when needed, stored electrical energy can be used. If the bottoming cycle is making power that the vehicle does not immediately require, this energy can be stored in the hybrid system battery.

Unfortunately, this combination of bottoming cycle and hybrid technologies means that two large, complex, and expensive systems must be packaged together in the vehicle. Making all systems fit in a truck, work together, and achieve reliability will be a daunting challenge for engineers.

Modeling Approach:

After studying the available literature, SwRI decided to model a steam turbine bottoming cycle using water as the working fluid. Water has a boiling temperature which makes it very attractive for extracting work from a relatively low temperature heat source. There are issues that would need to be dealt with if a water-based cycle is used. One of the biggest issues is the potential for freezing. A water-based bottoming cycle will require insulation, a heating system to prevent freezing during extended idle periods, and an emergency dump system to drain the water in case the heating system fails.

A sophisticated spreadsheet simulation of the bottoming cycle was created in order to evaluate alternative designs. The spreadsheet takes into account many parameters, and calculates temperatures, pressures, and flow rates through the system. Many assumptions must be made in order to model a bottoming cycle. The assumptions used in this project are listed on the following page.

- Working fluid: water
- Power turbine / expander efficiency: 70 percent at all operating conditions
- Feed pump efficiency: 100 percent (since the feed pump power is very low, this is not a major factor)
- Pump inlet conditions: saturated water at 40° C on a standard 25° C day (a range of inlet temperatures was evaluated to determine the sensitivity of the system to inlet temperature and thus to condenser performance)
- Maximum system pressure: 35 bar
- Pressure drop across all heat exchangers: 10 kPa (3” Hg)
- Approach temperature of all heat exchangers: 14° C (this is an assumption about the efficiency of the heat exchangers – we assumed performance similar to charge air coolers used on trucks)
- Expander outlet minimum quality = 0.9 (10 percent liquid water maximum, to protect the hardware from erosion damage)
- Variable speed feed pump (to match the system flow to the available heat)
- Variable speed/geometry expander (to match the available heat)
- Low side pressure: 0.07 bar (this is a substantial vacuum, which is required to get the condensation temperature of water down to 40° C)

- Minimum exhaust temperature after heat exchanger: 150° C (this was selected to avoid condensation issues in the exhaust)

- Exhaust stream temperature after the DPF and SCR systems is assumed to be 7° C lower than the turbocharger outlet temperature (based on SwRI test experience)

- 90 percent efficient electrical generator and electric drive motor (81 percent of the power from the bottoming cycle turbine is assumed to reach the vehicle transmission)

As noted above, SwRI evaluated the following four heat sources for the bottoming cycle:

1) engine coolant;
2) charge air from the turbocharger compressor;
3) EGR gas flow, and 4) exhaust gas flow.

The engine coolant carries a large portion of the power released by burning fuel, and therefore it is a significant potential source of heat for the bottoming cycle. Unfortunately, the quality (temperature) of the coolant heat is very low (about 90° C), so it is hard to extract much useful work from coolant heat. In other words, a bottoming cycle using waste heat from the engine coolant will have a large energy input, but very low efficiency, and therefore low power output.

Charge air is a more promising source because at high engine load, the temperature is much higher than coolant temperature. However, charge air temperature is very sensitive to engine speed and load. At typical cruise conditions, the amount of heat energy and the quality (temperature) of the energy is fairly low. SwRI's evaluation showed that a bottoming cycle using energy from the charge air would be fairly effective at full load, but not very effective over the vehicle drive cycle.

EGR gas flow is taken from the exhaust manifold before the turbocharger, so it offers the highest quality (temperature). Only about 25 to 30 percent of the exhaust flow is devoted to EGR, however, so this limits the total energy available from the EGR stream. Because of the high quality of EGR energy, it offers the best bottoming cycle efficiency.

Exhaust gas flow is lower in quality than EGR flow, since it is taken after the turbocharger turbine and the downstream exhaust aftertreatment systems. However, the total amount of energy available is high, so this is an attractive heat source.

In the evaluation performed by SwRI, by far the best performance was obtained by heating the bottoming cycle fluid first with the exhaust gas stream, and then adding additional heat from the EGR stream. This approach provided much better results than using either of the two sources alone. It was also far superior to using charge air and/or engine coolant as heat sources. Even when using both exhaust and EGR as heat sources, the amount of energy available from a bottoming cycle is strongly dependent on engine speed and load. At high speed and load, the highest temperatures and exhaust flow rates are achieved, which allows a high bottoming cycle power. However, the SwRI model shows that the bottoming cycle can provide power that is a significant percentage of engine power down to relatively low engine speeds and loads. For example, at 1200 RPM and 20 percent load, the bottoming cycle provides 7.3 percent of engine crankshaft power, which translates into a 7.3 percent reduction in fuel consumption and CO_2 emissions.

Note that there are many engineering problems that will need to be overcome in order to implement a bottoming cycle in a truck. Packaging of all the necessary hardware into a truck will be a challenge. The bottoming cycle hardware will introduce a weight penalty to the truck. Developing the system to operate over the range of ambient conditions encountered in service is also a major controls and design challenge. The bottoming cycle hardware and controls must also be able to function over the full engine speed/load operating range, as well as dealing with startup and shutdown transients. Another important issue is heat rejection. Since the proposed bottoming cycle takes energy from the engine exhaust, about 75 percent of that energy must be rejected by the bottoming cycle as waste heat. This increases the overall vehicle heat rejection requirement. Higher heat rejection can lead to a greater fan power requirement and higher aerodynamic drag, both of which would counteract the benefit of the bottoming cycle. As a result, some design compromise is probably required which would limit the maximum output (and thus heat rejection) of the bottoming cycle system. Achieving adequate bottoming cycle reliability and durability in a vehicle where high levels of vibration and wide temperature swings are a part of everyday service will be a very difficult task.

Bottoming cycles are widely used today in stationary power plants. In stationary power applications, however, many factors are more favorable than in a truck. These include the following:

- Stationary power is an essentially zero vibration environment
- In power plants, the operating and ambient temperature ranges are limited
- Space (packaging) is not a major concern
- Heat rejection capacity is not a major concern
- The large energy stream of a power plant can justify a high cost bottoming cycle system
- Operating conditions are far closer to steady state in a power plant than in a truck
- Power plant load factors tend to be higher than truck load factors. A high load factor favors bottoming cycle performance

Transmission System Technologies

Modeling Approach:

All transmission and vehicle simulations were made using RAPTOR, a commercially available vehicle simulation code developed by SwRI.

Automated Manual Transmission

Torque converter automatic transmissions are relatively rare in heavy-duty truck applications. There are several reasons for this, including cost. Torque converter automatics are generally used only in stop-and-go applications such as city buses, garbage trucks, and cement mixers. Most heavy-duty trucks use manual transmissions with 8 to 18 ratios available. The most common transmission for line haul applications is a 10 speed manual transmission with an overdrive top gear ratio.

Automated manual transmissions have been available on the market for over 10 years now, and they have been increasing in market share. Automated manuals allow the vehicle control module, rather than the driver, to decide when to shift. Pneumatic or hydraulic mechanisms then actuate the clutch and transmission controls to execute the shifts. An automated manual can shift as quickly as the best driver, and the shift schedule can be tailored to match the characteristics of the engine and vehicle. This reduces the fuel consumption and CO_2 emissions variability between drivers, making all drivers achieve results closer to those of the best drivers. Automated manual transmissions also reduce the level of skill required, which has become an advantage as the trucking industry struggles to replace retiring drivers.

Modeling Approach:

An Eaton 10 speed manual transmission was selected as the baseline transmission for the project. Inputs to the RAPTOR model include the gear ratios of each gear, along with assumptions regarding the efficiency of each gear. SwRI assumed 98 percent efficiency for the lower gears, and 99 percent efficiency for the tenth gear, which is direct (1:1 ratio).

A key factor in modeling a manual transmission is making assumptions about driver behavior. The driver can have an appreciable effect on truck fuel economy, and selection of shift points is a large part of this. If the driver keeps the engine operating at high RPM, the fuel economy will suffer. If the driver is aggressive in heavy traffic, the truck will experience more dramatic speed fluctuations than with a less aggressive driver, also affecting fuel economy. In the current study, the speed vs. time drive cycle was pre-determined. This ignores the effect of different drivers who will vary speed more or less, depending on temperament. Shift points are still a factor that will influence fuel economy on the drive cycle. SwRI chose to shift up at 1800 RPM in situations where the drive cycle called for full power. Downshifts were set to occur at a point resulting in 1700 RPM if full power is required. In situations where full power is not required, the shift points were selected to be lower to achieve good fuel economy. This is the approach a good driver will take. The good driver might also decide to sacrifice some vehicle performance in order to improve fuel economy and use lower shift points at full load.

The shift strategy used in the RAPTOR model also represents a typical shift strategy for a fully automated manual transmission. For the purpose of this study, there is no difference between the manual and automated manual transmissions, since both are modeled in the same way. In the field, there will be a difference between manual and automated transmissions. A very fuel conscious driver might be able to do a little better than an automated manual, while a more performance oriented driver is likely to use more fuel than an automated transmission.

Moderate Hybrid Systems

These systems are similar in concept to the mild hybrids used in light-duty applications using an integrated starter/generator. Engine start/stop is included, along with limited duration auxiliary power unit capability, electrified accessories, launch assist, and regenerative braking to recharge the battery. The battery size is kept modest to control cost and weight.

Modeling Approach:

A moderate hybrid system was not modeled for this project. The Steering Committee agreed that an aggressive hybrid offered much more potential fuel savings for heavy-duty trucks.

Aggressive Hybrid Systems

These systems are similar in concept to the full hybrids used in light-duty applications. Two approaches were considered in this study. The first approach has a 50kW motor/generator on the transmission with a 4 kW-hr battery. This is a parallel hybrid approach. Both the engine and the hybrid motor are connected to the drivetrain (although the engine does have a clutch). The parallel hybrid system uses a high voltage battery that allows electrification of all accessories including the engine cooling fan. This system can support start/stop and APU functions to greatly reduce idle time. Up to 50 kW of additional power is available for launch or hill climb support.

The second hybrid approach modeled for this study was a series hybrid. In this case, the engine is only connected to the drive wheels at highway speeds using two transmission ratios. At lower speed, the engine drives a generator which in turn is used to drive a 200 kW electric motor. The series hybrid has a larger capacity battery, allowing the vehicle to support hotel load of heating, cooling, and electricity supply (APU function) all night without charging. The larger battery also allows low speed operation of the truck without starting the diesel engine.

Modeling Approach:

RAPTOR includes extensive code for hybrid system simulation. Care is taken to make sure that the state of battery charge at the beginning and end of the cycle is the same, for example, to ensure comparability between design alternatives. A parallel hybrid system was evaluated in several configurations. The initial configuration had the electric motor on the engine side of the clutch, and used a 10 kW-hr battery. Better performance was achieved by moving the electric motor to the transmission side of the clutch. This allowed the engine to be disengaged during some braking conditions, which increases the amount of energy that can be captured from regenerative braking. The final version of the parallel hybrid system reduced the battery capacity to 4 kW-hr, in order to limit the cost and weight of the battery package. The system assumed that 50 percent of the battery capacity was available for use. This is done to achieve good battery life.

In the series hybrid analysis done as part of this study, we were unable to demonstrate significant fuel savings because we were not able to acquire the necessary controls strategies used by developers of series hybrids. Thus, the analysis for this study focused on the parallel systems.

Vehicle Technologies

Modeling Approach:

All transmission and vehicle simulations were done using RAPTOR, a commercially available vehicle simulation code developed by SwRI.

Accessory Electrification

The use of a hybrid system or electric turbocompound provides a source of electrical energy that can be used to drive accessories that are engine driven on today's vehicles. Given the availability of significant electric power, the following accessories can be converted to electric drive:

- Electric Power Steering (EPS)
- Electric Water Pump (EWP)
- Electric A/C compressor
- Electric air compressor
- Eliminate conventional alternator

If 30 kW of electric power is available, the engine cooling fan can also be converted to electric drive. In line haul applications, the efficiency savings from an electric cooling fan is limited, because the fan only runs as needed, and it is normally not required at higher vehicle speeds.

If electric power is not available, there are still some technologies that can be applied to reduce the parasitic power consumption of accessories. The alternator and air compressor can use clutches to disengage them when they are not required. This can provide a significant parasitic power reduction. Air compressors that are not pumping absorb about half the power of a pumping compressor, and compressors normally only pump a small percentage of the time.

Modeling Approach:

Good data providing power consumption values for each accessory over a range of operating conditions were not available. A simplified assumption was made that the average power demand for mechanically driven accessories is 5 kW, and the average power demand for electrically driven accessories is 3 kW. This provides a 2 kW advantage for the electrically driven accessories over the entire drive cycle. Since the average engine power level over the drive cycle is in the 100 to 200 kW range, this represents a 1 to 2 percent improvement in efficiency and reduction in CO_2 emissions. In general, the effect of accessory power consumption in trucks is much less than in cars. The average load on a car engine over a drive cycle may be in the 10 to 20 kW range. At this level, a 1 kW reduction in accessory loads makes a significant difference (5 to 10 percent). Given the higher loads experienced by truck engines, accessory demand is a much smaller share of overall fuel consumption.

Accessory power demand was modeled in RAPTOR as a continuous, steady state power draw of 5 kW for standard accessories, and 3 kW for electrical accessories. There is room for additional research to improve upon this very simple modeling approach by using actual measured data to improve the modeling assumptions.

Friction Improvements

Engine friction reduction is described in a previous section. Lower viscosity lubricants, and lubricants whose viscosity is less temperature sensitive, can also be applied in transmissions, differentials, and axles. In many cases, components need to be redesigned in order to be compatible with low friction lubricants. The benefits of friction reduction on the vehicle are sensitive to ambient temperature. Larger benefits are found in cold weather. These improved lubricants are normally higher cost synthetics. Synthetic low friction lubricants are already options in today's trucks and have become standard on a few models.

Modeling Approach:

The modeling of vehicle related friction improvements is very complex. Friction arises in the transmission, driveshaft joints, axles, and wheel bearings. Rather than deal with this complexity, friction reduction assumptions were included in the overall rolling resistance values that are used in Package 2, Package 3, and all subsequent packages, which use the Package 3 values. Package 2 assumes no change in vehicle friction, while Package 3 assumes a 10 percent reduction in vehicle friction.

Aerodynamic Drag Reduction

There are many technical features that are available or under development to reduce the coefficient of drag (Cd) of a heavy-duty truck. In many cases, reliable data are not available on the effect of individual features, or data are only available from the manufacturers of the features. Therefore, in this study, we simply modeled the effect of drag coefficient on the fuel economy and CO_2 emissions of the truck. Two packages were considered. The first package (Package 2) assumed a drag coefficient of 0.5, which was estimated to be the drag coefficient of a SmartWay tractor/trailer combination. The second, more aggressive package called "Advanced SmartWay" (Package 3) looked at a feasible drag coefficient for 2017. After much discussion in the Steering Committee, a drag coefficient of 0.4 was selected, based on available data.

The list of aerodynamic features that were discussed included: reduced tractor to trailer gap, trailer side skirts and undercarriage skirts, a boat tail, boat tail plates, integrated tractor roof fairings, a trailer "eyebrow," frontal area reduction (not implemented, in order to keep carrying capacity constant), trailer edge rounding, vortex generators, guide vanes, active and passive pneumatics, aerodynamic mirrors, replacement of mirrors with cameras, a trailer underbody wedge, fuel tank fairings, bumper fairings, "teardrop" shaped trailer, wheel fairings, and hidden vertical exhaust stacks.

It should be noted that Package 2 is available on the market today. The market share of vehicles equipped with the full package is very low, for a number of reasons. One of these issues is the fact that some tractor and trailer aerodynamic features are very damage prone, and that damage results in the loss of several years worth of fuel saving benefits. Another issue is that fleets are concerned about the down time related to the failure of a wide base single tire. Additional development is required to mitigate these issues to the point where most heavy-duty truck buyers find them cost effective.

Package 3 is much farther from being ready for wide-spread use. Other than a couple of laboratory demonstrations, Package 3 remains undefined in detail. There will be many challenges in the development of the Package 3 drag coefficient, especially in minimizing the impact on vehicle functionality (trailer volume, vehicle maneuverability, loading dock compatibility, damage resistance, and minimizing weight increase). It is the consensus of experts consulted in industry as well as members on the Steering Committee that these issues could be overcome by 2017.

Modeling Approach:

Modeling of aerodynamic features to determine their individual impact on drag coefficient is beyond the scope of this project. This type of modeling would require a sophisticated three dimensional computational fluid dynamics program. Therefore, in this study, we simply modeled the effect of drag coefficient changes on the fuel economy and CO_2 emissions of the truck. The two packages discussed above (SmartWay and Advanced SmartWay) were modeled. Drag coefficients of 0.5 (SmartWay) and 0.4 (Advanced SmartWay) were simply entered into the RAPTOR model along with vehicle frontal area. The model then calculated the drag power over the vehicle drive cycle.

Mass Reduction

There are opportunities to reduce the mass of a tractor / trailer. Reduced mass can benefit fuel efficiency and CO_2 emissions in two ways. First, if the truck is running at the GVW limit with high density freight, more freight can be carried. This increases the amount of freight that can be moved for a given amount of fuel. Second, if the truck is running with lower density freight, the total vehicle mass is reduced, which reduces rolling resistance and the power required to accelerate or climb grades.

There are two primary approaches for mass reduction. Material upgrades can achieve the same performance with lighter weight. Examples include the substitution of thinner high strength steels for standard steel, or the use of aluminum or composite in place of heavier materials. A second approach is to reduce the number of components required. The main example of this approach is to substitute single wheels and tires where dual wheels are used today. Single wheels and tires that can carry the same load as standard dual wheels are commonly known as wide base singles.

Modeling Approach:

Vehicle mass is an input to the RAPTOR model. The effect of vehicle mass changes was evaluated by changing the input value in the model. RAPTOR uses vehicle mass to determine the energy required to accelerate and slow the vehicle, as well as the vehicle rolling resistance.

Reduced Rolling Resistance

Lower rolling resistance reduces the power required to move the truck down the road, which directly reduces fuel consumption and CO_2 emissions. Tire design and tire inflation are the primary factors contributing to rolling resistance. Wide base single tires offer much lower rolling resistance than standard double wheels. Tire manufacturers are working on designs to decrease the rolling resistance of both standard and wide base single tires. Tire pressure monitoring and automatic tire inflation systems are available to ensure that tires are operated at the optimum pressure.

Modeling Approach:

The rolling resistance coefficient is an input to the RAPTOR model. The baseline number came from actual vehicle testing on a Kenworth T-600 truck and trailer combination. The lower rolling resistance values used in Packages 2 and 3 came from publications, unpublished data, or projections from EPA and/or Michelin. The rolling resistance assumption for Package 3 included an assumption of a 10 percent reduction in vehicle friction, in addition to tire-related improvements.

Lower Road Speed

Since aerodynamic drag is a function of speed squared, the fuel economy and CO_2 emissions of vehicles can be improved by reducing speed. Limits on this approach include increases in trip time and possibly increases in the number of trucks on the road that would be required to deliver a given amount of freight.

Modeling Approach:

The maximum road speed is defined by the drive cycle. The baseline drive cycle is defined in Chapter 2. To evaluate the effect of imposing lower road speed limits on trucks, the drive cycle was modified by limiting the maximum speed to 65, 60, and 55 MPH. RAPTOR then used the modified drive cycles to determine the fuel savings that can be achieved with lower road speeds.

Increased Vehicle Size and/or Weight

Some trucks run “cubed out.” In other words, the trailer is completely full with low density freight, and the vehicle is under the GVW limit. Other trucks run “grossed out,” which means that the trailer is not filled, but the truck is at the GVW limit. Some trucks operate less than full in either sense. To achieve good operating efficiency, trucking companies strive to load the truck until one of the two limits is reached. An increase in the permitted size and weight of trucks can reduce fuel consumption on a ton-mile basis and lead to lower CO_2 emissions for the fleet.

The advantages of increased truck size and weight are straightforward. Fuel consumption and CO_2 emissions are reduced. Traffic density is reduced, since fewer trucks are required to move a given amount of freight. Labor cost is reduced, since fewer drivers are required.

Unfortunately, there are also disadvantages to increased truck size and weight that must be dealt with. The first disadvantage is that there are both real and publicly perceived safety risks for larger and heavier trucks. This disadvantage might be dealt with by mandating vehicle performance characteristics such as stability control, braking performance, and crash compatibility. In addition, driver training and driver performance requirements could be put in place for operators of larger, heavier trucks. Another disadvantage is road damage from heavy trucks and the issue of whether trucks pay enough in taxes and fees to cover the damage they cause. This issue might be dealt with by limits on axle load, possibly with standards on suspension performance, and by adjustments to the tax and fee structure. Another factor that must be considered is the structural integrity of bridges. Some routes may require upgrades before heavier trucks could safely operate.

One final potential disadvantage of larger, heavier trucks is also one of the benefits: lower cost shipping. The concern here is that a more efficient trucking industry would lead to more shipping in general, and thus cancel some of the CO_2 advantage of larger, heavier trucks – frequently referred to as the “rebound effect.” In this study, the potential impact of “rebound” has not been included in the estimation of fuel use or CO_2 reductions in the longer/heavier truck cases.

Modeling Approach:

RAPTOR allows the use of any desired tractor and trailer combination. To explore the effect of allowing larger, heavier vehicles, the vehicle model was modified in RAPTOR. Higher empty vehicle weights were applied, the appropriate freight weights were applied, and the model was run to determine changes in fuel consumption and CO_2 emissions. In addition, the rolling resistance and Cd values were modified for some vehicle combinations. The rolling resistance of drive axle tires is higher than that for trailer tires, so if the ratio between drive axles and trailer axles changed, the rolling resistance coefficient was modified to account for the change. Similarly, the aerodynamic drag of a multi-trailer combination will be higher that that of a single trailer, because of an additional trailer-to-trailer gap and additional undercarriage elements. Thus, modified Cd values were also applied to account for the higher drag expected with multiple trailer combinations.

APPENDIX B: Summary of Incremental Costs for Technology Packages

TABLE B-1 **APPENDIX B**

TECHNOLOGY PACKAGES	FUNCTIONAL DESCRIPTION AND NOTES	INCREMENTAL RETAIL COST ESTIMATE*	PARTS COST*							COMMENTS
Package 1. 2008 baseline.	Kenworth T-600 with 10-speed manual, 2007 Volvo D-13 engine - adjusted to meet 2010 NOx emissions standards. Aero assumptions: Bumper fairing, partially aerodynamic mirrors, partial fuel tank fairing, integrated roof fairing, exhaust system out of the air stream (aero drag coefficient: .6298) (coefficient of rolling friction: .0068)									
Package 2. SmartWay package	SmartWay package. Includes: Additional aero streamlining sufficient to reduce the coefficient of drag from 0.63 to 0.5 to both the cab and the trailer. Fully aerodynamic mirrors, cab side extenders, integrated sleeper cab roof fairings, aerodynamic bumper, full fuel tank fairings. Trailer streamlining includes a side skirt fairing, and either a trailer gap fairing or a rear-mounted trailer fairing such as a boat tail. RR of 0.0055. Super singles and aluminum wheels. Idle reduction, improved lubricants	$22,930	Cab Streamlining: $2750	Trailer Aero - side skirts, gap reducer and rear flap: $2,400	Low Viscosity lubricants: $500	cab tires: replace 8 wheels w/4 super singles: (4 tires + wheels) x ($1,279/tire + $575/wheel) - (8 tires + wheels) x ($582/tire + $205/wheel) = $1,120	trailer tires: replace 8 wheels with 4 super singles, same calculation as for cab tires times three trailers ($1,120 x 3 = $3,360)	APU: $8000		see SmartWay “Technical Specifications and Requirements 2007 tractor and 2007 trailer”. SmartWay specifications, including: 10% - 20% improvement in FE overall (including idle reduction) idle reduction capable of providing 8 hours of idle free auxiliary power, heat and/or air conditioning - assume APUassumes one tractor and three trailers
Package 3. advanced aerodynamics - 2017.	An advanced aero & tire package for 2015 and beyond that includes: Full trailer aero (boat tail, full skirting); tractor-trailer gap optimization; further tractor streamlining and wheel fairings; reshaped aerodynamic trailer. Tires assume RR of 0.0045 using advanced super single tires. Also includes APU	$44,730	Cab Streamlining: $4,750	Trailer Aero - side skirts, gap reducer and rear flap: $4,500 ($1,500 times three trailers)	Low Viscosity lubricants: $500	cab tires - replace 8 wheels w/4 super singles: (4 tires + wheels) x ($1,279/tire + $575/wheel) - (8 tires + wheels) x ($582/tire + $205/wheel) = $1,120	trailer tires: replace 8 wheels with 4 super singles, same calculation as for cab tires times three trailers ($1,120 x 3 = $3,360)	APU: $8000	Trailer reshaping, including tear drop roof, rounded edges, etc	assumes CD of 0.4, tire RR of .0045 and one tractor and three trailers

TABLE B-1

APPENDIX B (continued)

TECHNOLOGY PACKAGES	FUNCTIONAL DESCRIPTION AND NOTES	INCREMENTAL RETAIL COST ESTIMATE*	PARTS COST*							COMMENTS
Package 4. Hybrid	Accessories not electric in package #2 would be electric here. Includes: 50 kW motor generator, battery storage pack - 4 kWh of which 2 kWh is useable, electrification of accessories, modified transmission and clutch assembly, power electronics, high voltage wiring and balance of plant. Engine off at extended idle, regenerative braking, launch assist.	low volume: $35,000 ($30,000 to $40,000). Higher volume $23,000 ($20,000 to $25,000).	50 kW Motor/ generator $1,500 higher volume assuming $30 per kW	4 kWh battery pack $3,200 assuming $800 per kWh	Power Electronics $1,500 assuming $30 per kW	Wiring, electrification of accessories and balance of plant $2,300 based on 25% of all other	modified clutch assembly and automated manual upgrade $2,000	electrification of accessories $1,000		Peterbilt M386 Class 8 hybrid presented at 2007 HTUF conference includes 60hp electric motor/ integrated starter-generator, power electronics, electric A/C, 4-kWh battery pack (2 kWh useable) capable of supporting hotel loads for 55mins after a 5 minute recharge cycle (anti-idle). Provided line haul truck manufacturers proceed to launch this HEV configuration as a product line, moderate volume (200-1000 per year) is expected in 2009-2012 and higher volume (2000-10,000 per year) is expected in 2013-2017. Total cost includes 2.0 RPE factor.
Package 5. Mechanical turbo compound	Based on the Scania 12 liter engine, and it is also very similar to the new Detroit Diesel DD15 engine. This would include port liners to retain thermal energy, variable valve actuation added to engine cylinders, high efficiency power turbine. Assumes a Scania design with a 12-liter engine powertrain.	$2,650	port liners: $500	VVA: $300	high efficiency power turbine: $1,850					Potential 2010 system design variability among engines due to thermal management of after treatment could cause prices to vary by 20% to 30% from what is projected here.
Package 6. Electric turbocompounding	Includes same components described above for mechanical turbo compound, plus an electric motor/ generator, associated power electronics, and electric accessories	$6,550	all components described for mechanical turbocompound = $2,650	40 kW motor-generator: $1,200	power electronics: $1,200 at $30 per kW	electric accessories at $1,000	balance of plant at $500			Includes same components as mechanical turbocompound.

TABLE

B-1

APPENDIX B (continued)

TECHNOLOGY PACKAGES	FUNCTIONAL DESCRIPTION AND NOTES	INCREMENTAL RETAIL COST ESTIMATE*	PARTS COST*							COMMENTS
Package 7. VVA	conventional lost motion VVA	$300	$50 per cylinder incremental cost for VVA implementation in production volumes							
Package 8. Bottoming cycle added to Sturman VVA.	VVA, steam Rankine bottoming cycle system. 30 kW rating at 1600 rpm full load and 100 F ambient. High speed turbine expander-generator, flywheel, air-cooled condenser, stainless steel EGR boiler, stack boiler, balance of plant, controls and power electronics, battery.	$15,100 (assuming thousands of units per year),	Turbine generator and flywheel: $2,160 for a 30 kW system	Air-cooled Condenser based on large mobile AC condensers; 90 kW2 and heat rejection; 13 ft^2 face area: $550	EGR boiler stainless steel: $400	stack boiler: $1,000	Packaging, assembly labor and balance of plant: $2,000	Controls and power electonics: $1,300 ($400 for controls plus $30/ kW for power electronics)	Energy storage: $150 (battery or ultra-capacitor sized to capture peak load for 10 seconds)	Total cost includes 2.0 RPE factor.
Package 9. Rocky Mountain Doubles with GVW increase	Rocky mountain doubles include one 28' trailer and one 48' trailer. Max GVW is 120,000 lbs. Includes increased engine size (increase of 3L), safety features (disc brakes, stability controls, vision systems), engine cooling and after treatment systems also increase proportionally. the transmission is also modified for higher loads.	$17,500	Increase engine size from 13L to 16L with after treatment and modify transmission: $7,500	Add safety features (disc brakes, antilock, vision assists, and stability controls): $4,000	Incremental cost of four doubles instead of three single trailers, including trailer aero, is $6,000					
Package 10. Reduced maximum road speed to 60 MPH applied to one of the above packages	no cost item	negligible cost increase								

TABLE B-1

APPENDIX B (continued)

TECHNOLOGY PACKAGES	FUNCTIONAL DESCRIPTION AND NOTES	INCREMENTAL RETAIL COST ESTIMATE*	PARTS COST*							COMMENTS
Package 11. Advanced EGR	Additional EGR cooler or enhanced primary EGR cooler, as well as additional corrosion-resistant plumbing to remove excess water, minor changes to the system control.	$750	cooler modifications: $500	balance of plant: $250						
Package 12. Bottoming cycle/ single trailer/ advanced aero/hybridization/lower road speed	combination of packages 3, 4, 8, 9, and 10, minus duplicate components	$71,630	package 3 = $44,730	package 4 = 15,000	package 8 = $15,100	package 10 = no cost	Credit for motor, pwr electronics = $3,600		$3,200 in duplicated components subtracted from total cost	
Package 13: electrical turbocompounding/ hybridization/double trailer/lower road speed	combination of packages 3, 4, 6, 9, and 10, minus duplicate components	$80,380	package 3 = $44,730	package 4 = 15,000	package 6 = $6,550	package 9 = $17,500	package 10 = no cost	Credit for motor, pwr electronics = $4,200	$3,400 in duplicated component costs subtracted from total cost	
Package 14: bottoming cycle/ hybridization/double trailer/lower road speed	combination of packages 3, 4, 8, 9, and 10, minus duplicate components	$89,130	package 3 = $44,730	package 4 = 15,000	package 8 = $15,100	package 9 = $17,500	package 10 = no cost	Credit for motor, pwr electronics = $3,600	$3,200 in duplicated components subtracted from total cost	

*unless noted, all costs were obtained as retail costs from published data. For two technologies - hybrid and bottoming cycle, ex-factory costs were first estimated and then a retail price equivalent (RPE) markup was applied to estimate the retail cost for these packages.

Appendix C: Detailed Information on TIAX Cost Analysis

Cost of Package 1: Baseline Vehicle

Kenworth T-600
10 speed manual
2007 Volvo D-13

Aero assumptions:
Bumper fairing, partially aerodynamic mirrors, partial fuel tank fairing, integrated roof fairing, exhaust system out of the air stream (aero drag coefficient: 0.63) (coefficient of rolling resistance: .0068).

Estimated Cost: $125,000 to $135,000 on a fleet purchase basis

Cost of Package 2: SmartWay 1

The “SmartWay 1” package as defined by SwRI includes the following upgrades over the baseline tractor-trailer:

- Additional aero streamlining sufficient to reduce the coefficient of drag from 0.63 to 0.5) to both the cab (fully aerodynamic mirrors, cab side extenders, integrated sleeper cab roof fairings, aerodynamic bumper, and full fuel tank fairings) and the trailers. The trailer streamlining includes a side skirt fairing, and either a trailer gap fairing or a rear-mounted trailer fairing such as a boat tail.

- Improved rolling resistance sufficient to reduce the coefficient of rolling resistance to 0.0055. We have assumed super single low rolling resistance (RR) tires and lightweight aluminum wheels. Super single tires have a steer tire RR coefficient of 0.0058, a drive tire RR of 0.0073, and trailer tire RR of 0.0052.

- Idle reduction (capable of providing eight hours of idle-free auxiliary power, heat and/or air conditioning).

- Improved lubricant package

For this package, TIAX assumed that an Auxiliary Power Unit was necessary at a cost of $8,000. The incremental cost of improved cab streamlining was estimated to be $2,750 for the tractor, while low viscosity lubricants were estimated to have a lifetime incremental cost of $500. A set of four super single low rolling resistance tires and their associated aluminum wheels are estimated to cost $1,120. One set of four is required for both tractor and for each trailer. The trailers also include $2,400 for aerodynamic

retrofits, which include skirts and either a front fairing or a boat tail. Trailer dimensions were 13' 5" to 13' 7" high, 48' - 53' long, and 102" wide).

Total marginal cost for this package was estimated at $22,930 including one modified tractor, three modified trailers and the APU.

Cost of Package 3: SmartWay 1 + SmartWay 2

This advanced SmartWay package (Package 3) includes additional trailer aerodynamic devices needed to achieve a reduction in C_D from 0.5 to 0.4. This package also includes lower rolling resistance tires sufficient to lower the coefficient of RR to 0.0045. The lower rolling resistance tires are assumed to be an incremental improvement from the super single tire package in Package 2 and therefore incur no additional cost. Achieving this level of aerodynamic improvement requires a combination of advanced drag reduction approaches that have not been demonstrated commercially. Achieving this level of drag reduction is very challenging given the present operational constraints of industry. Based on discussions with industry experts [Salari, Marinko] and a review of the available literature, we estimate that a C_D of 0.4 is feasible using the following combination of design modifications to the tractor and the trailer:

- **Smartway Tractor:** Going from the baseline (Package 1) "partial Smartway" tractor to a full Smartway tractor reduces C_D of the vehicle from 0.63 to 0.59. This represents a 6% reduction in C_D.

- **Advanced Smartway tractor modifications:** Additional streamlining of the tractor beyond the level offered by Smartway includes underbody treatments, down exhaust, a lowered ride height, as well as continued optimization of the tractor body. It would also require wheel skirts or hubcaps. We have assumed that these further design modifications could reduce C_D by an additional 4 to 6%.

- **Gap Treatments:** Improved integration between the tractor and trailer interface. This could take the form of a front fairing on the trailer, or extended cab side and roof fairing treatments. These types of devices have demonstrated reductions in C_D that range from 3% to 5% [TMA].

- **Trailer Roof Redesign:** Redesign of the trailer body to use a tear drop design that smooth airflows coming off the top and side of the tractor. In addition, an inset roll-up door and aerodynamic mud flaps can offer additional reductions. Don-Bur, a trailer manufacturer in England, currently manufactures trailer designs that demonstrate the type of design that could realize the proscribed benefits (Figure C-1). Although literature claims fuel consumption reduction on the order of 10%, these numbers are likely optimistic; we have instead assumed a 6 to 7% fuel consumption reduction. Given that roughly half of semi-trailer's road-load goes to overcoming drag at highway speed, this corresponds to a reduction in C_D of approximately 12 to 14%.

- **Full Skirting & Boat tail:** In combination, a full trailer skirt with a boat tail has been shown to reduce C_D by 16 to 20% [Marinko, TMA, Leuschen and Cooper]

To our knowledge, no such fully aerodynamic tractor/trailer combination has been tested. In the absence of such real-world testing, we can estimate the total CD benefit of the described package by combining the individual design modifications multiplicatively[1]. Combining the results in this fashion yields reductions in aerodynamic drag on the order of 35 to 42% from the original CD of 0.63. This would correspond to a total vehicle CD in the range of 0.36 to 0.41. However, given that many of the design modifications help streamline similar portions of the vehicle, this method of estimation likely overstates the benefits. In reality, we would expect the benefits of the full advanced smartway package to lie at the lower end of this estimate. As such, we have decreased the multiplicative estimate by several percentage points (33 to 38%), which gives a CD ranging from 0.39 to 0.42.

FIGURE C-1 EXAMPLE TRAILER DESIGN [DON-BUR]

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[1] i.e., $(1 - \% CD_{Mod\ 1}) \times (1 - \% CD_{Mod\ 2}) \times (\ldots)$

TABLE C-1 COSTS & C_D BENEFITS OF THE ADVANCED SMARTWAY (C_D = 0.4) PACKAGE

	DELTA C_D	PER TRAILER	QUANTITY	TOTAL (3 TRAILERS)
Tires + Wheels – cab	–	$1,120	Times 1	$1,120
Tires + Wheels - trailer	–	$1,120	Times 3	$3,360
Smartway cab	6%	$2,750	Times 1	$2,750
Advanced Smartway cab	4 to 6%	$2,000	Times 1	$2,000
Tear-drop trailer	12 to 14%	$7,500	Times 3	$22,500
Skirting, boat-tail, & gap treatment	18 to 21%	$1,500	Times 3	$4,500
APU	–	$8,000	Times 1	$8,000
Lubricants	–	$500	Times 1	$500
Total	**~33 to 38%**	**$23,990**	**–**	**$44,730**

The costs for such a package are highly uncertain, as no such design has been demonstrated commercially. The following assumptions are used to estimate the total cost of the advanced smartway package:

- It is assumed that as smartway trailer designs are more widely adopted, features such as boat-tails, side skirts, and trailer gap fairings are likely to be integrated into the design of the trailer. In addition, we have not included boat-tailing in the advanced smartway specification. These changes would dramatically reduce the cost of these features compared to the retrofit devices that were priced in package 1. We have assumed that the skirts, boat tail, plus gap fairing will cost on the order of $1,500 per trailer, down from the $2,400 assumed for the original Smartway package (package 2).

- The major additional cost comes from the trailer design modifications that have been proposed. No actual cost estimates are currently available for such a system in high-volume production; it is likely that demonstrator versions would cost about double a typical dry-box van trailer, which cost on the order of $30,000. In high volume, the cost of these design modifications would be significantly lower. We have assumed that in high volume, the price of this advanced tear-drop design would increase the cost of the trailer by 20%, giving an incremental price of $7,500 per trailer.

- Design modifications to the tractor are assumed to come at a slightly lower incremental cost to those anticipated for Package 2. The proposed modifications include evolutionary modifications to the tractor design (which may increase manufacturing costs), as well as underbody treatments and full skirting of the cab. In combination, we estimate these design modifications to cost on the order of $2,000.

The total incremental cost for this package if applied to the Baseline truck is estimated at $44,730 for one tractor and three trailers.

Cost of Package 4: Hybrid

Package 4 builds on Package 2 by converting all possible accessories to electric and adding a parallel hybrid electric system. The assumed HEV System for Class-8 Tractor Trailer Combination is typified by Kenworth and Peterbilt HEV trucks announced in 2008. The Eaton Parallel system and the ArvinMeritor series + parallel system were both modeled by SwRI as part of this study.

The HEV System includes the following major modules:

1. Motor Generator- 50 kW
2. Battery Storage Pack- 4 kWh of which 2 kWh is useable
3. Electrification of Accessories
4. Modified Transmission and Clutch Assembly
5. Power Electronics
6. High-voltage wiring and balance of plant

The hybrid includes a control system capable of the following energy saving features:

- Engine-off at extended-idle
- Power absorption during braking (regeneration)
- Launch Assist
- Maximizes utilization of electric motor at load-speed points corresponding to low efficiency engine operation, when battery SOC permits (modified transmission shift points and motor–assist logic).
- Electric AC and other accessories during hoteling (idle reduction capable of providing idle free auxiliary power, heat and/or air conditioning)

- Electrification of Cooling Fan, Steering, Brakes, Water pump

Cost Estimate and Assumed Timing of Market Introduction:

Moderate volume cost was estimated to be approximately $35,000 (range of $30,000 to $40,000). Higher volume cost was estimated to be approximately $23,000 (range of $20,000 to $26,000). Provided line haul truck manufacturers proceed to launch this HEV configuration as a product line, moderate volume (200-1000 per year) is expected in 2009-2012 and higher volume (2000-10,000 per year) is expected in 2013-2017. The details of these cost estimates are provided below.

The ex-factory cost of HEV-equipped heavy duty trucks can be expected to follow the common evolution from high premiums in the early years (as driveline suppliers attempt to at least partially recoup their non-recurring design-development investments), followed by price reductions due to increased sales volume (economies of scale of manufacturing and assembly). The price history of HEV-equipped transit buses can provide an indication of these early cost trends. For example in the early years when HEV bus sales were in the 10s per year, the price premium for an HEV-equipped transit bus was approximately $200,000 per bus. Later when sales volume rose to 50-100 per year, the price premium decreased to approximately $100,000 per bus. Now that BAE and Allison each have about 1000 HEV buses deployed, the initial investment is presumably largely recovered and prices are in position to decrease as volume increases more (currently 15% to 20% of all transit bus sales are HEV).

The Class-8 HEV truck cost evolution is expected to follow similar trends, only with a somewhat lower cost starting point (since the first HEV line-haul truck announced in 2008 leveraged the previous heavy-duty hybrid manufacturing infrastructure). The fleet buyer's decision for heavy-duty trucks will be much more sensitive to payback period and demonstrable fuel-saving benefits than was the case for the transit industry (where the FTA absorbs a large share of the investment of a new vehicle). A number of heavy-duty HEV trucks have already been purchased by fleets for demonstration and evaluation purposes, and in the early years these too have been priced at a significant (non-economic) premium, justified by the value of the early lessons and demonstration evaluation. Government funding has been available in some instances. In 2005-2007 a number of heavy-duty HEV truck models were announced to be in limited production, such as:

- In 2007 International launched their Class 6-7 Durastar-based HEV in volumes of about 200 trucks so far, reportedly at $53,000 premium with PTO ($43,000 without PTO).
- Eaton successfully completed their trial of a fleet of HEV delivery trucks (Class 4) and announced they are moving into production.
- Freightliner plans to produce 1500 M2 HEV trucks (Class 6-7) based on the Eaton system in the next three years.
- Peterbilt introduced a Class 8 hybrid using the Eaton system and an automated-manual transmission. Bill Kahn of Peterbilt reported $9,600 savings per year through 8% FE improvement and anti-idling; and

indicated a less than 3 year pay-off for the hybrid system.

- Volvo announced production of heavy-duty HEV trucks starting in 2009.
- Arvin Meritor agreed to supply Class 8 HEV trucks for Walmart.
- Azure/StarTrans producing Class 3 HEV Ford shuttle buses at approximately $35,000 premium.

As of the first quarter 2008, the aggregate number of heavy-duty HEV trucks in service (including delivery trucks) is estimated at 500 and the sales volume is expected to be about 200-400 per year in 2008, a figure which includes the Fed Ex, Purolator, UPS and Coca Cola HEV demonstration trucks (Reference: telecom with Bill Van Amburg of WestStart, March 2008). Although line haul HEV trucks are quite few in number, this is expected to change since Peterbilt, Volvo, International and other truck builders have recently announced Class 8 Line-Haul HEV demonstrator vehicles.

For the short term (2009-2011), given fuel price expectations, the interest in HEV trucks is relatively robust, and year-over-year sales are expected to be robust. If this scenario in fact comes true, the HEV truck sales volume will reach approximately 1000 (which is about 3-4% of sales) by the year 2010. This level of sales would not be expected to be enough to really drive down HEV prices significantly, but the HEV market would then be positioned to rapidly expand (see below).

The key assumption is that driveline suppliers such as Eaton, Allison and BAE will elect to offer a single common HEV architecture across all heavy duty truck models and body types. This will accomplish economies of scale and volume parts discounts in the assembly of HEV trucks. For example the new Peterbilt Class 8 HEV Line-Haul truck utilizes essentially the same Eaton-assembled HEV architecture and components as used in the Class 4 Eaton HEV delivery truck.

Another key assumption is that the driveline manufacturer does not have to reach an annual production volume of 20,000 units in order to reduce costs significantly. It is estimated that a new cost plateau can be reached at about 2500 or more annual production for any given driveline manufacturer (and this volume can be made up of diverse truck types such as HEV delivery trucks, HEV utility trucks, HEV line haul trucks, etc)[2]. One scenario is that HEV truck sales continue to rise after 2010 and this “trigger point” of 2500/year might be reached at some point in the 2014-2020 timeframe, depending on a number of factors.

The market for HEV trucks (including HEV line-haul trucks) will be driven by several factors:

- Diesel fuel prices sustained at well above $3.00 a gallon and/or increasing.
- Greenhouse gas policy actions by California and other states as well as the Federal government (carbon taxes, carbon cap and trade, LCFS measures, etc)
- Anti-idling and over-nighting restrictions set by state and local authorities

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[2] Telecon with Bill Van Amburg of WestStart, March 2008

FIGURE C-2

HEV COSTS AS A FUNCTION OF ANNUAL VOLUME

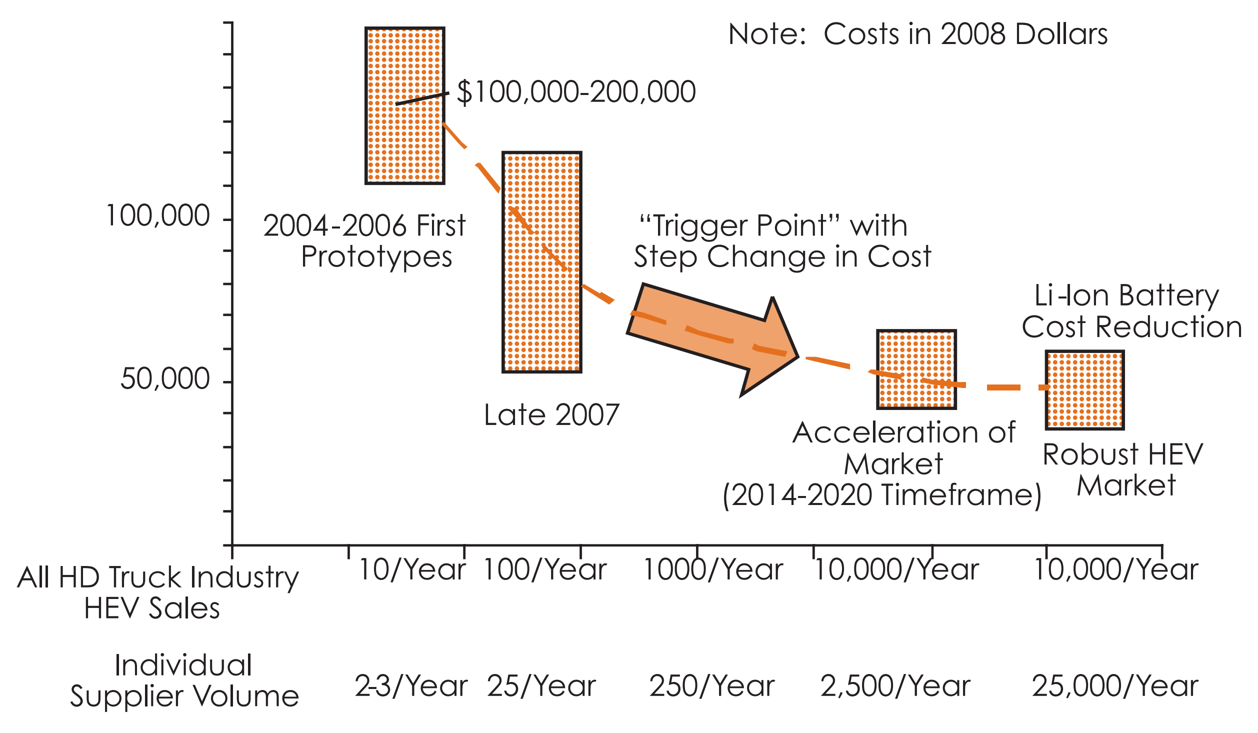


TABLE C-2

HEV SYSTEM COMPONENTS

DESCRIPTION	%	COMPONENT COSTS AT FACTORY
Motor/Generator 50kW	13%	$1,500 assuming $30 per kW
Battery Pack 4 kWh	28%	$3,200 assuming $800 per kWh
Power Electronics	13%	$1,500 assuming $30 per kW
Wiring/Balance of Plant	%20	$2,300 based on 25% of all other
Modified Clutch Assembly and Automated Manual Upgrade	16%	$2,000
Electrification of Accessories	9%	$1,000
Total Components Cost	100%	$11,500
Initial Low Volume Pricing		**$35,000**
Higher Volume Retail Pricing @ 2.0 RPE		**$23,000**

Estimated Pricing of the HEV Option for Class-8 Line-Haul Trucks (low volume)

It is instructive to review the rough costs of individual major components of a typical truck sized HEV system Table C-2 shows the major components of a typical HEV system and the cost of each component (not including such one-time investments as design and development testing).

Based on the above reasoning the premium pricing of the HEV option is presented in three timeframes as follows:

- Near term (low volume) $60,000 to $100,000 per truck
- Moderate volume of 200-1000 per year: $30,000 to $40,000 per truck
- Higher volume of 2000-10,000 per year: $20,500 to $26,000 per truck

In the year 2012-2015 the moderate volume might be applicable, and in the year 2015-2020 the higher volume might be applicable.

Fleet buyer's decision criteria as to HEV based on cost and benefits

The early adopters of HEV line-haul trucks are likely to be large fleet owners who might use a longer payback period as their threshold, whereas the sole-proprietors will be following later in the product lifecycle after volume is up and costs are somewhat reduced.

Forward pricing strategies are likely to come into play in the heavy-duty truck HEV market. The truck builders may offer artificial discounts on their HEV option in anticipation of driving up sales volumes enough to lower their unit production costs (ex-factory). It has been reported that Toyota used similar strategies in the early years of light-duty hybrid car sales, offering the Prius at a premium far under their true incremental cost.

Cost of Package 5: Mechanical Turbocompounding

Package 5 builds on Package 2 by adding a mechanical turbo compound system. This package, based on the Volvo D12 engine, is very similar to the new Detroit Diesel DD15 engine. The costs of a mechanical turbocompound system include the addition of port liners to retain thermal energy ($500), the addition of VVA to the engine cylinders ($300), and a high efficiency power turbine ($1,850). The package also incorporates a Scania design with a 12-liter engine power train. It is important to note the potential for 2010 system design issues and variability among engines due to thermal management of aftertreatment devices. This variability could cause a 20-30% price impact on estimated package cost. Total cost for this package was estimated at $2,650.

Cost of Package 6: Electrical Turbocompounding

Because there is a great deal of overlap between the electrical turbocompounding system and both the mechanical turbocompound and the hybrid system, the electrical turbocompound costs use similar assumptions to these other cost estimates. The electric turbocompound includes the same components as a mechanical turbo-compound. In addition, it adds an electric motor/generator, associated power electronics, and electric accessories. Because it includes several components in common with the hybrid, electric turbocompounding can be synergistically combined with the hybrid package at lower cost than would be suggested by our estimate of the two standalone systems.

The costs of an electrical turbocompound system include the mechanical turbocompound package cost of $2,650 (see above) plus the 40 kW motor-generator ($1,200), associated power electronics ($1,200 at $50 per kW), electric accessories at $1,000 and balance of plant at $500 for a total cost of $6,550.

Cost of Package 7: Variable Valve Actuation

Package 7 adds variable valve actuation (VVA) to Package 5 (mechanical turbocompounding). VVA is expected to work best when combined with a turbo compound system. There are two distinct designs of VVA, only one of which is in production:

- Full-Authority VVA, which is designed to be fully adjustable during engine transients, actuated with fast response devices such as camless or hydraulic-electric mechanisms (e.g. Sturman VVA technology)
- Conventional "lost-motion" VVA which has restricted preset valve settings which are cam actuated (e.g. Caterpillar VVA).

Full-Authority VVA Costs: Potential VVA technology suppliers such as Sturman have yet to show that their fully adjustable VVA system is market-ready; test data from prototypes are not available. The fully adjustable configuration of VVA is likely to carry a significant cost increase to the manufacturer. Hydraulic valve actuation or camless actuation mechanisms would add a significant cost in excess of any potential cost savings for manufacturers once control logic software is embedded in engine control software. Software advancements were assumed to be free. Presumably a significant portion of the cost associated with implementing any full-authority VVA package would be licensing fees and amortized development costs. We were not able to accurately estimate the cost for this type of VVA.

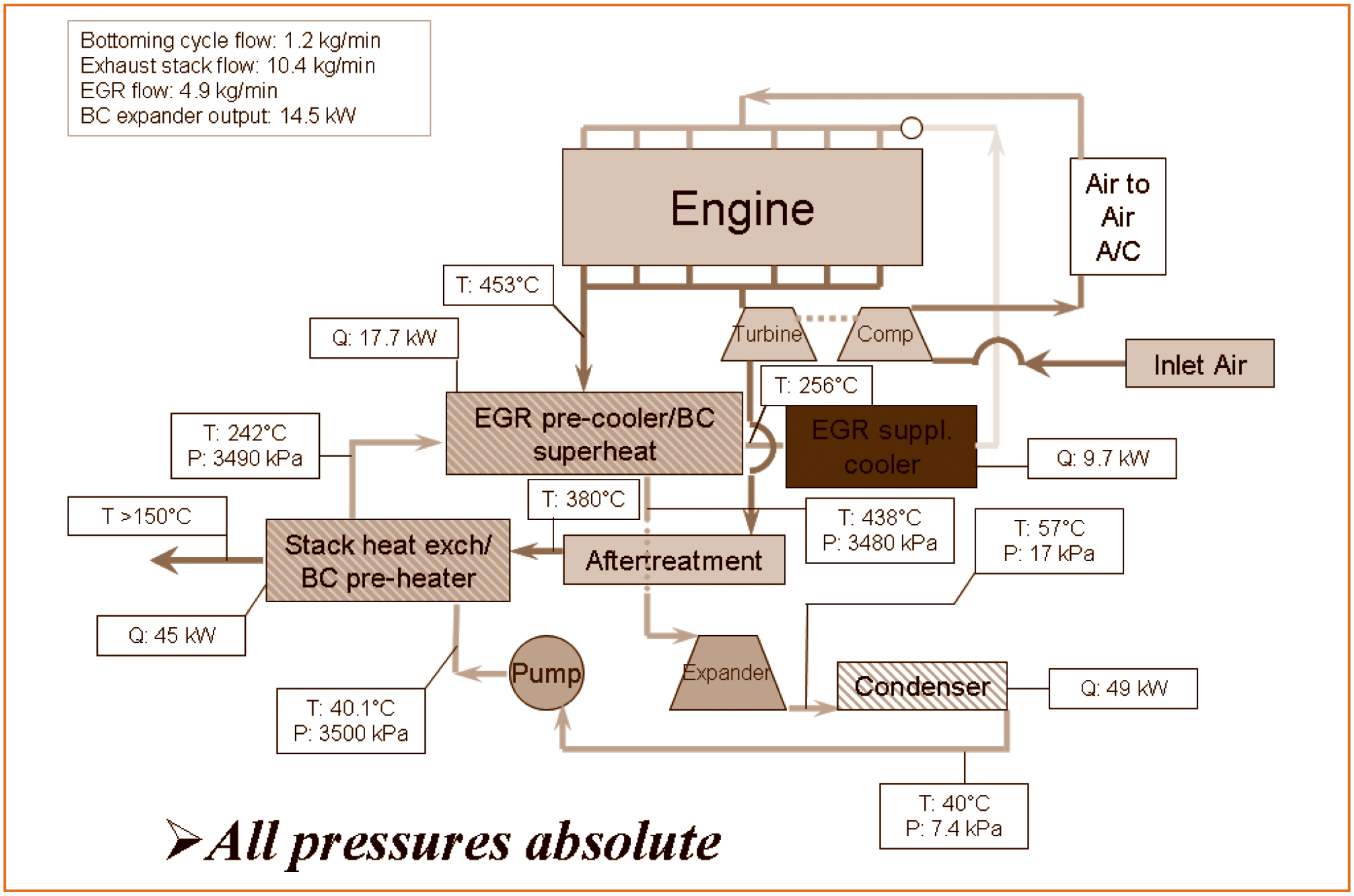
Conventional "Lost-motion" VVA Costs: This type of VVA design was selected as the basis for Package 7. An estimate of $50 per cylinder incremental cost was assigned for VVA implementation in production volumes. The total marginal cost therefore is estimated at $300 above the Package 5 Costs (see above).

Cost of Package 8: Bottoming Cycle

Package 8 combines VVA, SmartWay 2 (Package 3) and a Rankine bottoming cycle system recovering heat from both the EGR cooler and an exhaust stack boiler. It was assumed that the EGR cooler and bottoming cycle system would be co-designed as a package to meet both emissions and fuel economy targets. Bottoming cycles are a relatively mature technology for stationary diesel and natural gas engines in the 1,000 kW to 20,000 kW class, and bottoming cycle controls and packaging issues are relatively benign because of constant speed operation at relative steady load. Bottoming cycles have never been used for trucks, but early-stage designs currently are being explored by selected engine manufacturers. There are current examples from the 21st Century Truck program, including conceptual designs by Cummins and Caterpillar. For example, the Cummins Rankine cycle [reference to DOE advanced engine paper needed] uses heat from a massive EGR system. However, because these designs are preliminary, it was decided to develop a preliminary generic design for a truck bottoming cycle on which to base the costing. The system was designed to avoid impacting the DPF or NOx aftertreatment.

FIGURE C-3

SCHEMATIC OF RANKINE BOTTOMING CYCLE FOR TRUCK ENGINE



It was not clear to the study participants whether bottoming cycles will be feasible and practical for potential widespread adoption by the trucking industry within the timeframe of the study (out to 2017). Issues include cost, packaging, weight, maintenance/reliability and the needed controls to capture fuel savings potential. Our costing analysis attempts to capture these issues. However, the schematic is totally hypothetical and only one of several basic architectures that could be proposed.

Generic bottoming cycle for a long-haul truck (sized for operation at highway cruise)

SwRI provided a schematic of a generic steam bottoming cycle operating at the cruise point which is shown in figure C-3 for illustration.

As shown in figure C-3, the bottoming cycle would include four main components: (1) A high-speed turbine expander generator (80,000-200,000 rpm); (2) An air-cooled condenser; (3) An EGR heat recovery boiler, which is an upgrade of the baseline EGR cooler; and (4)an exhaust stack heat exchanger/boiler. The SwRI bottoming cycle design also includes additional battery storage to provide for absorbing excess power during rapid decelerations, hill climbs and other transient events.

System sizing for the line haul truck presents an interesting optimization problem which deserves a more detailed analysis than was possible under this project. The highway cruise point on level roadway requires only a 12-14 kW rated bottoming cycle, but this is seen as suboptimal considering the real life situations of accelerations and climbing at grades. At the other extreme, the full load operation can support a 57 kW rated bottoming cycle, but this is seen as overly costly since the truck engine only rarely operates at true full rated load and speed. Therefore an intermediate rating was selected as a basis for costing. The bottoming cycle system was assumed to be sized for 30 kW rating at 1600 rpm full load and 100 F ambient. The basic premise is that for a long-haul truck, if the bottoming cycle is not attractive at highway cruise, it probably will not make sense for the complete typical drive cycle. The available EGR heat is assumed to be supplemented by an exhaust stack heat exchanger. The condenser is a finned-tube air-cooled heat exchanger stacked with the engine radiator and assumes a heat transfer coefficient of 20 BTU per hr-ft^2-F. The fin-tube boiler has a volume of approximately 1 cubic ft.

Cost Estimate:

The total marginal cost estimated for the 30 kW bottoming cycle was $15,100 after production volumes become significant (thousands per year). This technology will not be available until 2015-2017 at the earliest and initial cost the first few years would be expected to be at least double ($34,000 to $40,000). The basis for this cost estimate is provided below.

Steam vs organic working fluid for Rankine bottoming cycle

The system assumed for Package 8 uses a steam Rankine cycle. Steam has better heat transfer characteristics and the potential for higher efficiency, but can present expansion-turbine design challenges at small scale. These challenges arise because high sonic velocity translates into high turbine RPM (~200,000 RPM) and large expansion ratio require multiple stages to realize efficiency potential. Organic working fluids have higher molecular weight, lower speed of sound, and lower pressure ratio, and hence offer better matching with small turbine expanders (and other types of expanders as well). Most bottoming cycle developers for stationary engines have selected an organic working fluid. These other working fluid systems could also be an appropriate design choice.

In order to size and cost the various components, we analyzed the steam cycle shown in figure C-XX above, assuming:

- Heat to boil and superheat (by 150°F) water is supplied by the recoverable heat from the exhaust, as defined above.
- Heat to preheat the water from the condensing temp to the boiling temperature is supplied by an economizer transferring heat from the exhaust leaving the boiler to the feed water.
- Rough estimates from steam tables T-s diagram, assuming 70% efficient expander.
- Condensing temperature is 200°F at 100°F ambient, 150°F at 60°F ambient and 100°F at 20°F ambient. There is a smaller temperature difference at

20°F ambient because there is no air conditioning load and less overall thermal stress on the cooling system.

The estimated bottoming cycle power output is 14 kW at the truck highway cruise point. This power output can be obtained at boiling temperatures of either 400°F or 500°F. At the higher boiling temperature (500°F), less heat can be recovered from the exhaust, but the Rankine cycle efficiency is higher; the reverse is true at the lower boiling temperature of 400°F.

The steam Rankine cycle requires a high speed (80,000-200,000 RPM) turbine expander – generator. The electric power output of this generator in turn powers a battery, with power extracted as needed to contribute to the engine shaft power output. The condenser is a finned tube air cooled heat exchanger, stacked with the other air cooled heat exchangers behind the front grill (air conditioning condenser, charge air cooler, bottoming cycle condenser, engine radiator). The estimated size and weight are based on the following assumptions: (1) 20 fins/inch; (2) An air side "h" of 20 Btu/hr-ft^2-°F; (3) Half of the overall heat transfer resistance occurs on the air side; and aluminum comprises approximately 15% of the volume solid material. The boiler is a finned tube HX with fins on the exhaust side. Its estimated size and weight are based on the following assumptions: (1) 10 fins/inch; (2) Exhaust side "h" of 20 Btu/hr-ft^2-°F; (3) Half of the overall heat transfer resistance occurs on the exhaust side; and aluminum comprises approximately 15% of the volume solid material.

Rough estimates of the dimensions and weights of the major bottoming-cycle components of a 30 kW output at 100°F ambient temperature are summarized in Table C-3. Figure C-3 shows the dimensions of the major components compared with the physical dimensions of a typical heavy duty truck engine.

TABLE
C-3 **ESTIMATED DIMENSIONS AND WEIGHT OF MAJOR COMPONENTS OF BOTTOMING CYCLE**

MAJOR COMPONENT OF 12 KW SYSTEM	APPROXIMATE DIMENSIONS	WEIGHT (LB)
Turbo expander – generator	6 inch diameter by 16 inches long	75
Air cooled condenser	36 inch X 20 inch X 1.5 inch deep	15
Exhaust heat recovery boiler	6 inch X 8 inch X 24 inch long	50
Exhaust Stack Heat Exchanger	6 inch X 8 inch X 24 inch long	50
Misc – working fluid, tubing, feed pump	~ 0.75 ft^3	50
Total	**~ 3 ft^3**	**240**

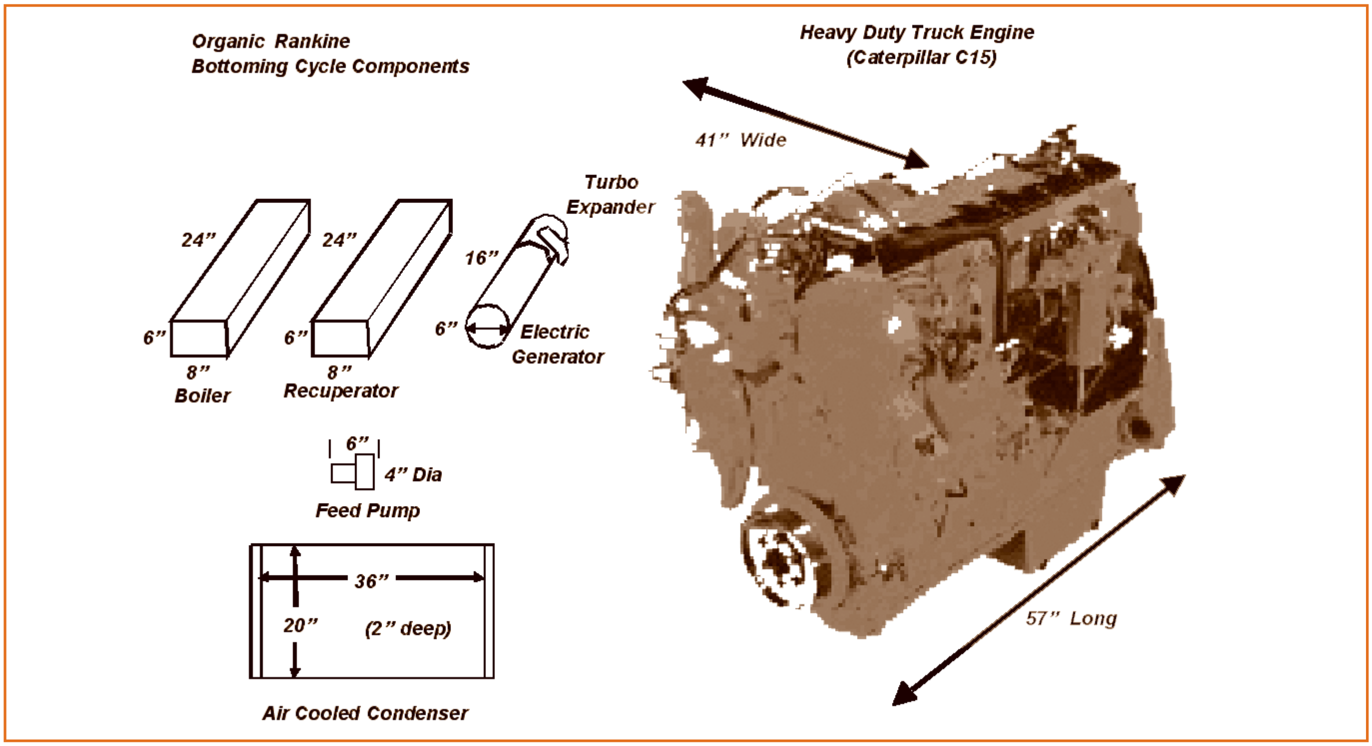
TABLE C-4

DETAILED COSTS FOR BOTTOMING CYCLE COMPONENTS

	12 KW	30 KW	57 KW	COMMENTS
Turbine Generator and Flywheel	$860	$2,160	$4,100	Based on turbocharger parts of $42/kW, $30/kW generator
Air-cooled condenser	$ 500	$ 550	$1,000	Based on large mobile AC condensers; 90 kW[3] and heat rejection; 13 ft^2 face area
EGR boiler (stainless steel)	$ 500	$ 400	$ 400	
Stack boiler	NA	$1,000	$1,500	Both boilers sized by capacity and log mean temperature difference
Packaging, assembly, and balance of plant	$1,500	$2,000	$2,500	
Controls and power electronics	$750	$1,300	$2,100	$400 for controls plus $30/kW for power electronics
Energy Storage	$100	$150	$300	Battery or ultracap sized to capture peak load for 10 seconds
Total Cost at Factory	$4,200	$7,550	$11,900	
Total Retail Cost	$8,400	$15,100	$23,800	Applied RPE of 2.00

FIGURE C-4

SIZE OF MAJOR COMPONENTS OF RANKINE BOTTOMING CYCLE COMPARED TO DIMENSIONS OF HEAVY DUTY TRUCK ENGINE



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[3] For the 30 kW system

Bottoming Cycle Component Costs:

Based on the sizes, materials, and weights of these components, and based on the typical costs of conventional HVAC manufactured items such as heat exchangers and compressors which are similar in function, cost for the bottoming cycle system were estimated. The estimated costs for these components are detailed in Table C-4.

Figure C-4 provides a schematic illustrating the size of the different bottoming cycle components relative to a heavy-duty truck engine.

Cost of Package 9: Longer / Heavier Trucks

Package 9 builds on Package 2 with "highway doubles" which create a gross vehicle weight (GVR) and volume increase. This package is assumed to be based on the Scandinavian approach of 60 metric tons (about 132,000 pounds) and 25 meters total combination length. We estimated the cost for this package by assuming three cost elements:

- Powertrain modifications for maintaining speed at grade
- Safety features
- Incremental cost of two doubles vs three singles (assuming that in fleets, ten "doubles" would suffice in place of fifteen single trailers).

In the power-train area, the base engine size would increase by approximately 3L to accommodate the added load. Besides the engine block itself, engine cooling and aftertreatment systems (as well as some other smaller systems) would also have to increase proportionally. The transmission would need to be modified for higher loads. We estimate the incremental cost of these power-train modifications to be $7,500.

Safety features such as disc brakes, stability controls, and vision systems were assigned a retail incremental cost budget of $4,000.

The incremental cost of two doubles over three single trailers was estimated at $6,000. This includes the added cost of the trailer, plus the additional aerodynamic devices and super single tires included in the Advanced Smartway package.

FIGURE
C-5 ROCKY MOUNTAIN DOUBLE

(Source: FHA)

The total retail incremental cost for this package was estimated at $17,500. It is interesting to note that Rocky Mountain Doubles could be a negative cost package, since fleet operators may find that they would need fewer cabs to move an equivalent amount of freight. This nuance is not captured in our analysis.

Cost of Package 10: Reduced Road Speed

This package assumes speeds would drop to 60 miles per hour or below. There were no hardware or technology costs associated with this package.

Cost of Package 11: Advanced EGR

The advanced EGR concept that was modeled requires additional cooling to a conventional EGR system. The lower temperature exhaust reduces NOx, which allows timing to be advanced, thereby offering incremental efficiency improvement. Such a system would likely require an additional EGR cooler (or an enhanced primary EGR cooler), as well as additional corrosion-resistant plumbing to remove excess water and minor changes to the system control. We estimate this package will cost on the order of $750 ($500 for the cooler modifications, plus $250 for the additional balance of plant).

Cost of Packages 12, 13, and 14: Maximum Technology Combinations

The costs of three modeled packages are described in this section – packages 12, 13, and 14. The costs of the maximum technology combination packages are calculated as the sum of the individual technology packages, less the cost of any duplicate components (e.g., both the hybrid and electric turbocompounding include a motor/generator):

Package 12: The maximum technology combination with a single trailer – is estimated to cost $71,630. This includes the cost of Package 3 ($44,730), Package 4 ($23,000), Package 8 ($15,100), and Package 10 (No cost), minus $3,200 in duplicated components between the hybrid and bottoming cycle systems (motors, energy storage, and power electronics). Package 12 also does not need the APU that is included as part of package 3, because the hybrid system already offers these idle reduction benefits; this reduces the cost by an additional $8,000.

Package 13: Is estimated to cost $80,380. As described in Chapters 2 and 3, this package includes a longer heavier trailer, advanced aerodynamics (package 3 - $44,730), hybrid (package 4 - $23,000), Package 6 ($6,550), Package 9 ($17,500), and Package 10 (No cost), minus $3,400 in duplicated components between the hybrid and electric turbocompounding systems and minus $8,000 for the omission of the APU.

Package 14: The maximum technology combination with a double trailer – is estimated to cost $89,130. This includes the cost of Package 3 ($44,730), Package 4 ($23,000), Package 8 ($15,100), Package 9 ($17,500), and Package 10 (No cost), minus $3,200 in duplicated components between the hybrid and bottoming cycle, and minus $8,000 with the removal of the APU.

O&M Costs

Operations and Maintenance (O&M) includes any additional maintenance or repair costs that are incurred with the addition of new technologies. For a typical long-haul truck, O&M accounts for 5% of the total capital cost every 100,000 miles [OOIDA]. We anticipate that many of the technologies examined would incur incremental O&M costs significantly lower than this, for a number of reasons: they typically do not require any additional routine maintenance; they may require variations on existing designs (and hence would have a similar repair schedule), rather than the addition of new components; and to the extent that new components are included, these are often highly reliable and may be expected to last the life of the vehicle. For packages that fall into this category, we estimated that O&M costs would be close to those seen in stationary applications, which are typically closer to 1% of the capital cost per year [IEA][4]. However, several packages include specific components or add complexity that would lead to significantly higher O&M costs. We estimated O&M for these systems on a case-by-case basis.

Package 2 (Smartway): *($0.004/mi)* The improved aerodynamic cab and trailer design is not anticipated to add significantly to O&M costs over the baseline vehicle. However, the additional cost of single wide tires is incurred every time tires are replaced and/or retreaded. OOIDA estimates tire replacement costs of approximately $2,800 per 100,000 miles. The super single tires that were specified cost approximately 10% more than the tires that they replace; hence, it is assumed that they incur a $280 incremental cost per 100,000 miles. In addition, it is assumed that the advanced lubricants need to be replaced every 300,000 miles.

Package 3 (Advanced SmartWay): *(negligible)* Includes only additional trailer aerodynamics, which we do not anticipate will add to O&M costs.

Package 4 (Hybrid): *($0.006/mi)* The hybrid includes the addition of an electric motor/generator, power electronics, electric accessories additional wiring, and a battery. The added electronics and motor tend to be highly reliable and should not require additional maintenance. Added O&M due to these components is estimated at 1% of capital per 100,000 miles. Real-world experience with batteries in trucking applications, which includes a service life of hundreds of thousands of miles, is limited. Batteries in light-duty hybrids have demonstrated service lives of 100,000 to 200,000 miles over a 10 year life. For long-haul trucking, we assume that batteries will last for 6 years. The O&M costs amortize the future (discounted at 7%) battery replacement cost over six years and include this cost in the per-mile O&M[5].

Package 5 & 6 (Mechanical & Electrical Turbocompounding): *($0.0003-$0.0007/mi)* Both packages require the addition of a power turbine and VVA; electrical turbocompounding requires a power turbine plus an additional motor and power electronics. These factors are estimated to incur 1% for every 100,000 miles.

Package 7 (VVA): *(negligible)* Requires design modification to the engine cylinders. This is not anticipated to add significantly to O&M costs.

Package 8 (Bottoming Cycle): *($0.003/mi)* The bottoming cycle adds considerable complexity to the vehicle. For this system, we assume a higher O&M cost of 2% for every 100,000 miles.

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[4] To equate capital costs in stationary applications (expressed in $/kWh) to mobile applications ($/mi), we assume an average vehicle speed of 60 MPH.

[5] The longer service life (in terms of mileage) compared to light-duty applications reflects that: (1) there is a limited window for calendar life-based degradation, which can be an important limit on battery lifetime; (2) the steady-state nature of most of the long-haul duty cycle suggests that the battery will not see nearly as many cycle as a battery in a light-duty duty cycle. These estimates will need to be validated against real-world experience.

Package 9 (Rocky Mountain Double): *($0.002/mi)* The Rocky Mountain Double includes a larger engine and exhaust system, additional safety features and brakes; these factors are not anticipated to add significantly to vehicle O&M. These are estimated to incur 1% for every 100,000 miles. In addition, because the Rocky Mountain Double includes 1.33 times more trailers, there is an added super single tire replacement cost equal to one third the tire replacement cost of the Smartway package.

Package 10 (60 MPH Speed Limit): *(negligible)* No added cost.

Package 11 (Advanced EGR): *(negligible)* As an enhancement to the conventional EGR system that already exists on the baseline vehicle, we do not anticipate additional costs.

Package 12 (Technology Packages): For the combined technology packages, O&M costs are estimated as the sum of the individual technology O&M costs.

The incremental cost of each technology package was estimated following the methods described in Chapter 2.

Cost-Benefit Results

Using the methodology described in Chapter 2, TIAX evaluated the cost effectiveness of different technology packages. As discussed previously, two different figures of merit were examined – the net cost of ownership over a fifteen year vehicle lifetime, and the net cost of ownership over a three year time horizon for both the 2008 EIA reference and high fuel price scenarios. The results of these calculations are shown in Figure C-6.

Two overarching themes emerge from these calculations. First, there are a number of technologies that appear very attractive when viewed over the fifteen time horizon (or over a three-year time horizon with high fuel prices). However, under the reference fuel price scenario (roughly $2.50 per gallon), only the lower priced, lower benefit technologies (VVA, advanced EGR, mechanical turbo-compounding), and the two packages that entail operational changes (speed limit reduction and longer, heavier trailers) have a negative cost of ownership. This finding illustrates the challenge of deploying new technologies in the fleet: while a technology may be cost effective over the vehicle's service life, if fuel prices remain low, it may not be adopted by the market.

Cost-Benefit Results of Individual Packages

Examining the results on a technology-by-technology basis, these cost-of-ownership calculations may be used to loosely group the technology packages into several categories:

Operational Changes – Speed limit & Longer, heavier trailers (Packages 9 and 10): These packages are highly cost-effective approaches to saving fuel. They each offer significant savings over both a fifteen-year time horizon and a three-year time horizon under both high and low fuel price scenarios. Implementing these packages is as much of a political question as they are an economic question.

Low Capital Cost Technologies – Advanced EGR, VVA, Mechanical turbo-compounding, electric turbo-compounding (Packages 5, 6, 7, and 11): These packages are generally low-cost (ranging from a few hundred dollars to $7,000 for electric turbo-compounding), and offer benefits that range from 1 to 4.5%. With the exception of electric turbo-compounding, they each offer payback within three years under the reference case fuel scenario; electric turbo-compounding achieves payback in just under four years under the reference case, and has a negative cost of ownership over a fifteen-year time horizon in both fuel price scenarios. These technologies are all relatively low technical risk and are likely to be available in the next several years. They would all potentially be attractive to buyers who are sensitive to first cost.

High Capital Cost Technologies – Smartway, Advanced Smartway, Hybrid and Bottoming cycle (Packages 2, 3, 4, and 10): These packages all offer significant fuel savings, but come at much higher cost than the technologies discussed above. None of these technologies achieve payback within three years under the reference fuel price scenario. However, both Smartway packages offer very high value over a fifteen year time horizon, and are also very attractive over a three-year time horizon with high fuel prices. The greatest barrier to widespread adoption of the Smartway package is that, given current standard practice in industry, the trailer aerodynamic devices must be deployed on three different trailers. The advanced Smartway package must also overcome this barrier to adoption; in addition, its implementation would require dramatic changes to trailer design. The bottoming cycle is a high technical risk package that could offer high single-digit or low double-digit fuel savings; it is likely to offer favorable payback over a fifteen-year time horizon, or over a three-year time horizon with high fuel prices. The hybrid package has a positive cost of ownership over a three-year time horizon, and just breaks even over fifteen years under the reference fuel price scenario. One of the key factors influencing the hybrid's payback is the amortized cost of battery replacement. However, there are synergies that may be realized when the hybrid system is combined with other electrification strategies.

Technology Combinations (Package 12, 13, and 14): The technology combination packages are highly cost-effective when viewed over a fifteen year time horizon, and are close to a negative cost of ownership over a three year time horizon under a high fuel price scenario. However, under the reference fuel price scenario, the realized fuel savings over the first three years are not great enough to overcome the high initial cost.

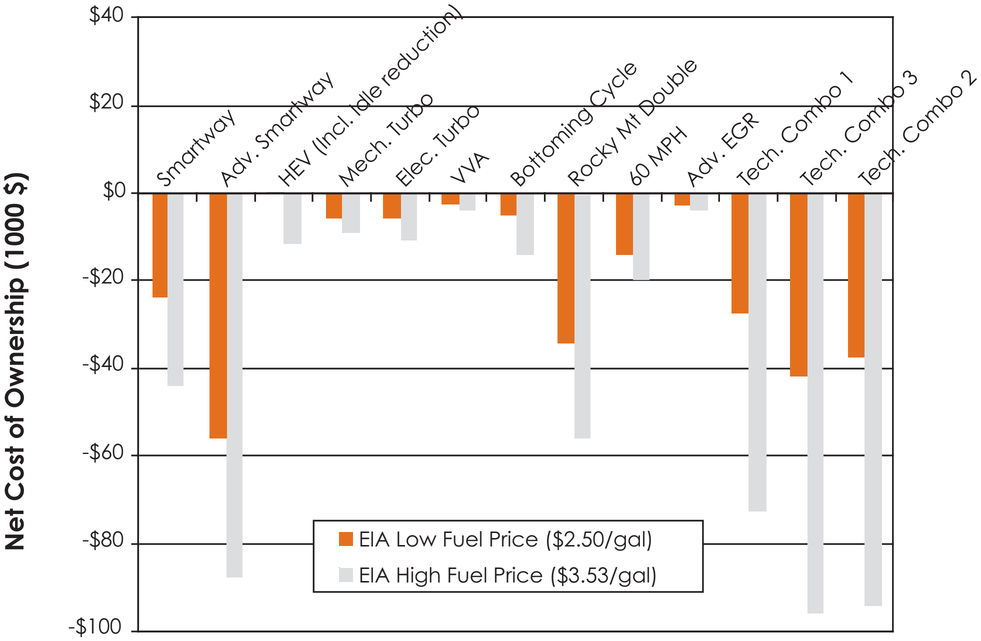
To the extent that the technology combination packages are cost effective, it is due primarily to the inclusion of the obvious winning technologies (Smartway, 60 MPH governor, and Rocky Mountain Double). In some respects, the cost-effectiveness of these individual technologies, reflected by their negative cost of ownership, masks the inclusion of other, less cost-effective approaches. At the same time, the technology combination packages do benefit from synergies between the hybrid system and electric turbocompounding (in the case of the "Low Cost Technology Combination"); and synergies between the hybrid system and the bottoming cycle (in the case of the two "Max. Technology Combinations"). Because there is significant overlap in the components needed to implement these increasingly electrified systems, the combinations are more cost-effective than the standalone systems.

Figures C-7 and C-8 summarize graphically the 3-year and 15-year payback analyses. Figure C-7 shows the results of the analysis for the 15-year payback case. The solid colored bars represent the EIA low fuel price scenario and the hatched bars represent the EIA high price scenario. In this graph, negative numbers indicate a savings for the truck owner.

FIGURE

C-6

NET COST OF OWNERSHIP CALCULATION FOR TECHNOLOGY PACKAGES – 15 YEAR TIME HORIZON WITH TWO FUEL PRICE SCENARIOS



FIGURE

C-7

NET COST OF OWNERSHIP CALCULATION FOR TECHNOLOGY PACKAGES – 3 YEAR PAYBACK WITH TWO FUEL PRICE SCENARIOS

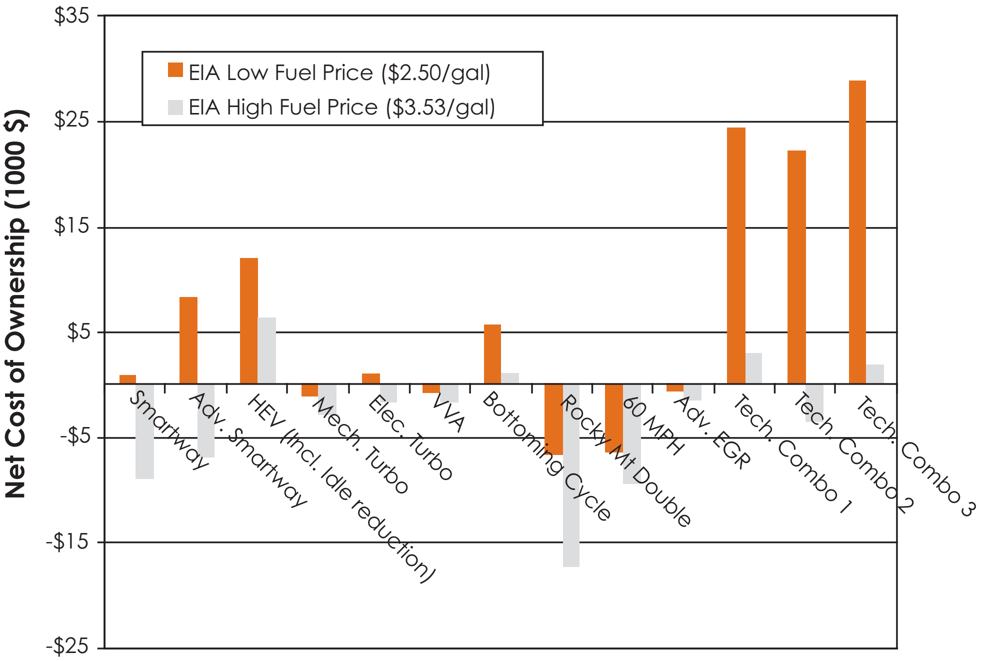


Figure C-7 illustrates the results of the 3-year payback scenario. In this Figure, solid bars also represent the EIA low fuel price of $2.50 per gallon of diesel in 2022 and the hatched bars represent the EIA high fuel price scenario of $3.53 per gallon in 2022.

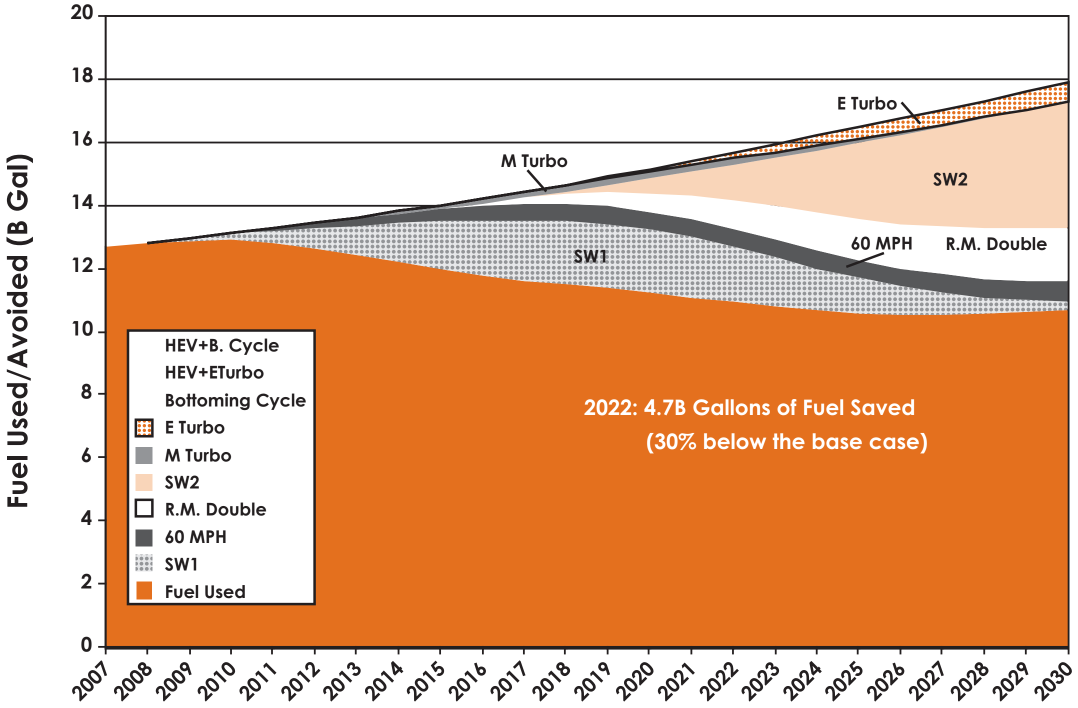
To assess the impact of fuel saving devices on the line-haul tractor trailer fleet, we incorporated the results of the above analysis into our bottom-up tractor trailer fleet model. Because these technologies focus primarily on the long-haul (as opposed to regional) portion of the fleet, the analysis focuses on this fleet sub-segment. Two different technology adoption scenarios were considered, and analysis was conducted for both high and low fuel prices scenarios.

Reference Fuel Price Scenario

Predicted Fuel Consumption Reduction under Scenario A

The fleet model estimates that the technologies adopted in Scenario A (the 15-year time horizon, which uses lifetime NPV to select technologies) have the potential to reduce fuel use in the long-haul truck fleet by 30%, or 4.7B gallons, by 2022 under the reference case fuel price scenario. These dynamics are illustrated in Figure C-6, which shows the total projected fuel use to 2030, as well as the avoided fuel use associated with individual fuel-saving technologies for the long-haul section of the tractor trailer fleet.

FIGURE C-8 ANALYSIS OF CO_2 AND FUEL USE AVOIDED IN THE U.S. LONG-HAUL FLEET ASSUMING ALL TECHNOLOGIES WITH A 15 YEAR PAYBACK ARE USED.



Note that the top 3 technologies in the legend are not used under this case.

As shown, fleet fuel use declines until 2022 to 2024, at which point it slowly begins to rise again. Initially, reductions are primarily due to phase-in of trucks with SmartWay 1 packages and the 60-MPH speed limit. Beginning in 2017, SmartWay 2 and Rocky Mountain doubles dominate the reduction wedge, although the turbo-compounding package also offers significant benefit. The increase in fleet fuel use beginning in 2022 arises due to continued growth in freight ton-miles, coupled with the fact that no new improvement options are introduced into the model after 2017. In reality, innovation will continue past this point, but this nuance is not captured in the model, as it is not clear which technology options will be available. Initially, mechanical turbocompounding is adopted. Because it has a net-negative cost of ownership and it offers greater fuel savings than VVA and advanced EGR, it supersedes these technologies in the fleet. Similarly, as the cost of electrical turbocompounding goes down and fuel prices rise, it supersedes mechanical turbocompounding in the market beginning in the 2017 to 2020 timeframe. Due to their high initial and O&M costs, neither the hybrid nor bottoming cycle packages are adopted under the reference fuel price scenario[6].

Fuel Price and Technology Adoption Scenario Comparison

Figure C-9 shows the avoided fuel use in five-year increments for both scenarios under the low and high fuel price scenario. As shown, Scenario A offers significantly more fuel savings than Scenario B, particularly in the reference fuel price scenario. As might be expected, the high fuel price scenario has a comparatively greater effect on Scenario B (market-driven adoption) than on Scenario A.

As shown, Scenario A already implements most of the available technologies across the entire fleet even under the low fuel price scenario. The additional improvements occur due to adoption of the bottoming cycle beginning in the 2020 timeframe.

The reduced fuel use in Scenario B stems from increased technology penetration across the board: the combined penetration of the two Smartway packages increases from 35 to 40% to over 60%, while Rocky Mountain Doubles become nearly fully adopted. In addition, both electric turbocompounding and the bottoming cycle increase their market share at the expense of mechanical turbocompounding, VVA, and advanced EGR.

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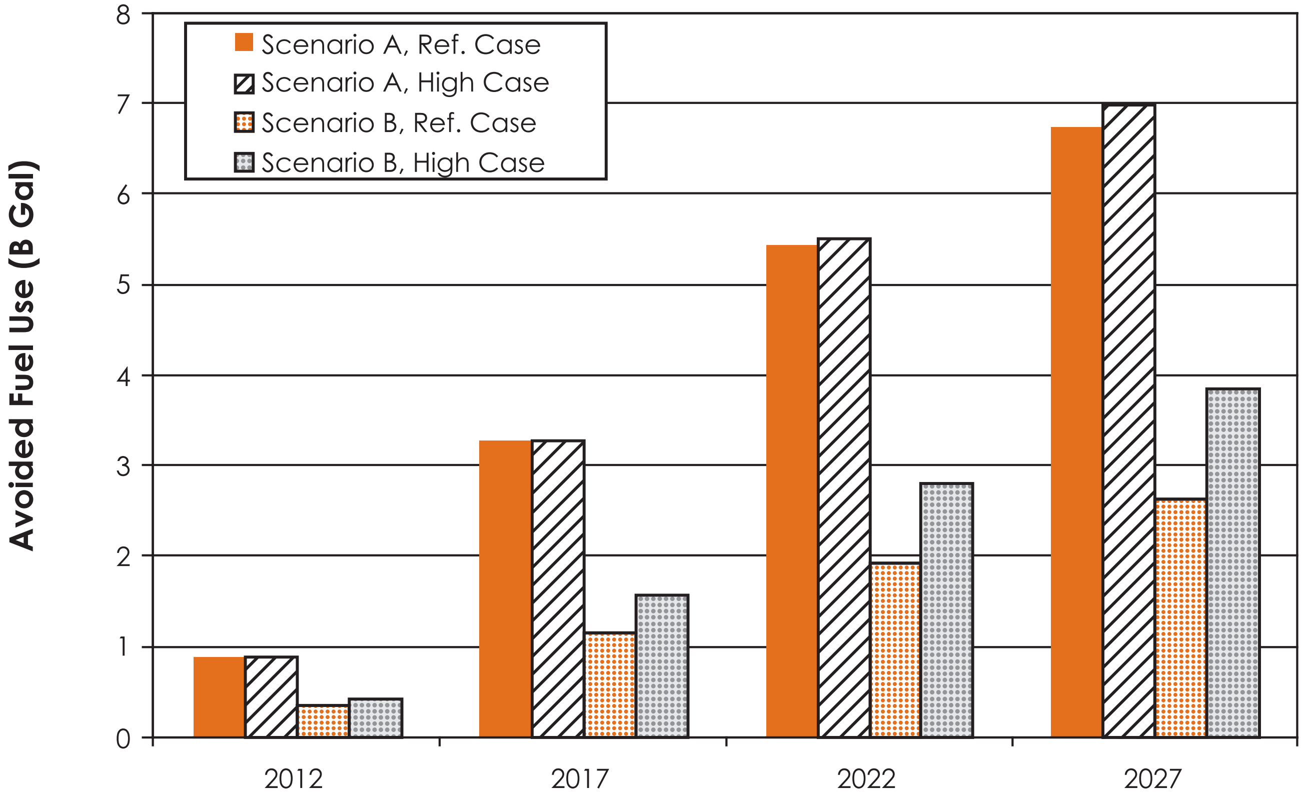
[6] Appendix E includes year-by-year market penetration of different technologies.

FIGURE C-9

AVOIDED FUEL USE ASSUMING TWO PAYBACK PERIODS AND TWO FUEL PRICES



Appendix D: Detailed Information on the Fleet Model Analysis

Fleet Model Methodology

The fleet model uses estimates of new truck sales, scrap rates, VMT, and fuel economy to develop a bottom-up estimate of fleet-wide characteristics, such as fleet fuel use, fleet VMT, and truck population. This approach is similar to that used by Bandivadekar et al [2008] for their analysis of the light-duty vehicle fleet.

For trucks that are n years old in year t, the total truck population ($pop_{tot}(n,t)$), mileage ($VMT_{tot}(n,t)$), and fuel use ($fuel_{tot}(n,t)$) for that particular vintage are calculated as follows:

$pop_{tot}(n,t) = sales(n,t) – scrap(n)$

$VMT_{tot}(n,t) = pop_{tot}(n,t) \times VMT(n)$

$fuel_{tot}(n,t) = VMT_{tot}(n,t) \times FE(n,t)$

Where t is the current year; n is the truck vintage; sales(n,t) is the new truck sales in the year (t-n); scrap(n) is the estimated retirement rate for a truck that is n years old; VMT(n) is the estimated mileage driven by an in-use truck that is n years old; and FE(n,t) is the average fuel economy of trucks sold in the year (t-n). he total truck population, VMT, and fuel use across all vintages in year t is then calculated as the sum of these factors across all vintages:

Truck population $(t) = \Sigma pop_{tot}(n,t)$

Total VMT $(t) = \Sigma VMT_{tot}(n,t)$

Total fuel use$(t) = fuel_{tot}(n,t)$

Fleet Characterization and Data Sources

The key assumptions and data sources used to characterize the regional and long-haul fleets are summarized in Table D-1.

TABLE D-1 TRACTOR TRAILER FLEET ASSUMPTIONS

	REGIONAL	LONG-HAUL	SOURCE
Fleet Size in 2008[1]	830,000	570,000	TEDB 2007, MOVES 2004
Fraction of TT sales	20%	80%	VIUS 2002
Tractor Trailer Sales[2]	87,000		Wards 2008, VIUS 2002
Fleet growth rate	1.7%/Yr		EIA 2008
2008 Fuel economy	6.0 MPG		TEDB 2007
Median Age	19 Yrs	7.5 Yrs	TEDB 2007
VMT per year	80,000 (Age = 0) 28,000 (Age = 15)	140,000 (Age = 0) 50,000 (Age = 15)	VIUS 2002

---

[1] 2008 bottom-up estimate; This estimate includes only that portion of the fleet which pulls box trailers.

[2] Five-year average (2002-2007) estimate for tractors. The available data segments new truck sales according to weight class, but not according to body type (i.e., combination vs single-body truck). As such, our estimate of combination truck sales uses published data for Class 8 trucks [Ward's 2007], and then assumes that 70% of Class 8 trucks are tractors (based on fleet segmentation data from VIUS). We further assume that 60% of these tractors are used to pull box trailers [VIUS 2002]. Hence, the fleet model assumes that 42% (i.e., 60% x 70%) of new Class 8 sales are tractor-box trailer combinations.

The data sources used to characterize the fleet include the Vehicle Inventory and Use Survey [VIUS 2002] from the U.S. Census Bureau, the DOE's Energy Information Administration [EIA 2008], the Transportation Energy Data Book [TEDB 2007] published by Oak Ridge National Laboratory, and Ward's Automotive handbook [Ward's 2007],. In addition, the EPA's MOVES [2004] emissions model was used to help guide our methodology.

In general, sources such as Ward's, TEDB, and the FHA provide the most accurate source of absolute numbers, such as total vehicle miles traveled (VMT) and vehicle population. The VIUS data, which is a broad-based survey of commercial truckers, was then used to add fidelity to these bottom-line numbers. For example, while VIUS's estimate of the total truck population is likely to be less accurate than the FHA's (which is based on actual registrations), it can provide useful estimates of the breakdown between regional and long-haul service or average annual VMT for trucks function of age.

An initial survey of the tractor-trailer fleet using VIUS indicated that these trucks exhibit widely varying duty cycles and annual mileage depending on the truck's age and vocation. For the first five to seven years of its life, a typical tractor-trailer would serve in "long haul" operation: this duty-cycle is characterized by high annual mileage (upwards of 100,000 miles per year); long-range trips (operates in a radius greater than several hundred miles); and travel primarily over interstate highways at highway speeds. As trucks age, an increasing fraction of these long-haul operators migrate to "regional" operation. These regional haulers generally drive much shorter distances (on the order of 50,000 miles per year); operate within a confined region; and may travel a significant number of miles in urban or exurban areas at lower speeds with more frequent stops. The median age of trucks in regional operation is on the order of 18 to 20 years.

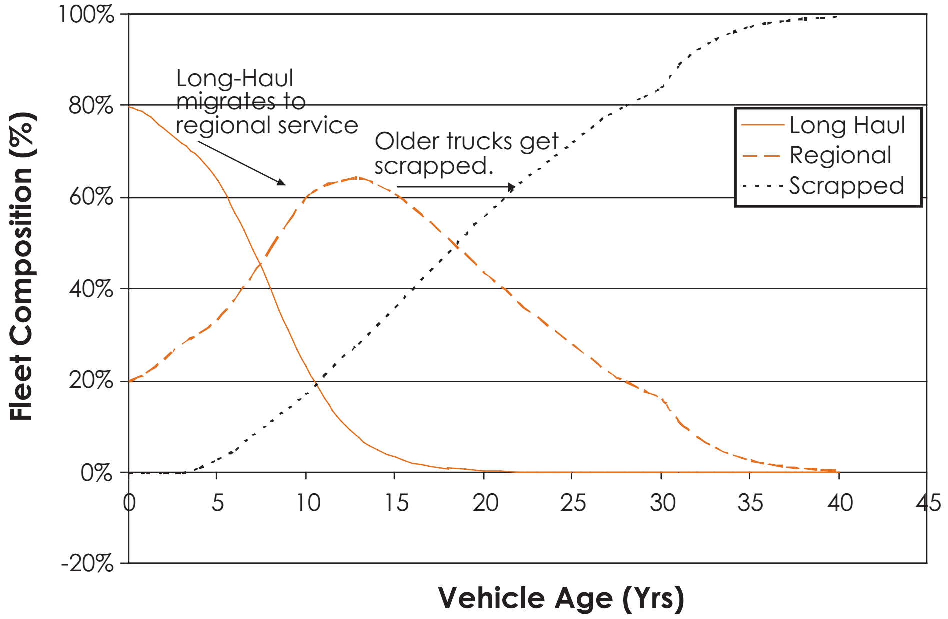
To capture the effect of these different operational profiles, we segmented the tractor trailer fleet into "regional" and "long haul" operators according to the average primary trip length: Regional haul includes those tractor-trailers that operate primarily within a 200-mile radius, while long-haul operators have a primary radius greater than 200 miles. Based on a review of available data, a profile for each subsegment of the fleet was developed. This profile includes vehicle miles traveled as a function of age, survivorship as a function of age, and the fraction of new vehicles that enter each of the different fleets.

For both the regional and long-haul sub-fleets, mileage is estimated to decline linearly with age to a minimum at 16 years, at which point the annual mileage is constant throughout the remainder of the vehicle's life. There is limited data regarding trucks older than 16 years; however, experience suggests that there is a floor to the miles that an operator can use a truck and maintain profitability. The average annual miles of a tractor trailer over a 19 year median life is about 74,000 miles.

The segmentation of the fleet between long-haul service, regional service, and retired trucks is estimated as a function of vehicle age, shown in Figure D-1. As discussed above, most new trucks (estimated at 80%) begin their life in long-haul service and then migrate into the lower-mileage regional segment. This migration is modeled using a "long-haul service" survivorship curve, and is based

FIGURE

D-1 MIGRATION AND SCRAPPAGE OF COMBINATION TRUCKS



on empirical data showing the distribution of long haul vehicles as a function of age [MOVES 2004]. In addition to the migration from long-haul to regional service, as vehicles age, an increasing fraction of trucks are retired altogether. The rate of retirement is estimated from scrappage statistics for in-use trucks [TEDB 2007][3].

Technology Adoption Methodology

Overview

To reflect the process by which technologies might reasonably be added to the fleet, each of the packages modeled by SwRI was ranked in terms of net cost of ownership over either a three year or a fifteen year time horizon, depending on the scenario. The logic employed assumes that a buyer would first select the most cost-effective available technology (Package 2), followed by the next most cost-effective technology (Package 3), and so forth[4]. As each technology is adopted into the fleet, the cost of ownership of the remaining technologies is recalculated to reflect that the baseline vehicles now use less fuel. To avoid double counting the fuel reduction benefits of different technologies, the technologies were grouped into four categories according to how they achieve their benefit. The fleet model only allows a single option from each category to be adopted onto a vehicle.

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[3] The scrap curves for 1980-vintage, rather than 1990-vintage, vehicles were used. As discussed in MOVES, the 1990-vintage projections show dramatically longer lifetimes than previous projections, and appear to be contradicted by more recent data; moreover, the later projections were based on a limited data set (as few trucks had yet reached their end-of-life).

[4] Although package 2 actually has a lower NPV than package 3, package 3 includes package 2, so package 2 would be implemented as a precursor to package 3.

TABLE D-2

GROUPINGS OF TECHNOLOGIES FOR FLEET ANALYSIS

AERODYNAMICS & ROLLING RESISTANCE	POWERTRAIN EFFICIENCY	HIGHER PAYLOAD	REDUCE ROAD SPEED
SmartWay Advanced SmartWay	VVA Adv. EGR Mech T.C. Elec. T.C. Bottoming Cycle HEV HEV + Elec T.C. HEV + Bot. Cycle	Rocky Mountain Double	60 MPH

TABLE D-3

ILLUSTRATIVE FLEET ADOPTION RATES FOR TECHNOLOGIES IN SCENARIO A

YEAR	AERO & ROLLING RES. PACKAGES		POWERTRAIN EFFICIENCY		HIGHER PAYLOAD	REDUCED SPEED
	SW1	SW2	MECH. TURBO	ELEC. TURBO	RMD	60 MPH
2007	0%	0%	0%	0%	0%	0%
2008	0%	0%	0%	0%	0%	0%
2009	20%	0%	0%	0%	0%	0%
2010	40%	0%	14%	0%	0%	20%
2011	60%	0%	29%	0%	0%	40%
2012	80%	14%	43%	0%	0%	60%
2013	71%	29%	57%	0%	0%	80%
2014	57%	43%	71%	0%	0%	100%
2015	43%	57%	86%	0%	9%	100%
2016	29%	71%	100%	0%	17%	100%
2017	14%	86%	100%	0%	26%	100%
2018	0%	100%	100%	0%	34%	100%
2019	0%	100%	86%	14%	43%	100%
2020	0%	100%	71%	29%	51%	100%
2021	0%	100%	57%	43%	60%	100%
2022	0%	100%	43%	57%	60%	100%
2023	0%	100%	29%	71%	60%	100%
2024	0%	100%	14%	86%	60%	100%
2025	0%	100%	0%	100%	60%	100%
2026	0%	100%	0%	100%	60%	100%
2027	0%	100%	0%	100%	60%	100%
2028	0%	100%	0%	100%	60%	100%
2029	0%	100%	0%	100%	60%	100%
2030	0%	100%	0%	100%	60%	100%

The total fuel consumption benefit of technologies is then calculated multiplicatively as follows:

$$\% FC_{total} = (1 - \% FC_{Tech1}) \times (1 - \% FC_{Tech2}) \times \ldots \times (1 - \% FC_{TechN})$$

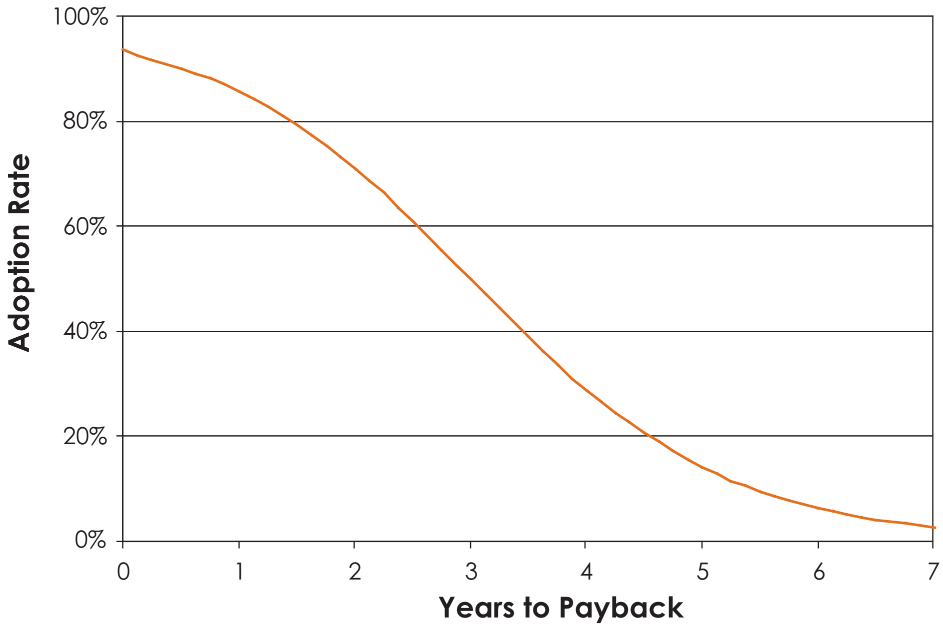
Technology Adoption Methodology for Scenario A

The first technology adoption scenario ("Scenario A") illustrates the rate of technology adoption that could be catalyzed by applying aggressive regulation, such as a fuel-economy standard, to the long-haul fleet. Under this scenario, the technology from each column in Table D-2 offers the highest fuel consumption benefit and that has a net- negative cost of ownership over fifteen years is fully adopted on new vehicles, subject to a five to seven-year phase-in period once the technology is market-ready[5]. An example of the dynamics of technology adoption for scenario A is illustrated in Table D-3. Technologies with 0% adoption are omitted for the sake of space. Note that the penetration of technologies of a given "type" (e.g., powertrain efficiency) can sum to at most 100%, and are further constrained by the multi-year phase-in requirement.

Technology Adoption Methodology for Scenario B

The second technology adoption scenario ("Scenario B") uses a rational buyer model to illustrate the rate of technology adoption that might be expected in the absence of regulation. This scenario segments truck purchasers into different categories based on the expected annual VMT of the truck. The rate of adoption is then calculated as a function of time to payback (which varies with annual mileage).

FIGURE D-2 ADOPTION RATE AS A FUNCTION OF TIME TO PAYBACK



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[5] SmartWay, which is already on the market uses a 5-year phase in. The 60 MPH speed limit uses a 5-year phase-in and applies to both new and in-use trucks.

The adoption rules use a three-year payback threshold, which assumes that 50% of fleet owners will adopt a technology if it offers discounted payback in three years or less; 70% adopt given payback in two years or less. The relationship between time to payback and adoption rate is shown in Figure D-2. The guideline of three-year payback (and 70% adoption at two years) was based on feedback from truck industry experts on the steering committee, who suggested that this was a reasonable methodology to adopt for our market-based model.

Unlike the criterion for adoption used in Scenario A, which either fully adopts a technology (subject to phase-in) or does not adopt it at all, the three-year payback model in Scenario B allows for varying fractions of the fleet to adopt a technology. One outcome of this approach is that different mutually-exclusive technologies (such as bottoming cycle and turbo-compounding, or SmartWay 1 and SmartWay 2) are allowed to compete in the market place. In these cases, the relative rate of adoption for competing technologies is calculated from the ratio of the estimated penetration rate of one technology to another[6].

An example of the dynamics of technology adoption for Scenario B is illustrated in Table D-4. Technologies with 0% adoption are omitted for the sake of space. Note that the penetration of technologies of a given "type" (e.g., powertrain efficiency) can sum to at most 100%, and are further constrained by the multi-year phase-in requirement.

---

[6] The actual adoption rate for two technologies (Technology 1 and Technology 2), assuming that technology 1 has the higher assumed penetration rate, is calculated as follows:

$$\text{Actual adoption rate, Tech 1} = A_{\text{Tech 1}} \text{ x } A_{\text{Tech 1}}/(A_{\text{Tech 1}} + A_{\text{Tech 2}})$$

Where $A_{\text{Tech 1}}$ is the adoption of technology 1 in isolation and $A_{\text{Tech 2}}$ is the adoption of tech. 2 in isolation. For example: If SmartWay 1 has a rate of payback that leads to 50% adoption, and SmartWay 2 has a rate of payback that leads to 25% adoption, then

$$\text{SW1} = 0.5 \text{ x } 0.5/(0.5 + 0.25) = 33\%$$
$$\text{SW2} = 0.5 \text{ x } 0.25/(0.5 + 0.25) = 17\%$$

TABLE
D-4

ILLUSTRATIVE FLEET ADOPTION RATES FOR TECHNOLOGIES IN SCENARIO B

YEAR	AERO & ROLLING RES. PACKAGES		POWERTRAIN EFFICIENCY				HIGHER PAYLOAD	REDUCED SPEED
	SW1	SW2	ADV. EGR	MECH. TURBO	ELEC. TURBO	VVA	ROCKY MT DOUBLE	60 MPH
2007	0%	0%	0%	0%	0%	0%	0%	0%
2008	0%	0%	0%	0%	0%	0%	0%	0%
2009	9%	0%	0%	0%	0%	14%	0%	0%
2010	16%	0%	0%	0%	0%	29%	0%	20%
2011	24%	0%	0%	0%	0%	47%	0%	40%
2012	29%	0%	4%	0%	0%	61%	0%	60%
2013	34%	0%	8%	0%	0%	76%	0%	80%
2014	34%	0%	14%	0%	0%	72%	0%	100%
2015	30%	2%	19%	4%	0%	64%	0%	100%
2016	26%	4%	24%	7%	0%	55%	0%	100%
2017	24%	6%	28%	12%	0%	47%	1%	100%
2018	23%	9%	31%	15%	0%	40%	2%	100%
2019	22%	11%	31%	20%	1%	36%	3%	100%
2020	21%	14%	29%	23%	2%	34%	5%	100%
2021	19%	16%	27%	25%	4%	32%	7%	100%
2022	18%	17%	27%	24%	6%	31%	9%	100%
2023	18%	17%	27%	24%	6%	31%	12%	100%
2024	19%	17%	27%	24%	6%	31%	13%	100%
2025	19%	17%	27%	24%	6%	31%	13%	100%
2026	19%	18%	26%	24%	7%	31%	14%	100%
2027	20%	18%	26%	24%	7%	31%	14%	100%
2028	20%	18%	26%	24%	7%	30%	14%	100%
2029	21%	19%	26%	24%	7%	30%	15%	100%
2030	21%	19%	26%	24%	8%	30%	15%	100%

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