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Vehicle Technologies Program Government Performance and Results Act (GPRA) Report for Fiscal Year 2014

Energy Systems Division

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NOTATION

ACRONYMS AND ABBREVIATIONS

ACE	Advanced Combustion Engine (R&D subprogram)
AEO	*Annual Energy Outlook*
BEDT	Batteries and Electric Drive Technology (subprogram)
BEV	battery electric vehicle
BEV100, 200, etc.	BEV with battery sized for range of 100, 200, etc. miles
BIC	best-in-class
CD	charge-depleting
CI	compression ignition
CNG	compressed natural gas
CO_{2eq}	CO_2 equivalent
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
FCV	fuel cell vehicle
FY	fiscal year
GDP	gross domestic product
GHG	greenhouse gas
GPRA	Government Performance and Results Act
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (model)
HEV	hybrid electric vehicle
HT	heavy- and medium-duty truck (includes Classes 4 through 8 unless otherwise noted)
HTEB	Heavy-Truck Energy Balance (model)
ICE	internal combustion engine
ICME	Integrated Computational Materials Engineering
LCD	levelized cost of driving
LDV	light-duty vehicle
MA^3T	Market Acceptance of Advanced Automotive Technologies (model)
NAS	National Academy of Sciences

OPEC	Organization of the Petroleum Exporting Countries
ORNL	Oak Ridge National Laboratory
PEEM	power electronics and electric motors
PEV	plug-in vehicle (includes both BEV and PHEV)
PHEV	plug-in hybrid electric vehicle
PHEV10, 20, etc.	PHEV with nominal charge-depleting range of 10, 20, etc. miles
PM	particulate matter
R&D	research and development
SI	spark ignition
SUV	sport utility vehicle
TAE	TA Engineering, Inc.
VMT	vehicle miles traveled
VSST	Vehicle and Systems Simulation and Testing (subprogram)
VTO	Vehicle Technologies Office

UNITS OF MEASURE

bbl	barrel(s)
bpd	barrel(s) per day
gal	gallon(s)
gge	gallon of gasoline equivalent, or 125,000 British Thermal Units
kW	kilowatt(s)
kWh	kilowatt-hour(s)
mpg	mile(s) per gallon
t	metric ton(s)
yr	year(s)

VEHICLE TECHNOLOGIES PROGRAM GOVERNMENT PERFORMANCE AND RESULTS ACT (GPRA) REPORT FOR FISCAL YEAR 2014

by

T.S. Stephens, A.K. Birky, and J. Ward

ABSTRACT

The U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy has defined milestones for its Vehicle Technologies Office (VTO) technology programs. This report provides estimates of the benefits that would accrue from achieving these milestones relative to a base case that represents a future in which there is no VTO-supported vehicle technology development. This was done by estimating fuel use, primary energy use and greenhouse gas (GHG) emissions from light-, medium- and heavy-duty vehicles, including energy and GHG emissions from fuel production for the base case and the program "target" case. The target case represented the future with completely successful deployment of VTO technologies. Market penetrations of different vehicle types with and without VTO technologies were projected using market share models, and a stock and energy accounting model was used to make projections of energy consumption and GHG emissions for the base and target cases. The differences between the base case and the target case were attributed to VTO technologies. Improvements in fuel economy of various vehicle types were attributed to individual VTO technology areas, which included batteries and electric drives, advanced combustion engines, fuels and lubricants, materials (i.e., reducing vehicle mass, also called "lightweighting"), and for medium- and heavy-duty vehicles, reduction in rolling and aerodynamic resistance.

Projections indicate that by 2030, the on-road fuel economy of both light- and heavy-duty vehicles would improve by 30% or more for the target case relative to the base case, and that this positive impact would be accompanied by a reduction in oil consumption of nearly 3 million barrels per day and a reduction in GHG emissions of more than 400 million metric tons of CO_2 equivalent per year. These benefits would have a significant economic value in the U.S. transportation sector and reduce its dependency on oil and its vulnerability to oil price shocks.

1 INTRODUCTION AND PROGRAM OVERVIEW

The Vehicle Technologies Office technology program (or the VTO Program) focuses on research and development (R&D) to (1) improve the energy efficiency of current cars, light trucks, and heavy vehicles and (2) develop new technologies that will help transition vehicles away from using petroleum fuels. These R&D activities could result in significant benefits as more hybrid electric vehicles (HEVs), plug-in vehicles, lightweight materials, low-temperature combustion regimes, and alternative fuels are used.

This document describes the benefits that could result from the VTO Program and how they were determined; that is, it describes the development of scenarios for the commercialization of vehicle technologies that are being developed under the VTO Program's current and soon-to-be-implemented R&D activities and the methodologies used to estimate the future benefits of the successful deployment of these technologies. The analysis of benefits involves relatively sophisticated models, including advanced vehicle simulation and power flow models, that convert R&D activities into fuel economy improvement metrics. Other models are used to estimate how more efficient vehicles penetrate the marketplace and the resulting reductions in energy use and greenhouse gas (GHG) emissions.

Section 2 of this report gives budget projections for the VTO Program and is followed by a description of VTO Program activities by technology area (or "subprogram") in Section 3. The benefits discussion in Section 4 opens with a discussion of a baseline "No Program" scenario against which to measure VTO Program benefits and of the important factors to consider when using this baseline to make comparisons. The second part of Section 4 discusses modeling of advanced vehicle technologies and how the estimated improvements in fuel economy are attributed to subprograms and key activities. Section 5 gives the resulting estimates of fuel economy improvements and discusses the projections of market penetration of VTO Program technologies. In Section 6, the benefits of the VTO Program to the entire U.S. fleet, in terms of reductions in energy use and GHG emissions, and some of the economic implications of these reductions are discussed.

2 ASSUMED BUDGET PROJECTIONS

Because a fiscal year 2014 (FY14) budget had not been finalized at the time of this analysis, this report assumes that VTO Program budget levels will remain flat, at historically appropriated levels, through FY17, the last year through which targets and goals have been set for many activities within each subprogram (DOE, 2013). A breakdown of this budget, by subprogram, is shown in Table 1.

TABLE 1 Vehicle Technologies Program: Assumed Budget Projections

	Funding ($1000) per Fiscal Year					
Subprogram	FY12	FY13	FY14	FY15	FY16	FY17
Batteries and electric drive technology	117,740	-	117,740	117,740	117,740	117,740
Advanced combustion engine R&D	58,027	-	58,027	58,027	58,027	58,027
Materials technology R&D	40,830	-	40,830	40,830	40,830	40,830
Fuels and lubricant technologies R&D	17,904	-	17,904	17,904	17,904	17,904
Vehicle and systems simulation and testing	47,198	-	47,198	47,198	47,198	47,198
Outreach, deployment, and analysis	39,267	-	39,267	39,267	39,267	39,267
Total	320,966	330,819	320,966	320,966	320,966	320,966

*FY2013 total based on the continuing resolution is shown.

3 PROGRAM ACTIVITIES, MILESTONES, AND OUTPUTS

In FY14, the VTO Program will continue to focus on the following technology areas (i.e., subprograms):

1. Batteries and Electric Drive Technology (BEDT);
2. Advanced Combustion Engine (ACE) R&D;
3. Materials Technology R&D;
4. Fuels and Lubricant Technologies R&D;
5. Vehicle and Systems Simulation and Testing (VSST); and
6. Outreach, Deployment, and Analysis.

For each of these technology areas/subprograms, the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) has established milestones. Achieving these milestones in the first four subprogram areas will significantly improve vehicle technologies and increase the fuel efficiency of light-duty vehicles (LDVs) and medium- and heavy-duty trucks (HTs). The success and deployment of these technologies will depend on the last two subprogram areas. The rest of Section 3 briefly describes the milestones for each subprogram area and the estimated benefits that could result from their achievement.

With regard to the first four technology areas, the contribution of each to achieving the milestones was estimated as the fraction of decrease in fuel consumption per mile by new vehicles, for each vehicle type, achieved as a result of the technology improvements to be made in that area (assuming program success). In the tables that follow in Sections 3.1 through 3.4, these decreased fuel consumption fractions are shown as percentages of the fuel consumed per mile by the baseline vehicle that has the same type of drivetrain as the new vehicle (1) in the same year that it was manufactured and (2) in the year 2012. These percentages were estimated from (1) component-level vehicle characteristics used in the Autonomie model for LDVs (ANL, 2013) and (2) power flows used in the Heavy-Truck Energy Balance (HTEB) model for medium- and heavy-duty trucks (as described in Section 4).

3.1 BATTERIES AND ELECTRIC DRIVE TECHNOLOGY

The BEDT subprogram addresses the development of low-cost, high-energy batteries and R&D of low-cost, efficient electric drive systems needed for plug-in electric vehicles (PEVs, including all-electric vehicles and plug-in hybrid electric vehicles). Battery/Energy Storage R&D supports the development of advanced batteries for PEVs and advanced materials to enable the development of next-generation batteries and systems. Advanced Power Electronics and Electric Motors R&D supports cost reduction and performance and reliability improvements of power electronics, electric motors, and other electric propulsion components as well as thermal management technologies necessary for increased vehicle electrification. Efforts aim to reduce the production cost of a high-energy battery to $125/kWh by 2022 (thereby enabling the cost-competitive market entry of plug-in HEVs [PHEVs]), and to reduce the cost of an electric-traction-drive system that can deliver 55 kW of peak power for 18 seconds and 30 kW of

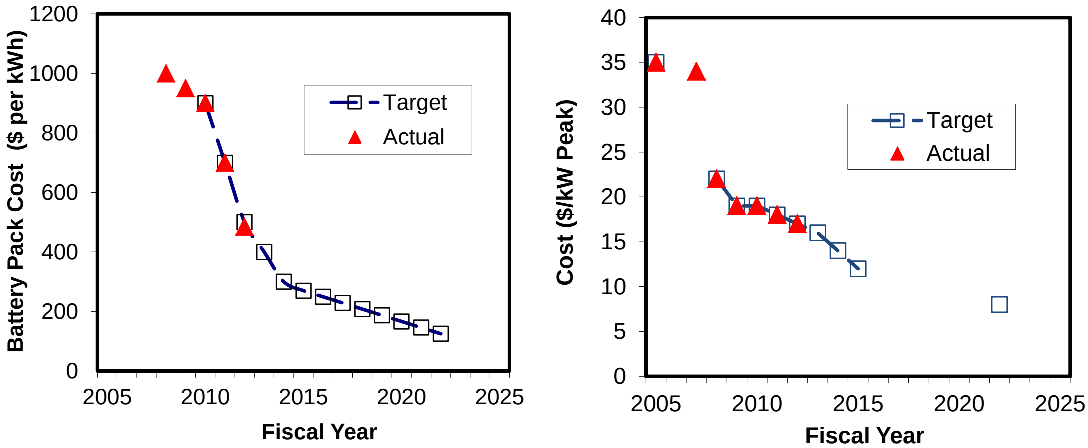

FIGURE 1 PHEV Battery Cost (left) and Combined Inverter/Motor Cost (right)

continuous power from $17/kW in 2012 to $8/kW in 2022 (thereby enabling the cost-competitive market entry of PHEVs and HEVs); see Figure 1.

In FY14, the BEDT subprogram will continue to accelerate the development of low-cost, high-energy batteries and the corresponding improvements in electric-drive systems (motors, power electronics, and electric controls) that are needed to make PHEVs cost effective. PHEVs have the potential to provide significant additional fuel savings, particularly when it comes to commuter and local driving, over the savings achieved by either combustion-powered or fuel-cell-powered hybrid passenger vehicles. The subprogram will also focus on the development of new materials and electrode couples that offer a significant improvement in either energy or power over today's technologies. The subprogram's Advanced Battery Development activity will continue to develop advanced electric drive vehicle batteries in cooperation with industry through contracts that are awarded under a competitive process and are cost-shared by developers; it will focus on the development of robust prototype cells that contain new materials and electrodes that offer a significant reduction in battery cost over existing technologies. Longer-term R&D in the Advanced Power Electronics and Electric Motors R&D activity will focus on cost reduction and improved reliability of power electronics, electric motors and other electric propulsion components as well as thermal management technologies necessary for increased vehicle electrification. Under the Batteries/Energy Storage Incubator and Advanced Power Electronics and Electric Motors Incubator activities, the subprogram will invest in Incubator Programs, partnering with businesses and researchers to bring new technologies into the EERE portfolio.

In Table 2, the improvements (decrease) in fuel consumption per mile, achieved by new vehicles having each type of drivetrain, that are attributable to VTO Program work on batteries and electric-drive technology are shown for the years 2030 and 2050. In the first (top) row, the improvement over the same-year baseline (No Program) vehicle of the same drivetrain type is shown, and in the second (bottom) row, the improvement over the year-2012 baseline vehicle of the same drivetrain type is shown. (In this table and throughout this document, SI refers to spark ignition, CI refers to compression ignition, PHEV40 refers to a PHEV with a nominal charge-depleting [CD] range of 40 miles, HT refers to medium- and heavy-duty trucks, and VMT refers to vehicle miles traveled.)

3.2 ADVANCED COMBUSTION ENGINE R&D

The ACE R&D subprogram focuses on removing critical technical barriers to commercializing more efficient, advanced internal combustion engines (ICEs) for passenger and commercial vehicles. Increasing the efficiency of ICEs is one of the most cost-effective approaches for reducing the amount of petroleum consumed by the nation's fleet of vehicles in the near- to mid-term. Using these advanced engines in HEVs and PHEVs would enable even greater fuel savings. Improvements in engine efficiency alone have the potential to dramatically increase vehicle fuel economy and reduce GHG emissions, and further gains can be achieved through waste heat recovery.

The targets for this subprogram are as follows:

- By 2015, increase the efficiency of engines for passenger vehicles to improve fuel economy by 25% for gasoline vehicles (as shown in Figure 2) and 40% for diesel vehicles; and by 2020, improve fuel economy by 35% and 50% for gasoline and diesel vehicles, respectively, compared to 2009 gasoline vehicles.

- By 2015, increase the efficiency of engines for commercial vehicles by 20%, from 42% (2009 baseline) to 50%; and by 2020, improve engine efficiency by 30%, from 42% to 55% (as shown in Figure 3).

- By 2015, increase the fuel economy of passenger vehicles by 5% by using thermoelectric generators that convert energy from engine waste heat to electricity; and by 2020, increase fuel economy by 10%.

In FY14, the Combustion and Emission Control activity will develop technologies for advanced engines with the goal of improving thermal efficiency by optimizing combustion, fuel injection, air handling, emission control, and waste heat recovery systems, along with reducing friction and pumping losses. Thermal efficiency of passenger and commercial vehicle engines will be improved by investigating innovative combustion processes, including homogeneous charge compression ignition and other modes of low-temperature combustion, lean-burn gasoline, and multi-fuel operation while also reducing engine-out emissions of nitrogen oxides and particulate matter (PM) to near-zero levels. Additionally, Advanced Combustion Engine R&D Incubator Activities will invest in the creation of Incubator Programs with a specific focus on partnering with businesses and researchers to bring “off-roadmap” impactful new technologies into the EERE portfolio. The Solid State Energy Conversion activity develops technologies to convert waste heat from engines and other sources directly to electrical energy to improve overall fuel economy and reduce emissions. This activity will pursue cost-shared cooperative agreements with industry and academia to develop and fabricate high-efficiency

TABLE 2 Target Benefits of Batteries and Electric Drive Technology Subprogram: Reduced Fuel Consumption per Mile Compared to That of Vehicles with Same Type of Drivetrain

		New-Vehicle Fuel Economy Impact (%)[a]									
		SI		CI		HEV		PHEV40		HT	
Key Focus	Metric	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
Energy storage, power electronics, and electric motors	Relative to baseline vehicle in the same year	-	-	-	-	9.3	10.4	5.3	5.1	0.2	0.3
	Relative to baseline vehicle in year 2012	-	-	-	-	13.8	16.5	7.3	8.5	0.2	0.3

[a] The fuel economy impact is the percent decrease in fuel consumption per mile due to DOE-sponsored improvements in batteries and electric drive technology in a new vehicle over a baseline vehicle having the same type of drivetrain in that year (top row) or in the year 2012 (bottom row). HT percentages are VMT- and sales-weighted average improvements. These projections are mere estimations and can change with new DOE or DOE-sponsored research activities.

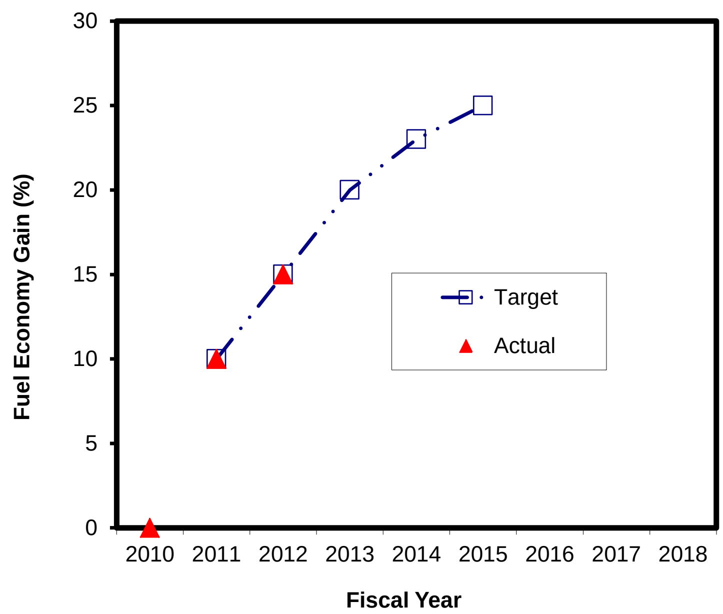

FIGURE 2 Fuel Economy Gains in Passenger Vehicles

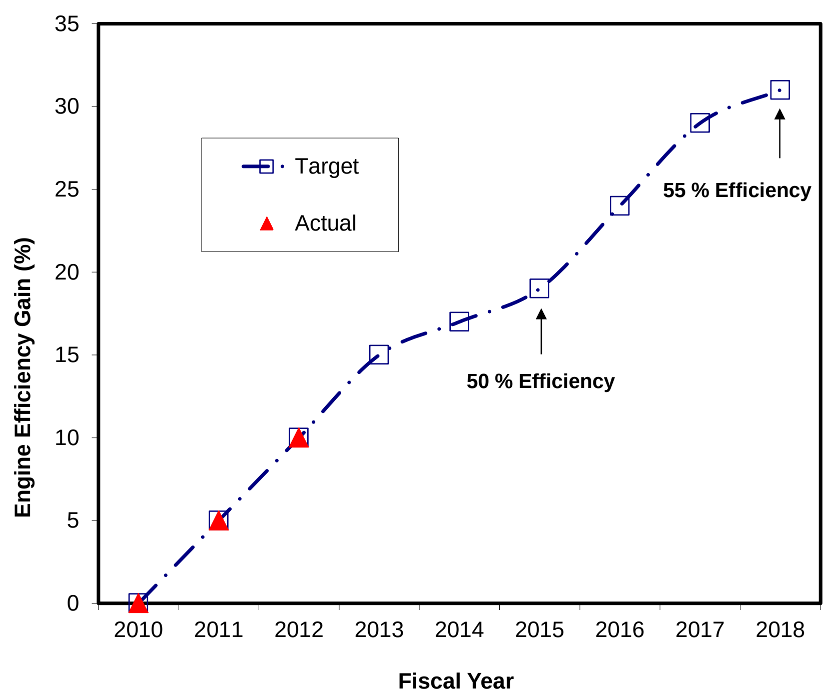

FIGURE 3 Engine Efficiency Gains in Commercial Vehicles

thermoelectric generators to produce electricity from waste heat in passenger vehicles. The activity will also investigate scaling up production of thermoelectric modules for demonstration in vehicle applications with the potential to improve vehicle fuel economy by up to 5%.

The SuperTruck partnership program, a DOE-funded, industry cost-shared initiative, has a goal to develop and demonstrate, by 2015, a 50% improvement in freight efficiency (ton-miles per gallon) for Class 8 long-haul trucks compared to current models. It is expected that at least 20% of this increase will be achieved through heavy-duty engine improvements. SuperTruck Partners are developing other technologies as well, such as hybridization, waste heat recovery, and reduction of aerodynamic and rolling resistance.

In Table 3, the improvements (decreases) in fuel consumption per mile achieved by new vehicles of each drivetrain type that are attributable to VTO Program efforts on combustion technology are shown for the years 2030 and 2050. In the first (top) row, the improvement over the same-year baseline (No Program) vehicle of the same drivetrain type is shown, and in the second (bottom) row, the improvement over the year-2012 baseline vehicle of the same drivetrain type is shown.

3.3 MATERIALS TECHNOLOGY R&D

The Materials Technology R&D subprogram develops higher-performing and more cost-effective materials that will enable lighter vehicle structures and more- efficient power systems. Lighter vehicles require less energy to operate and thus reduce fuel consumption. Likewise, better propulsion materials can enable more-efficient power systems, which contribute to reducing a vehicle's energy consumption. For example, a 10% reduction in the weight of a mid-sized or larger vehicle can result in a 6–8% increase in its fuel economy. This subprogram emphasizes a range of material types including carbon fiber composites, advanced high-strength steels, ferrous alloys, aluminum alloys, and magnesium alloys. The subprogram is revisiting technology targets, but the report resulting from the DOE Workshop on Lightweight and Propulsion Materials in March of 2011 (EERE, 2013) synthesizes input from industry experts on lightweight and propulsion material targets, gaps, and performance metrics, and it gives targets for performance, cost, repairability, recyclability and other metrics for many advanced structural and propulsion materials. Table 4, taken from the workshop report, gives a summary of targets for weight reductions in light-duty ICE vehicles.

In FY14, research efforts will support three activities: (1) Propulsion Materials Technology, (2) Lightweight Materials Technology, and (3) Materials Technology Incubator Activities. The Propulsion Materials Technology activity will fund projects to develop materials that enable downsized powertrains with reduced dependence on rare earth magnetic materials. The activity supports efforts to downsize ICEs, including the development of optimized materials for rotating components (crankshafts, camshafts, pistons, connecting rods, and turbocharger compressor/turbine wheels) with the improved performance necessary to meet the requirements of next-generation natural-gas and high-efficiency powertrains. The activity also supports design and validation activities for new engine blocks and cylinder heads that can achieve higher peak cylinder pressures using a portfolio of Integrated Computational Materials Engineering (ICME) tools, new cast alloys, and advanced processing techniques. Materials research supporting the EV Everywhere Grand Challenge reduces dependence on rare earth magnetic materials by developing new low-rare earth magnets and enabling processing techniques for higher-efficiency induction motors. The Lightweight Materials Technology

TABLE 3 Target Benefits of Advanced Combustion Engine R&D Subprogram: Reduced Fuel Consumption per Mile Compared to That of Vehicles with Same Type of Drivetrain

		New-Vehicle Fuel Economy Impact (%)[a]									
		SI		CI		HEV		PHEV40		HT	
Key Focus	Metric	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
Combined combustion portfolio	Relative to baseline vehicle in the same year	19.0	15.6	20.1	16.6	9.3	10.4	5.3	5.1	16.2[b]	19.2[b]
	Relative to baseline vehicle in year 2012	34.7	35.6	32.1	33.1	13.8	16.5	7.3	8.5	17.0[b]	20.1[b]

[a] Fuel economy impact is the percent decrease in fuel consumption per mile due to DOE-sponsored improvements in combustion engine technology in a new vehicle over a baseline vehicle having the same type of drivetrain in that year (top row) or in the year 2012 (bottom row). HT percentages are VMT- and sales-weighted average improvements. These projections are mere estimations and can change with new DOE or DOE-sponsored research activities.

[b] The benefits to HT fuel economy include improvements due to fuels and lubricant technologies.

TABLE 4 Targets for Weight Reductions for Systems of Light-duty ICE Vehicles

LDV Component Group	2020	2025	2030	2040	2050
Body	35%	45%	55%	60%	65%
Powertrain	10%	20%	30%	35%	40%
Chassis/suspension	25%	35%	45%	50%	55%
Interior	5%	15%	25%	30%	35%
Entire Vehicle	20%	20%	40%	45%	50%

Source: EERE (2013)

activity supports EV Everywhere and addresses technology gaps that currently prevent the further introduction of advanced lightweight materials into vehicles. In FY14, the activity will emphasize the development of ICME tools for carbon fiber composites to decrease the weight of both the body and chassis; explore manufacturing approaches to improve high-performance aluminum sheet and extrusion components; research fastening, bonding, and corrosion protection techniques for joining dissimilar materials; and design and validate lightweight structures constructed from a mix of lightweight materials. Materials Technology Incubator Activities invest in the creation of Incubator Programs, partnering with businesses and researchers to bring off-roadmap and impactful new technologies into the EERE portfolio.

In Table 5, the improvements (decreases) in fuel consumption per mile, achieved by new vehicles having each type of drivetrain, that are attributable to VTO Program work on materials technology are shown for the years 2030 and 2050. In the first (top) row, the improvement over the same-year baseline (No Program) vehicle of the same drivetrain type is shown, and in the second (bottom) row, the improvement over the year-2012 baseline vehicle of the same drivetrain type is shown.

TABLE 5 Target Benefits of Materials Technology R&D Subprogram: Reduced Fuel Consumption per Mile Compared to That of Vehicles with Same Type of Drivetrain

		New-Vehicle Fuel Economy Impact (%)[a]									
		SI		CI		HEV		PHEV20		HT	
Key Focus	Metric	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
Propulsion and structural materials	Relative to baseline vehicle in the same year	16.4	18.7	15.3	17.6	15.9	18.2	15.7	17.8	1.1	1.3
	Relative to baseline vehicle in year 2012	16.0	18.5	15.1	17.5	17.8	19.9	18.6	20.5	1.1	1.3

[a] The fuel economy impact is the percent decrease in fuel consumption per mile due to DOE-sponsored improvements in propulsion and structural technologies, which enable lighter weights, in a new vehicle over a baseline vehicle having the same type of drivetrain in that year (top row) or in the year 2012 (bottom row). HT percentages are VMT- and sales-weighted average improvements. These projections are mere estimations and can change with new DOE or DOE-sponsored research activities.

3.4 FUELS AND LUBRICANT TECHNOLOGIES R&D

The Fuels and Lubricant Technologies R&D subprogram evaluates the advanced fuels and fuel components, and develops and evaluates lubricants, that are used or proposed for use in current and advanced engines. The subprogram focuses on developing novel, high-efficiency combustion systems with ultra-low emissions on an engine-out basis and on exploitation of fuel properties for ignition and control, complementing activities under the ACE subprogram that are focused on the end-result heat release, emissions, and combustion system design.

In FY14, studies will continue on the effects of variations in physical and chemical properties of renewable and alternative fuels on the performance and emissions of advanced combustion engines. This work will be undertaken in close coordination with the ACE R&D subprogram. Fuels and Lubricant Technologies Incubator Activities will be expanded to establish partnerships with businesses and researchers to bring off-roadmap impactful new technologies into the EERE portfolio. The subprogram will also establish funding for a competitive solicitation for a program incubator to encourage innovative and potentially disruptive advanced fuels and lubricant technologies.

In Table 6, the improvements (decreases) in fuel consumption per mile achieved by new vehicles of each drivetrain type that are attributable to VTO Program work with fuel and lubricant technologies are shown for the years 2030 and 2050. In the first (top) row, the improvement over the same-year baseline (No Program) vehicle of the same drivetrain type is shown, and in the second (bottom) row, the improvement over the year-2012 baseline vehicle of the same drivetrain type is shown. Note that improvements in HT fuel consumption due to fuel and lubricant technologies are included with improvements in overall drivetrain efficiency shown in Table 3 and are not reported separately in Table 6. Although the percentages in Table 6 are smaller than the corresponding percentages in Tables 2–4, it should be noted that in all these tables, the percentage improvements shown are estimated at the individual vehicle level, and the resulting fuel savings at the fleet level depend on the number of vehicles having the technologies on board and on the vehicle miles driven. Advanced lubricants and friction reduction technologies can often be applied to a wide range of vehicles, not just to vehicles with certain powertrains, and in some cases, deployment can be rapid. Fleet-level benefits are discussed in Section 6.

3.5 VEHICLE AND SYSTEMS SIMULATION AND TESTING

The VSST subprogram provides an overarching vehicle systems perspective in support of the program's R&D activities. The subprogram uses analytical and empirical tools to model and simulate potential vehicle systems, validate component performance in a systems context, verify and benchmark emerging technologies, and validate computer models. Each of these activities is aimed at addressing the fundamental challenge that vehicle component technologies must be considered within the context of the overall vehicle system. The subprogram conducts research to elucidate the interactions between vehicle powertrain subsystems to ensure that the technologies developed under the VTO Program result in the maximum impact at the vehicle level. The subprogram has the objective of providing the simulation tools and testing capabilities

TABLE 6 Target Benefits of Fuels and Lubricant Technologies R&D Subprogram: Reduced Fuel Consumption per Mile Compared to That of Vehicles with Same Type of Drivetrain

		New-Vehicle Fuel Economy Impact (%)[a]									
		SI		CI		HEV		PHEV20		HT	
Key Focus	Metric	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
Fuels and lubricant technologies	Relative to baseline vehicle in the same year	0.8	1.2	0.8	1.2	0.8	1.2	0.8	1.2	–[b]	–[b]
	Relative to baseline vehicle in year 2012	0.8	1.2	0.8	1.2	0.8	1.2	0.8	1.2	–[b]	–[b]

[a] The fuel economy impact is the percent decrease in fuel consumption per mile due to DOE-sponsored improvements in lubricant and friction-reduction technologies in a new vehicle over a baseline vehicle having the same type of drivetrain in that year (top row) or in the year 2012 (bottom row). HT percentages are VMT- and sales-weighted average improvements. These projections are mere estimations and can change with new DOE or DOE-sponsored research activities.

[b] The benefits to HT fuel economy from fuels and lubricant technologies are included in the values reported for HT in Table 3.

to evaluate the impact of advanced vehicle technologies and to guide the R&D pathways of the other subprograms. VSST supports the development and maintenance of modeling software—in particular, the Autonomie modeling and simulation toolkit—to accurately represent the potential of advanced vehicle components and systems, and it continues to improve these models as the basis for all program vehicle-level analytical studies. The subprogram also has the objective of evaluating advanced vehicles in laboratory and real-world environments, in order to assess the efficiency characteristics of existing technologies and identify R&D pathways for improvements.

In FY14, the VSST subprogram will continue developing and utilizing advanced vehicle modeling and simulation tools to predict the performance and efficiency benefits of advanced components in a vehicle systems context. In support of the EV Everywhere Grand Challenge, the subprogram will conduct laboratory, track, and real-world testing of plug-in electric vehicles as they become available, to characterize the performance, efficiency, and cost benefits of these advanced technologies. The VSST subprogram will participate in activities to develop standards and test procedures related to plug-in vehicles and their charging infrastructure. The subprogram will also conduct research in enabling technologies, including aerodynamic improvements in heavy-duty vehicles as well as parasitic load reduction in powertrain components, advanced high-efficiency heating/ventilation/air-conditioning solutions, thermal management, and static wireless charging of electric vehicles in support of the EV Everywhere Grand Challenge. The subprogram will fund non-Recovery Act SuperTruck projects in FY14, with the objective of developing and demonstrating a 50% improvement in the overall freight efficiency of a heavy-duty Class 8 tractor-trailer combination by 2015, measured in ton-miles per gallon. In addition, the VSST subprogram participates in the EERE Grid Integration Initiative and will make funding available for development of technologies, tools, and system integration activities to support the deployment of plug-in electric vehicles and other clean energy technologies (i.e., wind and solar), focused on the following vehicle-related topics: (1) Grid systems analysis tools, (2) end-to-end communications and control, (3) interoperability and standards, and (4) owner economics.

In Table 7, no fuel economy impact values are shown, but the simulation and testing activities are critical to other subprograms.

3.6 OUTREACH, DEPLOYMENT, AND ANALYSIS

The Outreach, Deployment, and Analysis subprogram contributes directly to the VTO Program’s benefits to the climate and to reduction in petroleum use by accelerating the adoption of advanced technologies, strategies and projects that displace petroleum use through public/private partnerships between DOE and local coalitions of key stakeholders across the country (such as Clean Cities). In addition, the program produces the annual DOE/Environmental Protection Agency (EPA) Fuel Economy Guide publication and the associated website www.fueleconomy.gov, and disseminates related data (as required by law) to the public.

TABLE 7 Target Benefits of Vehicle and Systems Simulation and Testing Subprogram

		New-Vehicle Fuel Economy Impact									
		SI		CI		HEV		PHEV40		HT	
Key Focus	Metric	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
Vehicle and systems simulation and testing	2012: 62 million miles of on-road HEV/ PHEV/BEV[a] testing										
	2012: Finalized standards for grid-connected vehicle energy consumption measurement, communication, and safety practices							Critical enabling testing; no direct fuel economy benefit			
	2013: 102 million miles of on-road HEV/ PHEV/BEV testing					Critical enabling testing; no direct fuel economy benefit					
	2014: 107 million miles of on-road HEV/ PHEV/BEV testing					Critical enabling testing; no direct fuel economy benefit					

[a] BEV = battery electric vehicle

FY14 funding for vehicle technologies deployment will accelerate the introduction and adoption of alternative vehicles, like PEVs, through Alternative Fuel Vehicle Community Partner projects and community-based, highly leveraged government/industry partnerships. The subprogram will also support university-based activities that encourage university student engineers to participate in advanced technology development—helping to address the need for more highly trained engineers in hybrid and fuel cell technologies to overcome barriers in the marketplace. Vehicle Technology Deployment activities support efforts to (1) convene key community and business leaders to develop and implement projects and policies, leverage resources, and address local barriers; (2) provide DOE-developed tools and information to help consumers save money on fuel and help fleet operators understand their options for cost-effective alternatives to gasoline and diesel fuel; (3) provide DOE expertise to help local leaders address permitting and safety issues, technology shortfalls, and other project implementation barriers; and (4) competitively award financial assistance with Federal cost-share requirements that encourage initial private sector match and long-term investment related to infrastructure development and other vehicle deployment initiatives.

In Table 8, no fuel economy impact values are shown, but the outreach, deployment, and analysis activities are critical to achieving market penetration of technologies developed under the other subprograms.

3.7 SUMMARY OF FUEL ECONOMY IMPROVEMENTS BY TECHNOLOGY AREA

Figure 4 (left) shows the estimated reductions in fuel consumption (in gallon-of-gasoline equivalents or gge) per mile by LDVs due to the following four technology areas:

1. Batteries and Electric Drive Technology (Hybridization);
2. Advanced Combustion Engine R&D (Engine/Drivetrain Efficiency);
3. Materials Technology R&D (Mass Reduction);
4. Fuels and Lubricant Technologies R&D (Friction Reduction);

The estimated reductions in fuel consumption per mile by medium- and heavy-duty trucks (HTs) are shown in Figure 4 (right), with improvements due to engine and drivetrain efficiency and friction reduction combined. In addition, for HTs, fuel consumption improvements due to reductions in aerodynamic and rolling resistance are shown. Fuel consumption improvements for LDVs are sales-weighted averages of cars and light trucks; those for HTs are averages over Class 4–6, Class 7&8 single units and Class 7&8 combination units.

The improvements in fuel economy shown in Figure 4 are averages for types of vehicles. Estimated petroleum savings and GHG reductions at the U.S. fleet level are discussed in Section 6.

TABLE 8 Target Benefits of Outreach, Deployment, and Analysis Subprogram[a]

		New-Vehicle Fuel Economy Impact (gal/yr)									
		SI		CI		HEV		PHEV40		HT	
Key Focus	Metric	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
Clean cities	2012: Petroleum reduction	700 million (various vehicle platforms)									
	2014: Petroleum reduction	900 million (various vehicle platforms)									
	2015: Petroleum reduction	1 billion (various vehicle platforms)									

[a] These projections are mere estimations and can change with new DOE or DOE-sponsored partner activities.

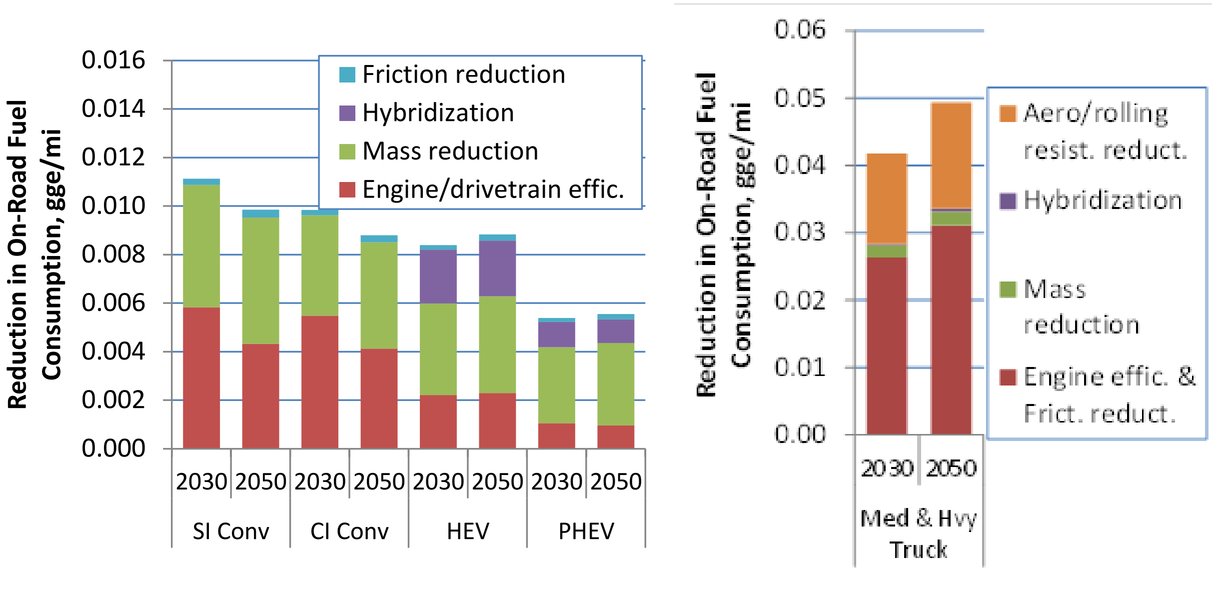

FIGURE 4 Reductions in Fuel Consumed per Mile by Technology Area in LDVs (left) and Medium- and Heavy-duty Trucks (right)

4 TRANSLATING PROGRAM GOALS INTO ENERGY MODEL INPUT PARAMETERS

4.1 BASELINE "NO PROGRAM" CASE

Benefits were calculated as reductions in energy use, fuel use, GHG emissions, and consumer expenditures relative to the baseline "No Program" case. The No Program case was developed to represent future vehicle technology, fuel use, and GHG emissions without the effects of technology improvements brought about by the VTO Program. The DOE Energy Information Administration's (EIA's) *Annual Energy Outlook* (AEO) is the most widely recognized DOE-wide projection and analysis of future U.S. energy supplies, demands, and prices. As such, it is an obvious choice for a baseline against which to compare an energy future enriched by DOE programs. However, the EIA's AEO reference case assumes that current policies remain in effect, and projections made in the AEO reference case thus incorporate assumptions about the market success of technologies historically supported by the VTO Program and the assumption that there will be continued support. This AEO reference case therefore is not an appropriate one to use for the baseline No Program case. Instead, an appropriate baseline case for LDVs and HTs must be constructed by projecting the reduced technological progress over time that is expected to occur without VTO-supported R&D.

For LDVs, a baseline case based on Autonomie simulations of future vehicles was developed by assuming that only incremental technology improvements would occur and that there would be no support from the VTO Program; associated data on vehicle performance, prices, and other attributes were generated for the years 2012, 2015, 2020, 2030, and 2045. This baseline case was developed on the basis of assumptions about future vehicle characteristics under Corporate Average Fuel Economy standards, including the new standards for the years 2017 through 2025. The Market Acceptance of Advanced Automotive Technologies (MA^3T) vehicle choice model developed by Oak Ridge National Laboratory (ORNL; Lin and Greene, 2010, 2011) was used to make projections of vehicle sales for the baseline case, and these sales shares were used as input for Argonne's VISION model (Ward et al., 2008) to calculate future energy consumption and GHG emissions by LDVs for the baseline case. Fuel prices were assumed to be those in the AEO 2012 High Oil price case, extrapolated to 2050 on the basis of the trend from 2030 to 2035. Full fuel-cycle GHG emissions for fuels and electricity from the Argonne GREET™ models were used to estimate GHG emissions (ANL, 2012), using the AEO 2012 electricity generation mix.

The baseline case for medium- and heavy-duty vehicles was developed by adjusting the AEO 2012 reference-case fuel economy values for new heavy vehicles in order to remove the benefits attributed to the projected penetration of advanced technologies supported by DOE funding. The EIA provided reference case data on the market penetrations of component technologies for HTs of various configurations (or "subclasses") that were included in the National Energy Modeling System fuel economy calculations. The contribution of DOE-supported technologies to new-fleet fuel economy was then removed by using AEO 2012 reference case input assumptions about the incremental improvements in truck fuel economy due to these component technologies at the subclass level. These subclass results were aggregated to the medium- and heavy-duty class level as reported in the AEO, using subclass market shares provided by EIA and additional input from the EPA's regulatory impact assessment and other documentation associated with the 2011 heavy-vehicle fuel efficiency standards (EPA, 2011a and 2011b). The resulting adjusted new-fleet fuel economies were used as input to the VISION model to calculate future energy consumption and GHG emissions by in-use HTs for the baseline case. Further detail on the development of the baseline case for HTs is given by TA Engineering, Inc. (2013).

For both LDVs and HTs, total vehicle sales were assumed to be the same as in the AEO 2012 reference case, extrapolated to 2050 (a linear extrapolation based on the 2030–2035 average slope).

4.2 GPRA ADVANCED TECHNOLOGY MODELING

In general, the analysis of advanced technologies for Government Performance and Results Act (GPRA) benefits estimation was based on a market-based approach requiring three steps. First, the average fuel economy and incremental cost of new vehicles that incorporate DOE-supported technologies were estimated. Second, consumer choice models were used to estimate the market shares of these platforms in future years. Finally, the projected fuel economies and market shares were used as inputs to the VISION model, which projects future in-use vehicle stock and estimates fuel consumption. This section provides details on this methodology applied specifically to the light-duty and heavy-duty vehicle markets.

Attributes of light-duty passenger vehicles were estimated for the years 2012, 2015, 2020, 2030, and 2045 by using Autonomie, with inputs based on experts from DOE and Argonne's original equipment manufacturer partners. Autonomie simulations were run for two cases[1]:

1. "No Program" case, which assumes there is no technology improvement or cost reduction due to the DOE VTO Program, as described above, and

2. "Target" case, which assumes that there are technology improvements and cost reductions that meet VTO Program goals.

For each case, starting assumptions about vehicle dimensions, weight, performance, and component characteristics were calculated on the basis of the current relevant vehicle data available in the Autonomie library and VTO Program cost and performance targets for the "Target" case.

[1] Autonomie simulations were also run for a case with an intermediate level of technology improvements, but these improvements are not discussed here.

In the first phase of GPRA LDV modeling, Autonomie was used to simulate five vehicle classes—compact car, midsize car, compact sport utility vehicle (SUV), midsize SUV, and pickup truck—with each one having various types of drivetrains, including these:

- Conventional SI;
- Conventional CI;
- Hybrid electric (HEV, both SI HEV and CI HEV);
- Plug-in hybrid electric, with SI engines, with nominal CD ranges of 10, 20, and 40 miles (PHEV10, PHEV20, PHEV40);
- Hydrogen fuel cell vehicle (FCV); and
- Battery electric, with batteries sized for ranges of 100 and 300 miles (BEV100, BEV300).

For each of the preceding powertrain architectures, the Autonomie model converted families of component-level input parameters (intended to describe component technologies at various points in the future for each technology scenario) to a virtual vehicle (appropriately sized to offer sufficient power, given vehicle weight and drivability requirements) and simulated that vehicle's fuel economy over city and highway drive schedules prescribed by the EPA. These simulations resulted in estimates of fuel economy for each vehicle class/drivetrain type for future years. The incremental costs associated with the fuel economy benefits offered by advanced powertrains were calculated by using a combination of (a) direct inputs from VTO Programs for advanced technologies and (b) third-party (Ricardo Engineering)-estimated costs for near-commercial technologies. Specifically, EERE cost and performance targets were used to estimate costs and performance for the target case for batteries, power electronics and electric motors, fuel cells, and on-board hydrogen storage; cost models developed by the Argonne Autonomie group and by Ricardo Engineering were used for estimating costs for other components.

Once Autonomie modeling was complete, outputs were used as inputs to the MA^3T vehicle choice model in the second phase of GPRA LDV modeling. For both the No Program and Target cases, sales shares of LDVs having each type of drivetrain were estimated for cars and light trucks by using the MA^3T vehicle choice model. This model predicts sales shares each year to 2050 on the basis of vehicle attributes for cars and light trucks. The model takes into account consumer preferences and attributes (based on survey and demographic data), vehicle prices, operating costs, and other attributes to estimate purchase probabilities for each vehicle type, which are taken to represent sales shares (Lin and Greene, 2010, 2011). In MA^3T, size classes are aggregated (i.e., only one size class each for cars and light trucks is represented), so attributes of midsize sedans were used for cars and attributes of midsize SUVs and trucks were used for light trucks. Flex-fuel and natural-gas-fueled vehicles were not modeled in MA^3T. Little public infrastructure for public charging of plug-in vehicles or fueling of hydrogen fuel cell vehicles was assumed for both the No Program and Target cases.

In the third phase of GPRA LDV modeling, after sales shares were calculated by using the MA^3T model, the sales shares and fuel economy of each LDV having each type of drivetrain were used as input to the VISION model for both the No Program and Target cases. The VISION model is an accounting spreadsheet that calculates output metrics of interest on a national scale;

by comparing the Target and No Program cases, it calculates petroleum savings and GHG reductions (Ward et al., 2008).

The sales shares, fuel economy, and retail price equivalent of each LDV having each type of drivetrain were used as input for the VISION model, for both the No Program and Target cases. Not all vehicle types modeled in MA^3T are represented individually in the VISION model, so some vehicle types were combined. Since four SI PHEVs with different CD ranges can be modeled in VISION (two each for cars and light trucks) but six SI PHEVs were modeled in MA^3T (three each for cars and light trucks, with nominal CD ranges of 10, 20 and 40 miles), the car and light-truck PHEVs with CD ranges of 10 and 20 miles were combined and were represented as a PHEV with attributes, such as CD range, fuel economy, and electricity consumption per mile, equal to the sales-weighted average of the attributes of the PHEVs with CD ranges of 10 and 20 miles. Similarly, BEVs were represented as a BEV with attributes equal to the sales-weighted averages of those of the BEVs with 100- and 300-mile ranges, since VISION includes one BEV car and one BEV light truck. For each drivetrain type, VISION applies a fuel economy adjustment factor to convert combined city/highway test-cycle fuel economy values (supplied by Autonomie) to on-road fuel economy values. These factors range from 0.7 to 0.85, depending on drivetrain type, and are based on factors used by the EIA in AEO or on EPA-recommended “mileage-based” equations (EPA, 2006).

Fuel economy improvements were attributed to VTO subprogram technologies (batteries and electric drives, advanced combustion, advanced materials, and fuels and lubricant technologies) by estimating the decrease in fuel consumption per mile in advanced vehicles due to improvements in technologies in each VTO Program area. The differences in the vehicle masses in Autonomie simulations for the Target and No Program cases were used to estimate the fuel saved by “lightweighting” (reducing the mass of the vehicle). For HEVs and PHEVs, changes in the masses of batteries and of power electronics and electric motors (PEEM) were not considered to be part of lightweighting, since the reduction in the masses of these components is attributed to the batteries and electric drive technologies used. It was assumed that the percent decrease in fuel consumption per mile was proportional to the percent decrease in vehicle mass (excluding battery and PEEM mass). For ICE vehicles, a proportionality constant of 0.66 was used (i.e., a 10% mass reduction corresponds to a 6.6% reduction in fuel consumption), and for HEVs, a constant of 0.59 was used, on the basis of previous vehicle simulations (Pagerit et al., 2006; Brooker, 2011). For PHEVs, it was assumed that the proportionality constant was slightly less than that for HEVs, and 0.55 was used.

The decrease in the amount of fuel consumed per mile resulting from reduced friction was attributed to the fuels and lubricant technologies used. A reduction in engine friction of 1% was assumed to reduce fuel consumption by 0.03%, and a reduction in drivetrain frictional losses of 1% was assumed to reduce fuel consumption by 0.05%, on the basis of power flows in vehicle simulations (EPA and DOE, 2011). A decrease of 10% in engine and drivetrain friction was assumed for the year 2030, and a 15% reduction was assumed for 2050.

Decreases in fuel consumption per mile from reductions in rolling resistance and aerodynamic resistance were estimated but were not attributed to the VTO Programs for LDVs, since none of these programs support the reduction of rolling resistance or aerodynamic resistance in LDVs.

For ICE vehicles, the remainder of the fuel savings was attributed to improvements in engine combustion efficiency (advanced combustion engine R&D). For HEVs and PHEVs, half of the remainder of fuel savings was attributed to improvements in engine combustion efficiency, and the other half was attributed to the battery and electric drive technologies used.

Heavy-truck GPRA advanced technology modeling followed a process flow similar to that just described for LDVs. In the first phase, TA Engineering, Inc. (TAE) defined advanced vehicle platforms using information on technology approaches and benefits obtained during analysis of the SuperTruck program benefits as well as prior years' GPRA analyses. The HTEB model (augmented by a dynamic version, HTEBdyn) was used to analyze the following heavy-vehicle classes and platforms that are consistent with VTO Program research areas and goals:

- Class 4–6 diesel delivery
  - Best-in-class (BIC) conventional diesel CI
  - Advanced conventional diesel CI
  - Parallel hybrid diesel-electric CI

- Class 8 combination unit
  - BIC conventional diesel CI
  - Advanced conventional diesel CI
  - Parallel hybrid diesel-electric CI

- Class 7 and 8 single unit
  - BIC conventional diesel CI
  - Advanced conventional diesel CI
  - Parallel hybrid diesel-electric CI

The incorporation of the BIC platform in addition to an advanced conventional vehicle is new for the GPRA FY14 analysis. This vehicle was included to capture the differences between the baseline vehicles used to establish the EPA/National Highway Traffic Safety Administration fuel economy standards and consistent with the AEO base-year vehicles and the vehicle characteristics used by the SuperTruck industry for its baseline vehicles. Therefore, it represents real differences among existing product offerings as of the 2011–2012 model years and incorporation of very-near-term technologies for the 2012–2015 timeframe. The BIC configurations are similar to the actual products that likely will be used to meet the fuel economy standards.

The technology characterizations developed for the advanced truck platforms in analysis years 2011 (BIC only), 2015, and 2025 were based on technology approaches being pursued by SuperTruck industry teams (TA Engineering, 2012) and information contained in the National Research Council (NRC) study documented by TIAX (2009) and NRC (2010). TAE then used the component costs from the NAS study to develop platform incremental costs, relative to the baseline truck, associated with these technology characterizations. Fuel economy improvements in the Target Case vehicles were estimated for these same years using the HTEB and HTEBdyn models, and linear interpolation was used for intervening years. For years after 2035, the fuel economy of advanced vehicles was held constant.

In the second phase of the GPRA heavy-truck analysis, the fuel economy improvements and estimated costs resulting from the HTEB/HTEBdyn analysis were applied to the TRUCK vehicle choice model (TA Engineering, 2010) to project market penetration of the advanced platforms. TRUCK determines market acceptance by comparing incremental costs and the value of fuel savings to buyer preferences for different payback periods. Since the use of fuel-efficient technology is more cost-effective for trucks with above-average annual mileage, the payback algorithm is applied to multiple mileage cohorts rather than assuming the fleet average mileage for all trucks. TRUCK then reports market share as a fraction of total miles driven by trucks of a particular model year in the first year of ownership.

For the market penetration analysis, the penetrations of three technology packages were estimated for each of the weight-class groups (Class 4–6, Class 7&8 combination units, and Class 7&8 single units). In each weight class, the 2011 BIC truck represents the highest fuel economy expected with technology currently on the market, while the 2015 BIC truck represents incorporation of very-near-term technologies, e.g., advanced EPA SmartWay aerodynamics and next-generation wide-base tires. The advanced conventional and hybrid combination unit trucks represent SuperTruck goals. The technologies used to achieve these goals are extended to class 7&8 single-unit and class 4–6 trucks where applicable. These vehicles utilize approaches being investigated by the SuperTruck industry teams. In each truck class, the hybrid platform incorporates all technologies included on the advanced conventional vehicle and assumes synergies between hybridization and waste heat recovery systems (turbo-compounding and organic Rankine cycle). As discussed above, market penetration depends in part on the payback period of the advanced technology vehicles, which depends on assumed fuel prices. Market penetrations were calculated for fuel prices from the AEO Reference case and the AEO High Oil Price case (both extrapolated to 2050). Results shown below are for the High Oil Price case fuel prices.

For the third and final step of the HT GPRA benefits analysis, fuel use by HTs under the Target case was compared to the baseline No Program consumption. For HTs, the VISION model is used to project fuel consumption in the Target case. Unfortunately, VISION currently is not configured to analyze all the heavy-vehicle platforms modeled for the FY14 GPRA analysis. Therefore, the VISION truck sales, age-specific average annual mileage, cumulative scrappage rates, and various correction factors were applied in an additional spreadsheet tool that tracks the stock of heavy vehicles sold in 2010 and later. Fuel use by these trucks is calculated by first assuming the simulated fuel economies and TRUCK market penetrations and then assuming the baseline No Program fuel economy for all trucks. The difference between these two calculations provides a projection of energy and carbon emission savings due to the DOE program.

The projected HT fuel consumption and carbon benefits were allocated to each program area by using results from the Autonomie-calibrated HTEBdyn model. HTEBdyn was used to estimate power losses by vehicle component, and these results were used to calculate fuel consumption by technology area. The fuel consumption by area for each advanced vehicle was compared to that of the base vehicle to determine the reduction in duty cycle average gallons per mile due to each. These values were then converted to a percentage of the total fuel consumption savings and are shown in Figure 5 above. For the BIC configuration, percentages were calculated for 2011 and 2015 and interpolated for the intervening years. The 2015 values were then held constant through 2050. For the remaining technologies, values were calculated for 2015 (year of introduction) and 2025, and interpolated for the intervening years. The 2025 values were held constant for 2025 through 2050.

5 RESULTS OF MODELING: MARKET PENETRATION AND FLEET FUEL ECONOMY

Sales share projections of LDVs, by drivetrain technology, were estimated for the years 2010 through 2050 by using the MA^3T model on the basis of vehicle attributes developed from Autonomie simulations for the No Program and Target cases. The slight differences between the sales shares in the two cases in the years 2010-2012 are due to differences in assumptions about vehicle characteristics in these years. The sales share for each drivetrain technology is shown in Figure 5, and sales shares are listed in Table 9 for these two cases. The difference between the market shares estimated for the two cases is listed in Table 10.

Market penetration estimates from MA^3T modeling of LDVs show market shares of HEVs and PHEVs increasing over time. For the Target case, HEVs penetrate early, and PHEV penetration follows. The HEV shares shown in Figure 5 include both gasoline HEVs and diesel HEV shares. Diesel HEV shares reach 5 to 6% in the Target case in years 2030–2050, but diesel ICE shares remain low in both the Target and No Program cases and are not shown. Low penetration of diesel ICE vehicles is presumably due to their higher purchase price, which makes them less competitive with gasoline ICE vehicles or HEVs. Likewise, BEVs and FCVs achieve only low sales shares in both the No Program and Target cases and are not shown. The low penetration by BEVs and FCVs is due, in part, to the assumption of very little public infrastructure for charging or hydrogen fueling. The penetration estimates for HEVs and PHEVs are significantly higher for the Target case, indicating a strong influence of VTO Program technologies. The PHEV market share in the Target case is roughly twice the market share in the No Program case, with rapid penetration occurring significantly earlier in the Target case. Differences in market penetration are due to differences in purchase prices and in operating costs (fuel costs and amortized battery replacement costs for PHEV and BEVs). This result indicates the importance of reducing vehicle purchase prices to enable the widespread adoption of vehicles with new drivetrain technologies. It also indicates that market share estimates are sensitive to assumptions about the factors that drive vehicle costs (including the costs of batteries and power electronics, lightweight materials and manufacturing processes, and more efficient engine and drivetrain technologies) as well as to assumptions about fuel prices.

The fleet average fuel economy increases significantly in the Target case when compared with the No Program case. Figure 6 shows the fleet average unadjusted fuel economy for new cars, light trucks, and the entire new LDV fleet for the Target and No Program cases. By using these fuel economy values for new vehicles and the stock model in VISION, with assumed on-road degradation factors, the on-road fleet average fuel economies were calculated for both cases.

Figure 7 shows the on-road fleet average for cars, light trucks, and the entire LDV fleet for the No Program and Target cases. Fuel savings track with increases in on-road fuel efficiency, so the significantly higher on-road fuel economy averages imply significant fuel savings, as discussed next.

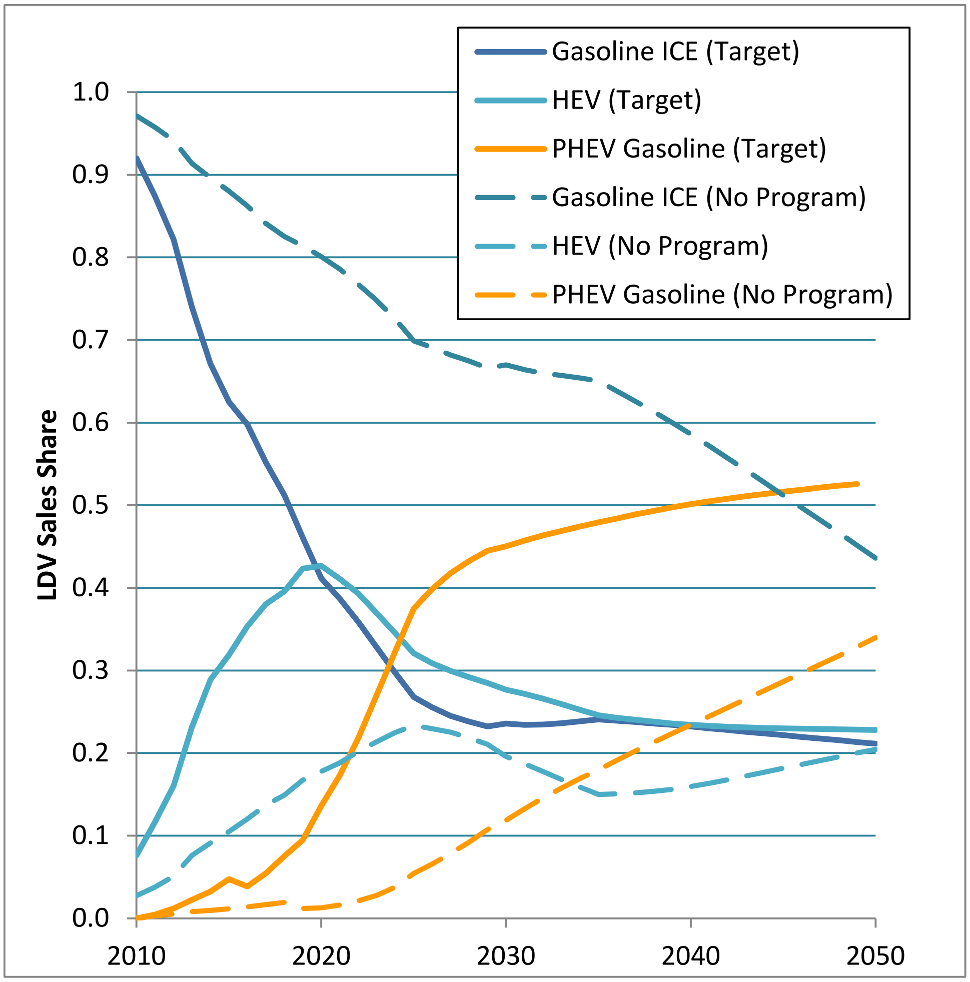

FIGURE 5 LDV Market Penetration Estimates for No Program and Target Cases (slight differences between the sales shares in the two cases in the years 2010-2012 are due to differences in assumptions about vehicle characteristics in these years)

TABLE 9 LDV Market Penetration Estimates (%) for No Program and Target Cases

Case	2020	2030	2040	2050
No Program				
Gasoline ICE	80.1	67.0	58.6	43.6
Diesel ICE	0.7	0.4	0.2	0.2
HEV gasoline	17.3	18.7	14.3	18.3
HEV diesel	0.5	0.9	1.7	2.1
PHEV gasoline	1.3	11.8	23.4	34.0
BEV	0.2	1.1	1.9	1.8
FCV	0.0	0.0	0.0	0.0
Target				
Gasoline ICE	41.1	23.6	23.2	21.1
Diesel ICE	2.1	1.4	0.5	0.2
HEV gasoline	40.3	21.2	17.4	17.2
HEV diesel	2.4	6.5	6.0	5.6
PHEV gasoline	13.6	45.0	50.1	52.8
BEV	0.5	2.3	2.7	3.0
FCV	0.0	0.1	0.1	0.1

TABLE 10 Difference (%) in LDV Market Penetration Estimates between Target and No Program Cases (Target Minus No Program) (Percentages shown are changes in sales shares as a fraction of total LDV sales.)

Case	2020	2030	2040	2050
Gasoline ICE	–39.9	–43.4	–35.4	–22.5
Diesel ICE	1.4	0.9	0.4	0.0
HEV gasoline	23.0	2.5	3.1	-1.1
HEV diesel	1.9	5.6	4.4	3.5
PHEV gasoline	12.3	33.2	26.7	18.8
BEV	0.4	1.2	0.8	1.3
FCV	0.0	0.0	0.0	0.0

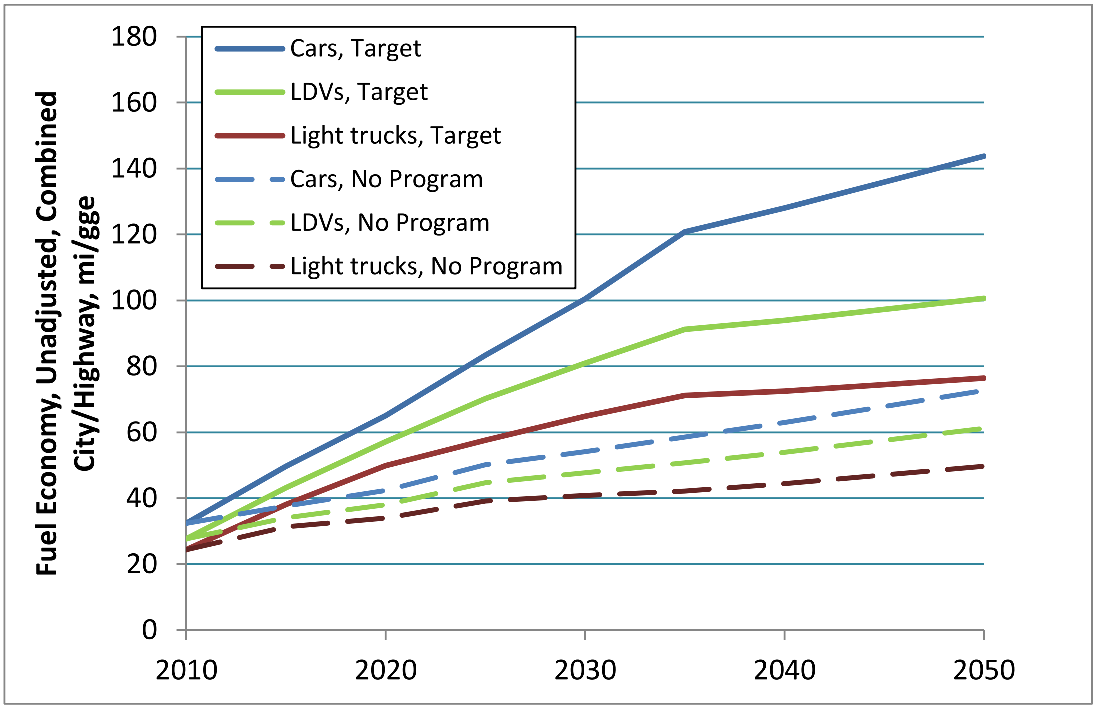

FIGURE 6 Fleet-Average Fuel Economy of New Cars, Light-Duty Trucks, and LDV Fleet for the No Program Case (dashed lines) and Target Case (solid lines)

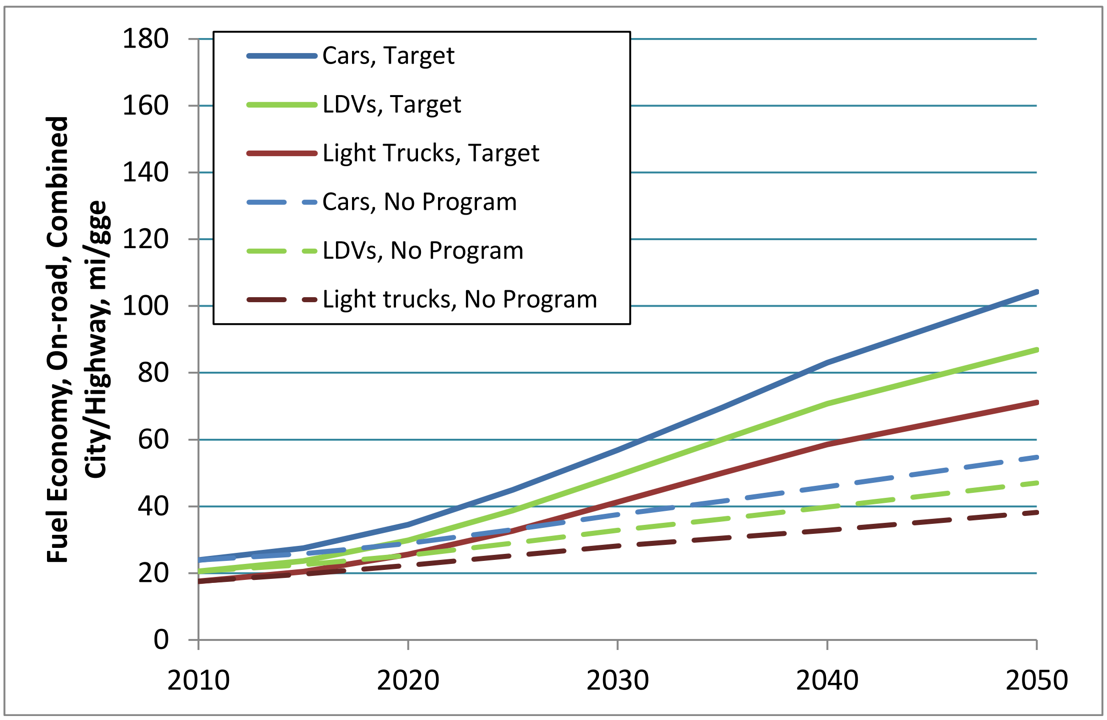

FIGURE 7 Average On-Road Fuel Economy of Cars, Light-Duty Trucks, and LDV Fleet for the No Program Case (dashed lines) and Target Case (solid lines)

Levelized cost of driving (LCD) was estimated for future LDVs with different drivetrains for the No Program and Target cases. The LCD was calculated from the estimated retail price equivalent for each vehicle and the estimated fuel expenditures and miles driven over five years of vehicle ownership. Fuel expenditures were discounted at 7% annually, intermediate between the high discount rates (often over 20%) at which some vehicle consumers discount future fuel savings (Greene, 2010) and a low discount rate (near zero) appropriate for discounting of social costs (OMB, 2012). The LCD is given by the ratio of the sum of the vehicle price and the present value of fuel consumed in five years of operation to the miles driven in five years. The LCD is shown in Figure 8 for midsize cars with several of the drivetrains analyzed, in 2010 dollars. These LCD values were calculated assuming that vehicles were driven 14,500 mi/year and assuming the following fuel prices for the year 2035: $5.05/gal for gasoline, $4.89/ gge for diesel, $1.81/gge for compressed natural gas (CNG), and $2.22/gge for hydrogen for the No Program case and $3.55/gge for the Target Case.

Figure 8 show the total LCD as the sum of costs of the fuel and the vehicle, by component. The breakdown by component shows the tradeoff between the higher price and lower fuel costs of advanced vehicles. In the Program case, the LCDs of HEVs and PHEVs are close to that of the Advanced SI vehicle, indicating that these electric drive vehicles can be cost-competitive. The LCD of CNG vehicles, BEVs and FCVs are projected to be quite low, largely owing to low fuel costs, but market acceptance may be low unless fuel infrastructure is provided and the range limitation of the BEV is overcome. Overall, future vehicles are projected to have lower LCD than the reference vehicle (having current fuel economy and vehicle price). If VTO Program technologies are successfully deployed, consumers will have a range of drivetrain technologies to choose from, including some that use fuels other than petroleum fuels.

Projections of the market penetration of advanced technology HTs are given in Table 11 as a fraction of total VMT by new trucks in a calendar year. Market penetration estimates are based on the time it takes for the fuel savings to offset the technology's additional cost—a calculation that depends on annual miles of travel. Therefore, fuel-saving technologies are adopted at a higher rate in applications with above-average annual mileage. Since the miles traveled correlate with fuel consumption, using a simple percentage of truck sales does not provide an accurate accounting of new-fleet fuel economy.

For the class 7 and 8 combination-unit trucks, the BIC platform shows very high market penetration in the early years. This result is due to the inclusion of relatively inexpensive component technologies that provide improvements in fuel economy and which are very cost-effective for the high-mileage trucks in this class.

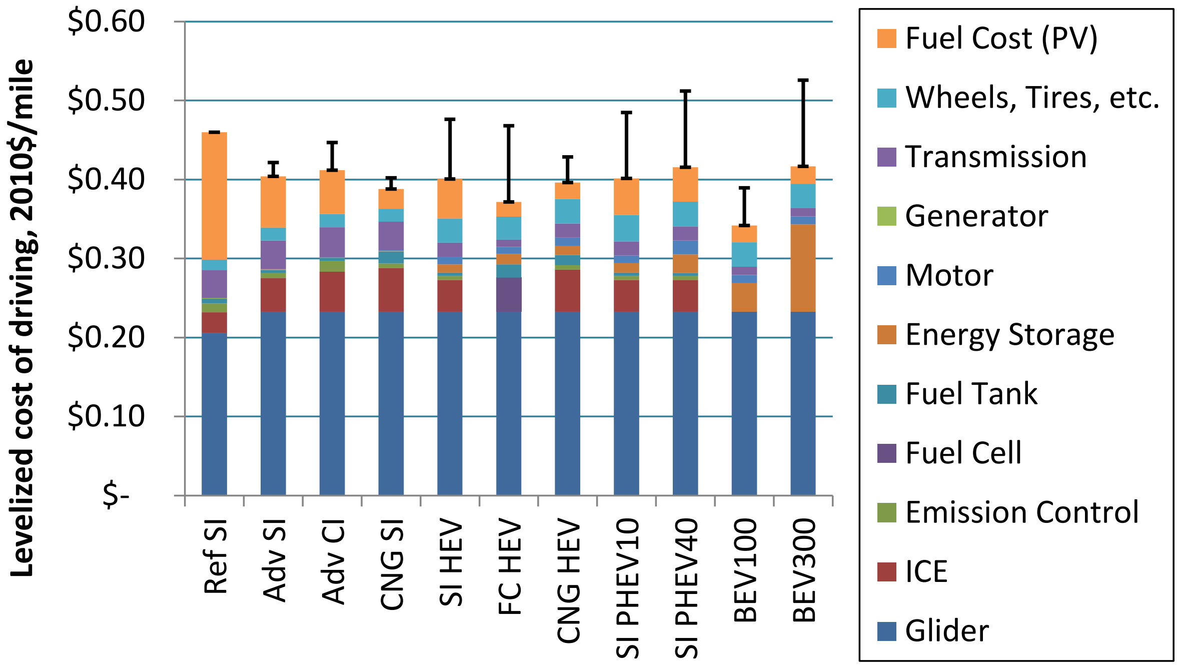

FIGURE 8 Levelized Cost of Driving (LCD) of LDVs. The bars show the LCD of the Target Case, and the upper ends of the error bars show the LCD of the No Program Case. Present value (PV) of fuel cost is shown assuming a 7% discount rate.

TABLE 11 Medium- and Heavy-Duty Truck Market Penetration Estimates for the Target Case, as Percentage (%) of VMT

Vehicle	2020	2030	2040	2050
Medium (Class 4–6) diesel				
Baseline	72.1	67.5	62.8	62.2
BIC Conventional	14.0	14.8	17.7	17.8
Advanced conventional	13.2	14.9	16.2	16.6
Diesel HEV	0.7	2.8	3.3	3.5
Heavy (Class 7, 8) combination unit				
Baseline diesel	28.2	21.3	18.0	17.0
BIC Conventional	37.8	34.0	34.8	35.2
Advanced conventional	24.3	26.6	27.6	27.7
Diesel HEV	9.7	18.1	19.6	20.1
Heavy (Class 7, 8) single unit				
Baseline diesel	80.1	74.4	68.0	67.4
BIC Conventional	13.3	15.1	19.5	19.8
Advanced conventional	5.4	7.2	8.5	8.7
Diesel HEV	1.1	3.3	3.9	4.1

The advanced conventional diesel trucks also show significant market share for the combination unit trucks in the first year of introduction, but less than the BIC conventional trucks owing to higher incremental cost. Following its introduction in 2015, this platform becomes less expensive but also more efficient and it steadily gains market share and share of VMT, growing from 24% of VMT in 2020 to 28% in 2050. Meanwhile, the hybrid truck initially gains only a small market share, owing to high incremental cost and little fuel economy benefit relative to the advanced conventional truck due to the long-haul-type driving cycle. However, the hybrid truck realizes greater cost reductions over time owing to the assumptions of both increasing manufacturing experience (learning) and increasing production volumes. By 2020, the hybrid platform achieves a 10% share of vehicle miles in the combination unit class. This grows to 20% by 2050. The total share of alternative vehicles reaches about 83% of vehicle miles by 2050.

The results for single-unit trucks are quite different, owing to the lower annual miles traveled by trucks in this class. The BIC platform initially captures about 13% of VMT but loses share as the baseline gradually improves. The advanced conventional truck platform achieves only 5% of VMT by 2020 and reaches a maximum of 9% in 2050. Although the hybrid drivetrain provides more fuel consumption benefits over the vocational drive cycle, the low annual mileage of the single-unit trucks results in longer payback periods. As a result, the hybrid platform achieves a maximum share of about 4% of VMT.

Overall, the advanced technology platforms achieve lower penetrations within the class 4-6 truck market than the class 7&8, reflecting the fact that these trucks see the lowest annual mileage of the classes analyzed. The BIC trucks initially capture roughly a third of class VMT and then decline in share with the introduction of the advanced conventional platform and improvements in the baseline truck's performance. After the baseline levels off in 2025, the BIC truck gradually increases to 18% of VMT by 2050. The advanced conventional trucks achieve shares similar in to the BIC trucks' share in 2020 at 13% of VMT, growing to nearly 17% by 2050. The hybrid shares in this class are very similar to those in the 7&8 single-unit class, capturing 3.5% of class VMT by 2050. In total, advanced vehicles account for only about 38% of VMT in 2050. The lower penetration of advanced technologies in this class reflects the much lower annual miles of travel and associated longer payback periods compared to class 7&8 trucks.

The new-vehicle fleet fuel economy values for medium- and heavy-duty trucks are shown in Figure 9 for the Target and No Program cases. Fleet averages are mileage-weighted values. As a result of DOE-supported technologies, the fuel economy of the fleet of all new class 7&8 trucks is projected at 1.54 times that of the baseline truck in 2030 and 1.6 times the baseline in 2050. Because of the lower annual usage of class 4–6 diesel trucks, the impact of DOE-funded technologies is smaller in these vehicles, with a fuel economy ratio of 1.13 in 2030 and 1.16 in 2050.

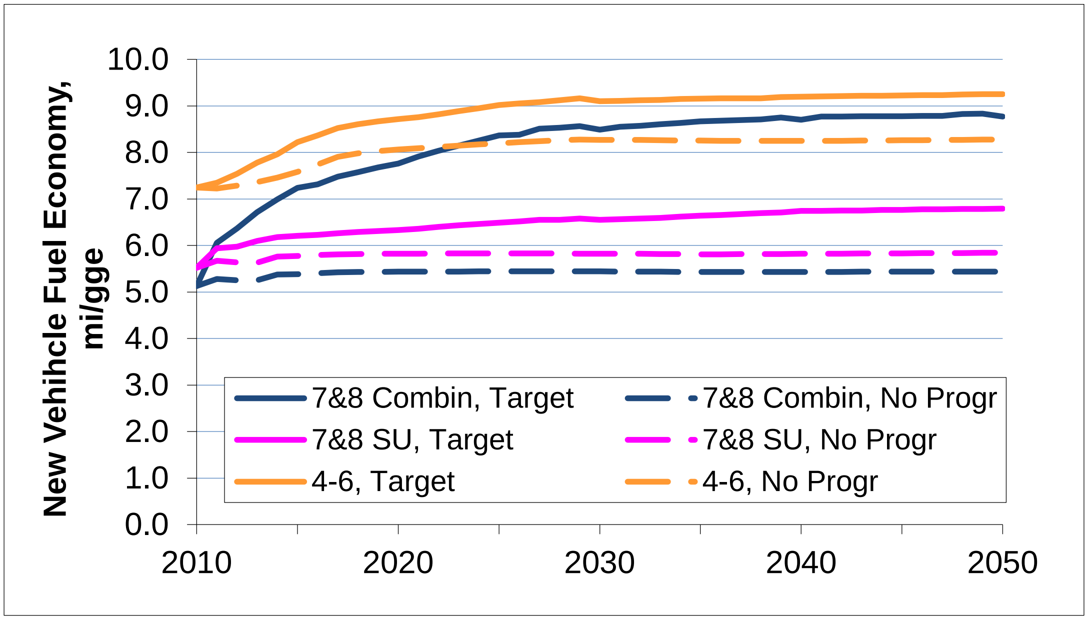

FIGURE 9 Fleet-Average Fuel Economy of Medium- and Heavy-Duty Trucks for the No Program Case (dashed lines) and Target Case (solid lines)

6 RESULTS OF MODELING: OVERALL BENEFITS FOR THE VEHICLE TECHNOLOGIES PROGRAM

Fuel savings, primary energy savings, and GHG reductions for the entire U.S. fleet and the benefits from both LDVs and HTs were estimated as described previously. Table 12 shows the total benefits estimated from VTO Program technologies.

The issue of energy security is largely an issue of oil security. Since the transportation sector accounts for about 70% of the oil consumed in the United States, reductions in the use of oil for transportation are necessary for the nation to move toward energy security. The estimates of the benefits from the VTO Program show that a successful program could reduce oil use in 2030 by 2.8 million bpd (barrels or bbl per day). In relative terms, these oil savings amount to 20% of total AEO-projected transportation oil use in 2030.

The estimated cumulative GHG emission benefit in 2030 is 4,300 million metric tons (t) of carbon dioxide equivalent ($CO_{2\ eq}$); again, these estimates are shown in Table 12. These CO_2 reductions are substantial and will help the nation move toward a lower GHG total in 2030. Various dollar values have been placed on a ton of CO_2. Assuming CO_2 values ranging from $10 to $50 per metric ton, these estimated VTO Program carbon reductions would range in value from $43 billion to more than $200 billion (not discounted).

Improving fuel economy offers benefits to consumers, who pay lower prices for fuel and transportation-dependent commodities. The mpg improvement metric in Table 12 serves as a means of personalizing the oil savings metrics: improved fuel economy reduces the individual consumption of oil for personal mobility and therefore reduces consumer expenditures. However, the increases in LDV fuel economy shown in Table 12—70% in 2030 and 65% by 2050 (over the No Program case)—do not capture the full benefit to the consumer. The increase in average U.S. fuel economy means that vehicle drivers use fuel more efficiently, thus depending less on large amounts of petroleum fuel, and they are therefore more insulated from potential oil shocks. Dependency on oil decreases further as consumers move from conventional ICE vehicles to plug-in vehicles, which are powered by electricity in addition to petroleum.

Oil security considerations are especially important in light of the presumption in EIA's AEO publication, which serves as the foundation for the baseline case used herein. This presumption is that the availability of the petroleum supply will be sufficient to meet demand. In a future where that presumption did not hold, oil shocks would be more likely. Shielding America's transportation sector from being vulnerable to such shocks is critical. Conversely, it is possible, if domestic production increased significantly and remained strong, or efficiency and renewable energy measures in nontransportation sectors were sufficiently successful on a global scale, that petroleum supply would be sufficient to keep petroleum fuel prices low. These low prices would, in turn, inhibit the penetration of advanced technology vehicles and decrease the benefits attributed to the VTO Program in this report.

The significant premium placed on oil security in the United States is worth exploring further than by simply studying what is indicated by the reduced oil use figures just mentioned.

According to an analysis by Greene and Leiby (2006) at ORNL, oil security benefits can be estimated using an Oil Security Metric Model that they developed. An economic value can be assigned to oil security that reflects the potential reduction (as a consequence of the VTO Program) in damage done to the U.S. economy by oil supply disruptions. The benefits that can be measured monetarily are (1) the transfer of wealth, (2) economic surplus losses, and (3) macroeconomic disruption costs. The transfer of wealth is equal to the quantity of actual oil imports at the higher price, multiplied by the difference between the actual price of oil and what the price would have been in a competitive (or undisrupted) market. Economic surplus losses are deadweight losses that accompany changes in the amounts of oil supplied and in prices. Macroeconomic disruption costs are those that occur when sudden changes in the oil price cause economic dislocations that result in temporary underemployment and misallocation of resources, and thereby a temporary excess loss of gross domestic product (GDP) beyond what the higher price level alone would induce. These disruption costs result from job destruction and creation, and they cause a temporary period of increased unemployment and lost productivity. Greene and Leiby (2006, pp. 67–73) used their model to estimate the dollar savings from a 1.6 million-bpd reduction in oil use in 2030, which they projected to result under a scenario that assumed a high penetration by HEVs (which replaced conventional LDVs). They estimated the oil security benefit from this petroleum reduction to be between \$22 and \$58 billion (in 2004 dollars). The wide range results, in part, from uncertainty in the response by OPEC to reduced U.S. oil demand and the resulting changes in the global oil price. However, from the reduction in oil use projected for the Target case (2.8 million bpd, Table 12), the oil security benefit of successful deployment of VTO Program technologies may be almost double this amount. These oil security benefits are very large and have a positive effect on the nation’s economy.

Taken together, these benefits demonstrate that a successful VTO Program will significantly reduce (1) oil consumption (and thus dependence on oil), thereby saving energy; (2) GHG emissions; and (3) consumer energy expenditures. Moreover, the VTO Program offers additional benefits that are not explicitly captured in the table, i.e., maintaining Americans’ personal mobility and reducing their exposure to potential oil price shocks.

TABLE 12 Vehicle Technologies Program Benefits Metrics[a]

Impact	Metric	Year 2015	2020	2030	2050
Energy security	Oil savings, cumulative (billion bbl)	0.4	2.3	10.3	35.9
	Oil savings, annual (million bpd)	0.5	1.4	2.8	3.8
	New vehicle mpg improvement (%)[a]				
	LDVs	27	50	70	65
	HTs	29	35	46	50
	On-road mpg improvement (%)				
	LDVs	5	18	50	85
	HTs	8	18	33	42
Environmental	CO_2 emissions reduction,[b] cumulative (million t $CO_{2\ eq}$)	200	1,000	4,300	15,000
	GHG emissions reduction, annual (million t $CO_{2\ eq}$/yr)				
	LDVs	55	154	291	406
	HTs	37	82	147	216
	Total	92	236	438	622
Economic	Primary energy savings,[b] cumulative (quads)	2	12	53	188
	Primary energy savings, annual (quads/yr)	1.3	3.5	6.8	9.6

[a] Improvement relative to baseline (No Program) fleet in the same year.

[b] "Reductions" and "savings" are calculated as the difference between the results from the baseline (No Program) case (i.e., in which there is no future DOE funding for this technology) and the results from the Target case (i.e., in which requested DOE funding for this technology is received and the program is successful). All cumulative metrics are based on results beginning in 2010.

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