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Vehicle Technologies Program Government Performance and Results Act (GPRA) Report for Fiscal Year 2015

Energy Systems Division

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Vehicle Technologies Program Government Performance and Results Act (GPRA) Report for Fiscal Year 2015

prepared by
T.S. Stephens,[1] A.K. Birky,[2] and J. Ward[3]
[1]Energy Systems Division, Argonne National Laboratory
[2]TA Engineering, Inc., of Baltimore, MD
[3]U.S. Department of Energy Office of Energy Efficiency and Renewable Energy

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ACRONYMS

ACE	Advanced combustion engine
AEO	Annual energy outlook
BEDT	Batteries and Electric Drive Technology
BEV	Battery electric vehicle
BIC	Best-in-class
CD	Charge-depleting
CI	Conventional ignition
CO_2	Carbon dioxide
DOE	Department of Energy (United States)
EERE	Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency (United States)
EV	Electric vehicle
FCV	Fuel cell vehicle
GHG	Greenhouse gas
GPRA	Government Performance and Results Act
HEV	Hybrid electric vehicle
HT	Heavy duty truck
HTEB	Heavy Truck Energy Balance (model)
ICE	Internal combustion engine
ICME	Integrated Computational Materials Engineering
LCD	Levelized cost of driving
LDV	Light duty vehicle
NHTSA	National Highway Transportation Safety Administration
NRC	National Research Council
ORNL	Oak Ridge National Laboratory
PEEM	Power electronics and electric motors
PEV	Plug-in electric vehicle
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
R&D	Research and Development

SI	Spark-ignition
SUV	Sport utility vehicle
TAE	TA Engineering
VMT	Vehicle miles traveled
VSST	Vehicle and Systems Simulation and Testing
VTO	Vehicle Technology Office

VEHICLE TECHNOLOGIES PROGRAM GOVERNMENT PERFORMANCE AND RESULTS ACT (GPRA) REPORT FOR FISCAL YEAR 2015

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's Vehicle Technologies Office (VTO) invests in research, development, demonstration, and deployment of advanced vehicle technologies under a diverse set of technology programs. This report provides estimates of the benefits that would accrue from successfully developing and deploying these technologies 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 and the resulting fuel savings by the on-road vehicle stock 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 average fuel economy of the on-road, light-duty vehicle stock would improve by more than 40%, and that of the on-road medium- and heavy-duty vehicle stock would improve by over 25% in the Target case relative to the Base case, and that this would result in a reduction in oil consumption of approximately 2.4 million barrels per day and a reduction in GHG emissions of about 400 million metric tons of CO_2 equivalent per year. These benefits would have 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 (VTO) technology 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 estimated; that is, it describes the development of scenarios for the commercialization of vehicle technologies that are being developed under the current and soon-to-be-implemented VTO R&D activities and the methodologies used to estimate the future benefits of the successful deployment of these technologies. The analysis of benefits involves a number of models, including advanced vehicle simulation and power flow models, which relate the impacts of R&D activities on future fuel economy improvements. 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.

The analyses documented here were made assuming that VTO budget levels will remain flat through FY17, the last year through which targets and goals have been set for many activities within each subprogram (DOE, 2013). The technology development plans and milestones for each VTO program technology area are described at the beginning of Section 2.

Section 2 gives a description of VTO program activities by technology area (or “subprogram”) and gives the estimated fuel savings attributed to each subprogram.

Section 3 opens with a discussion of a baseline “No Program” scenario against which to measure VTO program benefits and the important factors to consider when using this baseline to make comparisons. The second part of Section 3 discusses modeling of advanced vehicle technologies and how the estimated improvements in fuel economy are attributed to subprograms and key activities.

Section 4 gives the resulting estimates of fuel economy improvements and discusses the projections of market penetration of VTO program technologies.

In Section 5, 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 PROGRAM ACTIVITIES, MILESTONES, AND OUTPUTS

In FY15, 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 2 briefly describes the milestones for each subprogram area and the estimated benefits that could result from their achievement.

The fuel savings resulting from the first four subprogram areas was estimated from the improvement in fuel economy (or reduction in fuel consumed per mile) estimated to result from application of each of the technologies in combination, as described in Section 3.2. Vehicle stock models were used to track fuel use by vehicle type, taking into account the projected number of each type of vehicle and the vehicle-miles traveled (VMT) by each in the Target case and in the No Program case, as described in Section 3.2.

2.1 BATTERIES AND ELECTRIC DRIVE TECHNOLOGY

The BEDT subprogram addresses the development of low-cost, high-energy batteries and 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, 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. Technical targets of the BEDT subprograms include reducing the production cost of a high-energy battery to $125/kWh by 2022, and reducing the cost of an electric-traction-drive system that can deliver 55 kW of peak power for 18 seconds and 30 kW of continuous power from $17/kW in 2012 to $8/kW in 2022. Subprogram targets by year and recent progress are shown in Figure 1. Meeting these targets will enable the cost-competitive market entry of plug-in HEVs (PHEVs).

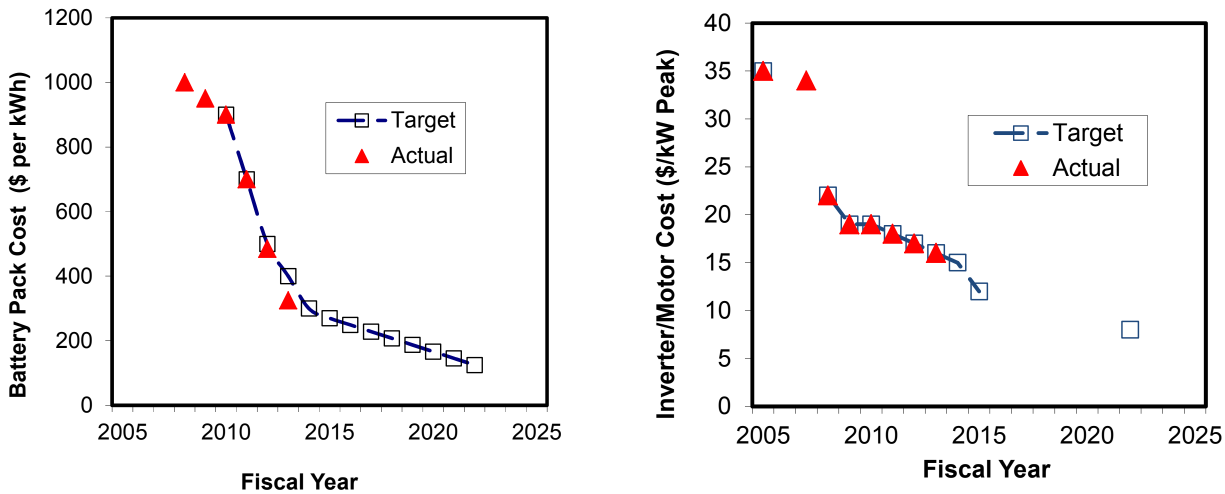

FIGURE 1 PHEV Battery Cost (left) and Combined Inverter/Motor Cost (right)

In FY15, 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) needed to make PHEVs cost effective. PHEVs have the potential to provide significant fuel savings through greater efficiency and through use of electricity instead of liquid fuel. 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 1, the percentages of the improvement (decrease) in fuel consumption per mile, achieved by vehicles having each type of drivetrain, that are attributable to VTO Program work on BEDT are shown for the years 2030 and 2050. The first (top) row gives the percentage of the improvement in new vehicle fuel consumption in the Target case over the same-year baseline (No Program) vehicle of the same drivetrain type due to BEDT, and the second (bottom) row gives the percentage of the improvement in the on-road stock fuel consumption over the baseline stock of vehicles of the same drivetrain type in the same year due to BEDT. (In this table and throughout this document, SI refers to spark ignition (gasoline-powered), PHEV10 and PHEV40 refer to PHEVs with nominal charge-depleting [CD] range of 10 and 40 miles, respectively, HT refers to medium- and heavy-duty trucks, and VMT refers to vehicle miles traveled.) Percentages shown for SI vehicles, HEVs, PHEVs are sales-weighted averages (top row) and stock- and VMT-weighted averages of values for cars and light trucks. HT percentages are stock- and

VMT-weighted averages of values for trucks of size classes 4 through 8. Reductions in fuel consumption due to fuel economy improvement in each drivetrain type are considered, but electricity consumption is not included here. Note also that these reductions do not represent the full fuel savings attributable to this technology subprogram, since it does not include the fuel savings due to changes in the mix of powertrain technologies in the vehicle stock, which in the Target scenario contains more advanced-technology vehicles, including larger fractions of hybrid and plug-in vehicles. A full accounting of fuel savings attributable to each subprogram is given in Section 2.7 below.

2.2 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%.

- 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 future years, the Combustion and Emission Control activity will continue to 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. The Solid State Energy Conversion activity will develop technologies to convert waste heat from engines and other sources directly to electrical energy to improve overall fuel economy and reduce emissions.

Additionally, new 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 new technologies with high potential impacts into the EERE portfolio.

In addition, the SuperTruck Partnership, an industry cost-shared initiative, supported by the Advanced Combustion Engine R&D, Vehicle and Systems Simulation and Testing, and Materials Technology subprograms, 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 2, the percentages of improvements (decreases) in fuel consumption per mile achieved by new vehicles of each drivetrain type that are attributable to VTO efforts in advanced combustion engine technology are shown for the years 2030 and 2050. In the first (top) row, the percentage of the improvement in new vehicle fuel consumption over the same-year baseline (No Program) vehicle of the same drivetrain type due to ACE technology is shown, and in the second (bottom) row, the percentage of the improvement in the on-road stock fuel consumption over the baseline stock of vehicles of the same drivetrain type in the same year due to ACE technology is shown.

TABLE 1 Projected Benefits of Batteries and Electric Drive Technology Subprogram: Percentage of Reduction in Fuel Consumption per Mile Compared to That of Vehicles with Same Type of Drivetrain

Key Focus	Metric	Year	SI	HEV	PHEV10	PHEV40	HT
Energy storage, power electronics, and electric motors	New-vehicle fuel economy improvement [a]	2030	-	18%	21%	23%	0.5%
		2050	-	16%	19%	20%	1%
	On-road stock fuel economy improvement [a]	2030	-	21%	22%	24%	0.5%
		2050	-	16%	19%	20%	1%

SI: Spark-Ignition, HEV: Hybrid Electric Vehicle, PHEV*xx*: Plug-in HEV with *xx* mile charge-depleting range

[a] The percentages shown are the fraction of the decrease in fuel consumption per mile in a new vehicle from that of a baseline vehicle of the same type of powertrain in the same year (top row), or in the average on-road stock from the baseline stock (bottom row) due to DOE-sponsored improvements in batteries and electric drive. LDV percentages are averages of improvements for light-duty vehicles, and HT percentages are VMT- and sales-weighted average improvements for heavy- and medium-duty trucks. These projections are estimates and can change with new DOE or DOE-sponsored research activities.

TABLE 2 Projected Benefits of Advanced Combustion Engine R&D Subprogram: Percentage of Reduction in Fuel Consumption per Mile Compared to That of Vehicles with Same Type of Drivetrain

Key Focus	Metric	Year	SI	HEV	PHEV10	PHEV40	HT
Combined combustion portfolio	New-vehicle fuel economy improvement [a]	2030	55%	43%	48%	53%	66% [b]
		2050	53%	37%	43%	47%	65% [b]
	On-road stock fuel economy improvement [a]	2030	54%	48%	51%	56%	66% [b]
		2050	55%	37%	44%	48%	65% [b]

SI: Spark-Ignition, HEV: Hybrid Electric Vehicle, PHEV*xx*: Plug-in HEV with *xx* mile charge-depleting range

[a] The percentages shown are the fraction of the decrease in fuel consumption per mile in a new vehicle from that of a baseline vehicle of the same type of powertrain in the same year (top row), or in the average on-road stock from the baseline stock (bottom row) due to DOE-sponsored improvements in combustion engine efficiency. LDV percentages are averages of improvements for light-duty vehicles, and HT percentages are VMT- and sales-weighted average improvements for heavy- and medium-duty trucks. These projections are estimates 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.

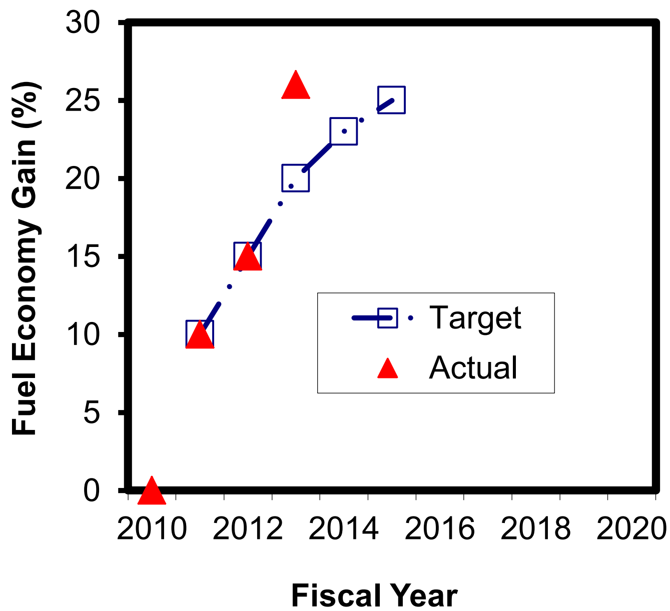

FIGURE 2 Fuel Economy Gains in Passenger Vehicles

2.3 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 3, taken from the workshop report, gives a summary of targets for weight reductions in light-duty ICE vehicles.

Planned Materials Technology research efforts will support three activities in (1) Propulsion Materials Technology, (2) Lightweight Materials Technology, and (3) Materials Technology Incubator. 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 moving components 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

TABLE 3 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)

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 magnets that contain little or no scarce materials such as rare earth elements and enabling processing techniques for higher-efficiency induction motors. The Lightweight Materials Technology activity addresses technology gaps that currently prevent the further introduction of advanced lightweight materials into vehicles. Materials Technology Incubator activities will invest in the creation of Incubator Programs, partnering with businesses and researchers to bring new, impactful technologies into the EERE portfolio.

In Table 4, the percentages of improvements (decreases) in fuel consumption per mile achieved by new vehicles of each drivetrain type that are attributable to VTO Materials Technology R&D are shown for the years 2030 and 2050. In the top row, the percentage of improvement in new vehicle fuel consumption over the same-year baseline (No Program) vehicle of the same drivetrain type due to Materials Technology is shown, and in the bottom row, improvement in on-road stock fuel consumption over the baseline stock of vehicles of the same drivetrain type in the same year due to Materials Technology is shown. No percentages are shown for HT, since it was assumed that lightweighting of class 7 and 8 combination unit trucks would result in higher payloads and therefore increased freight efficiency (in ton-miles of freight) rather than increased fuel economy of the loaded vehicle. Effects of lightweighting for class 7 and 8 single unit and class 4-6 trucks were combined with effects of reduced aerodynamic and rolling resistance, except for hybrid trucks, for which lightweighting effects were combined with hybridization effects .

2.4 FUELS AND LUBRICANT TECHNOLOGIES R&D

The Fuels and Lubricant Technologies R&D subprogram evaluates 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 future years, 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 done 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 new, impactful technologies to the EERE portfolio. The subprogram will also fund a competitive solicitation for a program incubator to encourage innovative and potentially disruptive advanced fuel and lubricant technologies.

In Table 5, percentages of improvement (decrease) in fuel consumption per mile achieved by new vehicles of each drivetrain type that are attributable to VTO Program Lubricant Technologies R&D are shown for the years 2030 and 2050. In the top row, the percentage of improvement in new vehicle fuel consumption in the Target case over the same year baseline (No Program) vehicle of the same drivetrain type due to Materials Technology is shown, and in the bottom row, the improvement in on-road stock fuel consumption over the baseline stock of vehicles of the same drivetrain type in the same year due to Materials Technology 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 2 and are not reported separately in Table 5. 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 many cases, deployment can be rapid, including deployment to legacy vehicles. Fleet-level benefits are discussed in Section 2.7.

TABLE 4 Projected Benefits of Materials Technology R&D Subprogram: Percentage of Reduction in Fuel Consumption per Mile Compared to That of Vehicles with Same Type of Drivetrain

Key Focus	Metric	Year	SI	HEV	PHEV10	PHEV40	HT
Combined combustion portfolio	New-vehicle fuel economy improvement [a]	2030	36%	30%	23%	18%	- [b]
		2050	35%	31%	24%	19%	- [b]
	On-road stock fuel economy improvement [a]	2030	35%	24%	20%	14%	- [b]
		2050	34%	35%	27%	23%	- [b]

SI: Spark-Ignition, HEV: Hybrid Electric Vehicle, PHEV*xx*: Plug-in HEV with *xx* mile charge-depleting range

[a] The percentages shown are the fraction of the decrease in fuel consumption per mile in a new vehicle from that of a baseline vehicle of the same type of powertrain in the same year (top row), or in the average on-road stock from the baseline stock (bottom row) due to DOE-sponsored improvements in combustion engine efficiency. LDV percentages are averages of improvements for light-duty vehicles, and HT percentages are VMT- and sales-weighted average improvements for heavy- and medium-duty trucks. These projections are estimates 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 5 Projected Benefits of Fuels and Lubricant Technologies R&D Subprogram: Percentage of Reduction in Fuel Consumption per Mile Compared to That of Vehicles with Same Type of Drivetrain

Key Focus	Metric	Year	SI	HEV	PHEV10	PHEV40	HT
Fuels and lubricant technologies	New-vehicle fuel economy improvement [a]	2030	36%	30%	23%	18%	- [b]
		2050	35%	31%	24%	19%	- [b]
	On-road stock fuel economy improvement [a]	2030	35%	24%	20%	14%	- [b]
		2050	34%	35%	27%	23%	- [b]

SI: Spark-Ignition, HEV: Hybrid Electric Vehicle, PHEV*xx*: Plug-in HEV with *xx* mile charge-depleting range

[a] The percentages shown are the fraction of the decrease in fuel consumption per mile in a new vehicle from that of a baseline vehicle of the same type of powertrain in the same year (top row), or in the average on-road stock from the baseline stock (bottom row) due to DOE-sponsored improvements in combustion engine efficiency. LDV percentages are averages of improvements for light-duty vehicles, and HT percentages are VMT- and sales-weighted average improvements for heavy- and medium-duty trucks. These projections are estimates and can change with new DOE or DOE-sponsored research activities.

[b] The benefits to HT fuel economy due to fuels and lubricant technologies are included in Table 4.

2.5 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 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 the future, 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. 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).

In Table 6, no fuel economy impact values are shown, but the simulation and testing activities are critical to other subprograms.

2.6 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 to the public (as required by law).

Clean Cities' primary goal is to reduce petroleum use in the United States by 2.5 billion gallons per year by 2020. To achieve this goal, Clean Cities employs three strategies:

- Replace petroleum with alternative and renewable fuels,
- Reduce petroleum consumption through smarter driving practices and fuel economy improvements, and
- Eliminate petroleum use through idle reduction and other fuel-saving technologies and practices.

Clean Cities coalitions and stakeholders have saved more than 5 billion gallons of petroleum since the program's inception in 1993. Clean Cities efforts have helped deploy thousands of alternative fuel vehicles and the fueling stations needed to serve them, aided in the elimination of millions of hours of vehicle idling, and helped accelerate the entry of electric-drive vehicles into the marketplace.

Future vehicle technologies deployment activities 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 student engineers to participate in advanced technology development—helping to address the need for more highly trained engineers in hybrid and fuel cell technologies. 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 7, 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. Fuel savings from previous years' Clean Cities activities are reported in the Clean Cities Annual Metrics report, which estimated that in 2012 Clean Cities core activities resulted in a fuel savings of over 720 million gallons of gasoline equivalent (gge), and 180 million gge was saved through Clean Cities outreach, education and training events (Johnson, 2013).

TABLE 6 Projected Benefits of Vehicle and Systems Simulation and Testing Subprogram

Key Focus	Metric	Year	SI	HEV	PHEV10	PHEV40	HT
Vehicle systems simulation and testing	Miles of on-road HEV/ PHEV/BEV testing	Critical enabling testing; no direct fuel economy benefit					

SI: Spark-Ignition, HEV: Hybrid Electric Vehicle, PHEV*xx*: Plug-in HEV with *xx* mile charge-depleting range, HT: Heavy- and medium-duty truck, BEV: Battery Electric Vehicle

TABLE 7 Projected Benefits of Outreach, Deployment, and Analysis Subprogram

Key Focus	Metric	Year	SI	HEV	PHEV10	PHEV40	HT
Clean Cities	Reduce petroleum use by 2.5 billion gallons per year by 2020	Critical enabling deployment and outreach activities					

SI: Spark-Ignition, HEV: Hybrid Electric Vehicle, PHEV*xx*: Plug-in HEV with *xx* mile charge-depleting range, HT: Heavy- and medium-duty truck, BEV: Battery Electric Vehicle

2.7 SUMMARY OF FUEL SAVINGS BY TECHNOLOGY AREA

The fuel savings projected to result from VTO subprograms by vehicles of all types was estimated by adding up the fuel saved by the vehicles with the relevant technologies on the road in a given year. Table 8 shows the estimated reductions in fuel consumption in quadrillion Btu (quads) per year in the years 2030 and 2050 by the U.S. fleet of 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); and
4. Fuels and Lubricant Technologies R&D (Friction Reduction).

Table 8 also shows the estimated total reduction in fuel use by the entire U.S. LDV fleet in quad/yr. The total is slightly larger than the sum of the reductions due to each technology area, since some reductions result from improvements in aerodynamic and rolling resistance which are not currently included in the VTO Program portfolio of projects applicable to LDVs.

The estimated reductions in fuel consumption in quad/yr in the years 2030 and 2050 by medium- and heavy-duty trucks (HTs), including classes 4 through 8, are shown in Table 9, 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. The technologies listed in Table 9 do not correspond to the VTO Technology subprograms, but to the types of technologies being developed and demonstrated under the SuperTruck partnership.

TABLE 8 Projected Reductions in Fuel Consumption by U.S. Light-Duty Vehicle Fleet Attributable to DOE VTO Technology Program by Technology Area (quad/yr)

VTO Technology Area	2030	2050
Batteries and electric drive technology	1.48	1.34
Advanced combustion engine R&D	0.99	1.52
Materials technology R&D	0.47	0.93
Fuels and lubricant technologies R&D	0.06	0.09
Total LDV Fleet Petroleum Use Reduction	3.08	4.10

TABLE 9 Projected Reductions in Petroleum Consumption by U.S. Fleet of Medium- and Heavy-Duty Trucks (Classes 4-8) Attributable to DOE VTO Technology Program by Technology (quad/yr)

VTO Technology Area	2030	2050
Drivetrain efficiency	1.04	1.72
Aerodynamic and rolling resistance reduction	0.46	0.76
Idle Reduction (non-hybrid)	0.08	0.12
Hybridization	0.01	0.03
Other (accessories and auxiliaries)	0.00	0.00
Total HT Fleet Petroleum Use Reduction	1.59	2.63

The projected petroleum consumption reductions in the year 2030 by technology area are shown in Figure 3. The percentage of the reduction that is attributable to each technology area is shown above each bar. Figure 4 shows the petroleum consumption reductions in the year 2050 by technology area with analogous percentages. Fuel savings are shown in million barrels per day (bpd) where 1 million bpd = 1.917 quad/yr (based on 125,000 Btu per gallon and 42 gal per barrel).

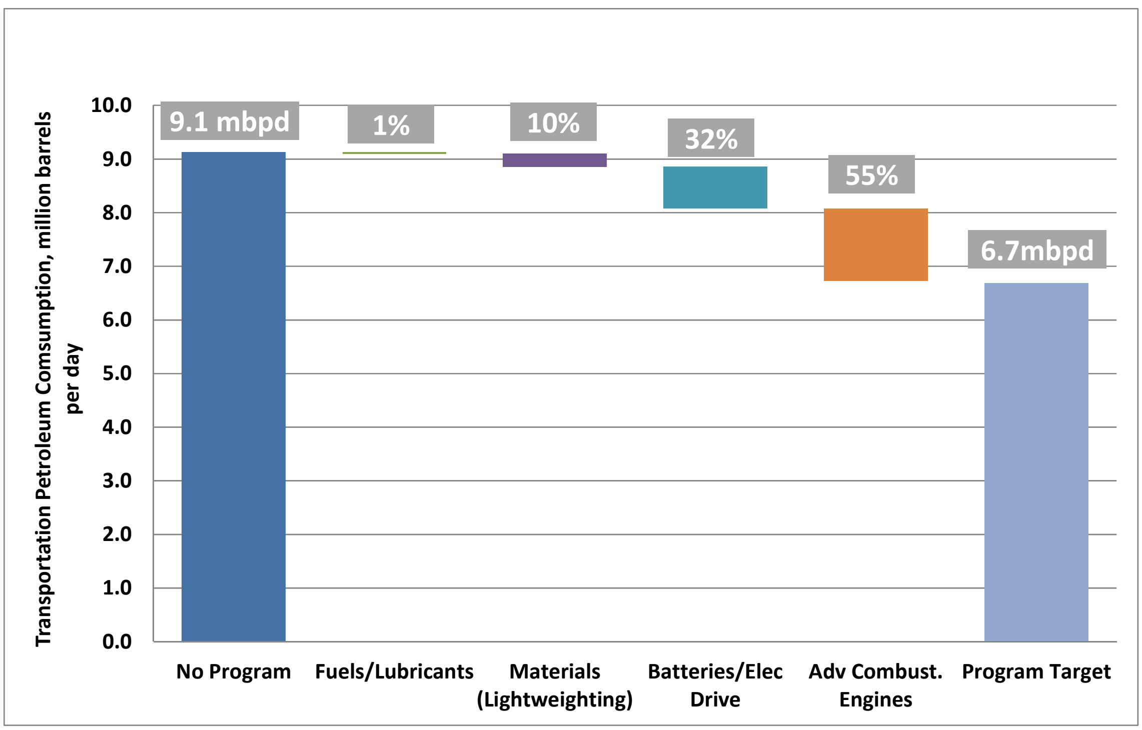

FIGURE 3 Reductions in Petroleum Consumption Attributable to VTO Technology Areas in the Year 2030

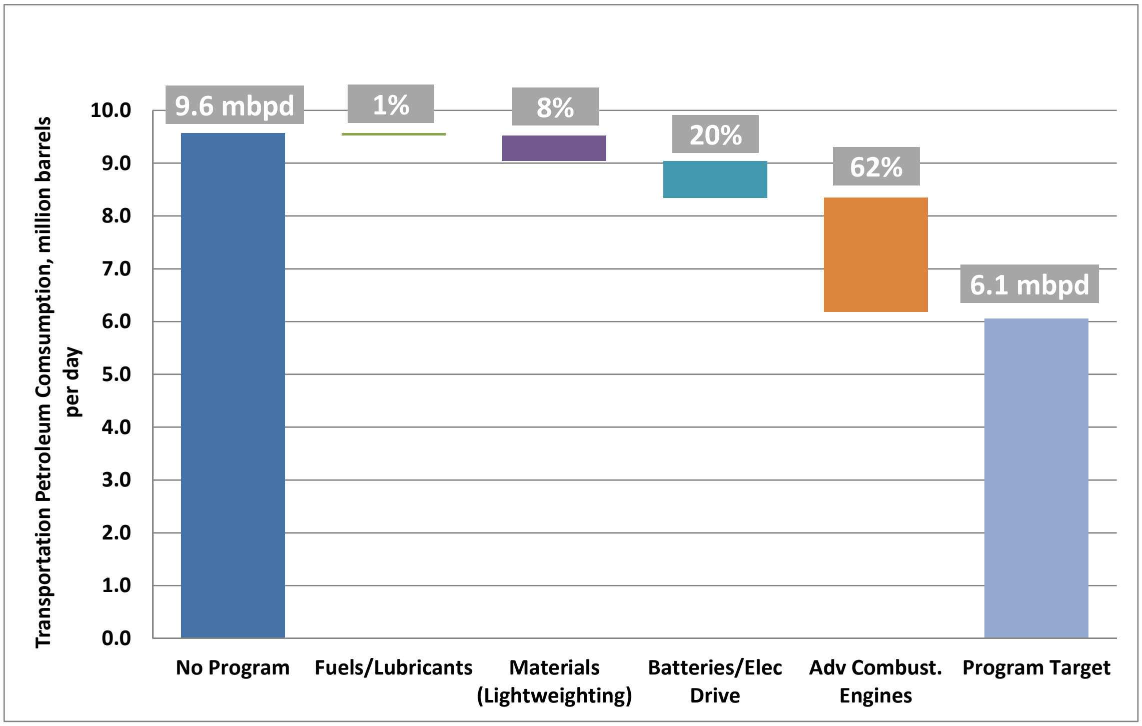

FIGURE 4 Reductions in Petroleum Consumption Attributable to VTO Technology Areas in the Year 2050

It should be noted that all fuel consumption reductions projected for medium- and heavy-duty trucks are attributed to the ACE Technology area, since these are being developed under the SuperTruck partnership (which is under the ACE subprogram).

From these results, we conclude that the technologies being developed under the ACE subprogram are attributed the largest share of the projected reduction in petroleum, followed by the BEDT subprogram, then by Materials R&D (Lightweighting), and lastly by Fuels and Lubricants R&D. Altogether, the reduction in petroleum use is substantial.

3 TRANSLATING PROGRAM GOALS INTO ENERGY MODEL INPUT PARAMETERS

3.1 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. Therefore, this AEO Reference case 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 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 (Moawad and Rousseau, 2014). 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 2013 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 2013 electricity generation mix.

The baseline case for medium- and heavy-duty vehicles was developed by TA Engineering (TAE) by adjusting the AEO 2013 reference-case fuel economy values for new heavy vehicles in order to remove the benefits attributed to the projected penetration by advanced technologies supported by DOE funding. The EIA provided individual component technology contributions to truck fuel economy and market penetration of these technologies in the AEO reference case. The technology penetrations are calculated at a finer level of disaggregation than that in the AEO output tables. Therefore, the penetrations were analyzed in subclasses consistent with the EPA/NHTSA fuel consumption rules (EPA and NHTSA, 2011a).

TAE used the AEO base year (year 2011 in AEO 2013) vehicle fuel economies for these subclasses, as documented in the AEO input files, in conjunction with the technology penetration tables, in order to determine the contribution of VTO-supported technologies to the reference case new fleet fuel economies. This analysis was performed for two years: 2017 (the year the fuel economy standards become fully effective) and 2040 (the last AEO projection year). TAE's evaluation of the AEO reference case in 2017 determined that 13.3% of the projected fuel economy improvement of the 2017 new fleet of class 7 and 8 sleeper cab tractors is attributable to non-VT technologies. The contributions of non-VTO technologies for class 7 and 8 day cab tractors, class 7 and 8 vocational trucks, and class 4-6 vocational trucks were estimated at 13.7%, 16.2%, and 19.6% respectively.

Since the AEO new fleet fuel economies are reported in the output tables for a single heavy class, the results of the three class 7 and 8 truck sub-classes were combined using sales shares obtained from EIA. Although the standard AEO output tables report results for a single medium class of trucks, EIA models class 3 trucks separately from class 4-6 and provided results tables for these subclasses separately. As was done for GPRA 2014, TAE analyzed only class 4-6 diesel trucks, and not the class 3 diesel or class 3-6 gasoline trucks. Because class 4-6 gasoline trucks account for a relatively small fraction of class 4-8 fuel consumption, benefits arising from penetration of VTO technologies in the class 4-6 gasoline trucks are likely very small. The AEO new medium (class 4-6) and heavy (class 7 and 8) truck fuel economy projections were then modified to eliminate the VT technology contributions.

Finally, representative baseline vehicles were developed in the HTEBdyn model (the dynamic version of TAE's Heavy Truck Energy Balance model) using inputs on vehicle and engine characteristics consistent with the 2010 baseline used by EPA and NHTSA in establishing the fuel economy standards. Most inputs were derived from the regulatory impact assessment and associated documentation (EPA, 2011a, 2011b). Where input values were not available, TAE relied on prior analyses to determine reasonable ranges and adjusted values within these ranges to obtain results consistent with the AEO base year fuel economies. The HTEBdyn model was used to estimate the fuel economy of the representative vehicles on the EPA-specified duty cycles. Further detail on the development of the baseline case for HTs is given in TAE (2013).

For both LDVs and HTs, total vehicle sales were assumed to be the same as in the AEO 2013 Reference case, extrapolated to 2050 (a linear extrapolation based on the 2035-2040 average slope). Fuel prices were taken from the AEO 2013 High Oil Price Case, but were extrapolated to 2050 from the trend from 2035 to 2040; however, hydrogen prices were supplied by the EERE Fuel Cell Technologies Office. Assumed fuel prices are shown in Figure 5.

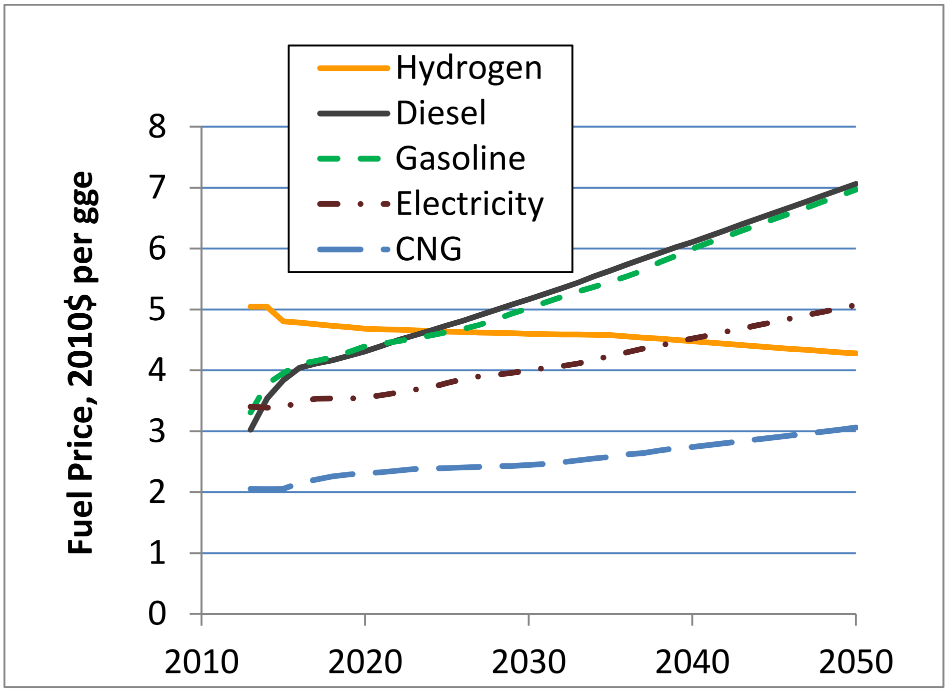

FIGURE 5 Fuel Prices Assumed in the Scenarios, in 2010 dollars per gge (1 gge = 125,000 Btu)

Use of biofuel, e.g., E85 or biodiesel, was not modeled, except for the ethanol content in gasoline. Fuel prices were assumed to be independent of fuel demand (no price elasticity). The miles driven by light duty vehicles (annual VMT per vehicle) was assumed to be slightly dependent on the cost per mile, with an elasticity of demand for travel of about -0.1. No elasticity of travel demand was assumed for heavy trucks, since these are primarily commercial vehicles, and fuel costs are passed through to the customer.

3.2 GPRA ADVANCED TECHNOLOGY MODELING

The analysis of advanced technologies for the Government Performance and Results Act (GPRA) benefits estimation was based on a three-step market-based approach. 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 and GHG emissions. 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 2013, 2015, 2020, 2030, and 2045 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 a

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 weight, performance, and component characteristics were established 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.

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

- Conventional SI (both gasoline and compressed natural gas [CNG]);
- Conventional CI;
- Hybrid electric (HEV, including SI HEV, CI HEV, and CNG 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 these powertrain architectures, the Autonomie model was used to take sets of component-level input parameters over future years (intended to describe component technologies in the future for each technology scenario) to simulate future vehicles (appropriately sized to offer sufficient power, given vehicle weight and drivability requirements) and to estimate each vehicle's fuel economy in 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-estimated (Ricardo Engineering) 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

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1 Autonomie simulations were also run for a case with an intermediate level of technology improvements, but these improvements are not reported here (see Moawad and Rousseau, 2014). Please note that some vehicle attributes reported by Moawad and Rousseau, 2014, were revised after this report was prepared.

other components. Further detail on vehicle attribute modeling and vehicle simulations can be found in Moawad and Rousseau (2014).

Once Autonomie modeling was complete, outputs were used as inputs to the MA^{3}T vehicle choice model in the second step 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^{3}T vehicle choice model[2]. 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^{3}T, 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 vehicles were not modeled in MA^{3}T. Little public infrastructure for public charging of plug-in vehicles or fueling of natural gas or hydrogen fuel cell vehicles was assumed for both the No Program and Target cases.

In the third step of GPRA LDV modeling, after sales shares were calculated using the MA^{3}T model, the sales shares and fuel economy of each LDV having each type of drivetrain were used as inputs 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 gives projected petroleum savings and GHG reductions (Ward et al., 2008).

For both the No Program and Target cases, the sales shares, fuel economy, and retail price equivalent of each LDV having each type of drivetrain were used as inputs to the VISION model. Not all vehicle types modeled in MA^{3}T 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^{3}T (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 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 drive, advanced combustion, advanced materials, and fuels and lubricant technologies) by estimating the decrease in fuel consumption per mile in advanced vehicles due

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2 MA^{3}T version 20120218

to improvements in technologies in each of the subprograms. 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, 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 conventional SI vehicles, a proportionality constant of 0.5 was used (i.e., a 10% mass reduction corresponds to a 5% reduction in fuel consumption). This constant is based on the analytical results of a number of studies showing that a 10% decrease in mass with engine downsizing at constant performance gives approximately a 6.5% decrease in fuel consumption per mile, while without downsizing, the decrease is 3.5% (Pagerit et al., 2006; Bandivadekar et al,. 2008). Here, an intermediate value of 5% was used to estimate the portion of the fuel economy benefit attributable to the Materials R&D subprogram, under the assumption that the remainder of the benefit was due to engine downsizing, which was attributed to the Advanced Combustion Engines R&D subprogram. For HEVs, a value of 4.5% was used on the basis of previous vehicle simulations (Pagerit et al., 2006; Moawad and Rousseau, 2012). For PHEVs, it was assumed that the value was slightly less than that for HEVs, and 4% 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. As opposed to other DOE technologies, which were assumed to be deployed only in new vehicles, friction reduction was assumed to be used in all vehicles in a given year, since new lubricants can be used in new and used vehicles.

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 conventional SI vehicles, the remainder of the fuel savings was attributed to improvements in engine combustion efficiency (Advanced Combustion Engine R&D). For HEVs and PHEVs, 70% of the remainder of fuel savings was attributed to improvements in engine combustion efficiency and 30% was attributed to the battery and electric drive technologies used. The value of 70% was used since comparisons of fuel economies of HEVs and similar conventional SI vehicles indicate that HEVs consume approximately 70% of the fuel per mile that similar conventional SI vehicles do, that is, hybridization gives a 30% reduction in fuel consumption per mile. This same percentage was used for PHEVs as well.

In addition to the fuel savings resulting directly from greater efficiency of vehicles of each drivetrain type, fuel savings will result if more efficient vehicles, such as HEVs, substitute for conventional SI vehicles, and also from substitution of conventional SI vehicles and HEVs by vehicles that use electricity, such as PHEVs and BEVs. As discussed in Section 4, the Target case has higher sales shares of more efficient drivetrain vehicles, which give shares of vehicle types in the on-road stock that are different from the No Program case. The amount of fuel saved by the entire LDV fleet was estimated using the VISION model as described above, which includes both the savings due to improved fuel economy of each vehicle type, as well as the savings due to the change in mix of vehicle types in the on-road stock. The fuel savings due to the change in shares of HEVs, PHEVs and BEVs in the on-road stock was calculated by difference, i.e., the fuel savings not attributed to increased fuel economy of each vehicle type was attributed to Batteries and Electric Drive Technologies, since these technologies enable these vehicles to compete for market share in the vehicle market. Fuel savings from conventional CI (diesel) vehicles and FCVs were neglected, since the projected shares of these vehicles in the LDV stock were low, and did not significantly affect fuel consumption.

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 consistent with VTO Program research areas and goals, such as:

- 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 BIC platform 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 vehicle characteristics used by the SuperTruck industry for its baseline vehicles. Therefore, it represents real differences between existing product offerings as of model years 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 will likely 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 (TAE, 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 NRC study to develop platform incremental costs, relative to the baseline truck, and 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 (TAE, 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 and 8 combination units, and Class 7 and 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 and 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 in 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 discussed in Section 4 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 Table 9. 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.

4 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 using Autonomie simulations for the No Program and Target cases. The sales share for each drivetrain technology is shown in Figure 6 and sales shares are listed in Table 10 for these two cases.

Market penetration estimates from MA^3T modeling of LDVs show market shares of HEVs and PHEVs increasing over time in both the No Program and Target cases, but with more rapid penetration to higher levels of PHEVs in the Target case. Displacement of conventional vehicles by HEVs and PHEVs is quite rapid in the Target case, indicating a strong influence of VTO Program technologies. Projections of market penetration by diesel ICE vehicles were low in both cases, 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. The low penetration by BEVs and FCVs is due, in part, to the assumption of very little public infrastructure for charging or hydrogen fueling. Market share projections for diesel vehicles and FCVs were less than 1% and are not shown in Figure 6.

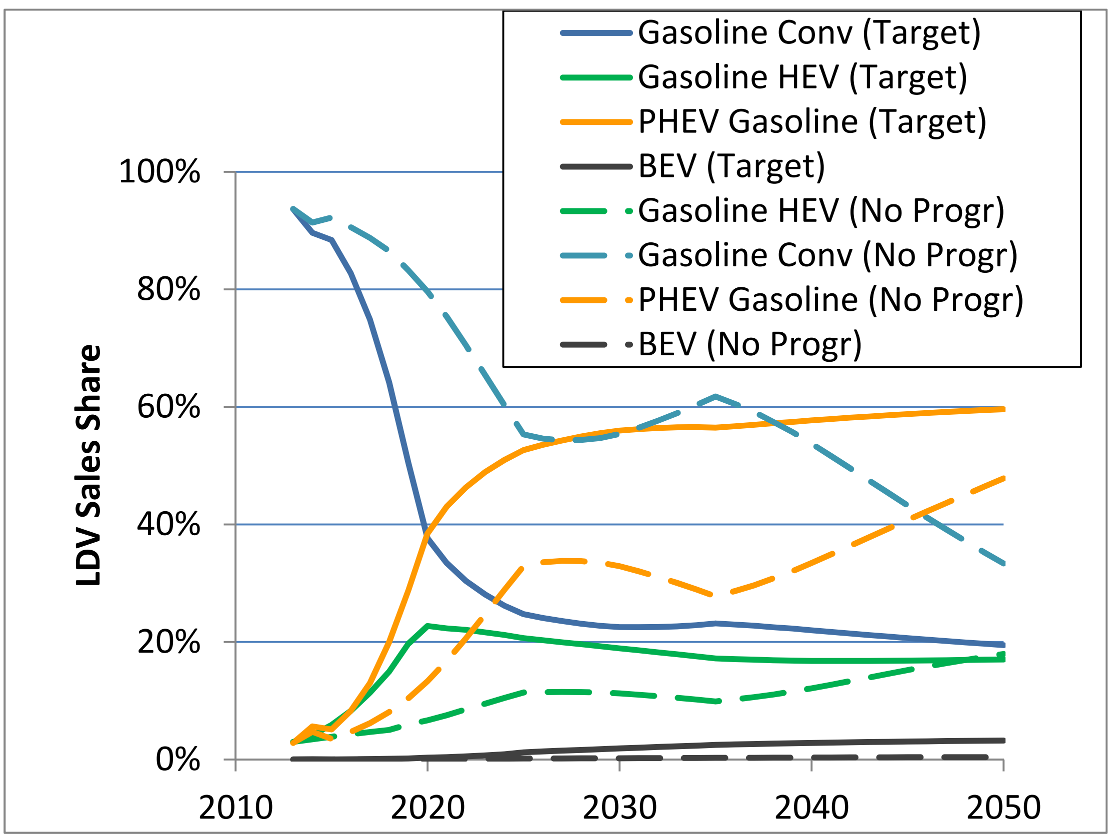

FIGURE 6 LDV Market Penetration Estimates for No Program and Target Cases

TABLE 10 LDV Market Penetration Estimates (%) for No Program and Target Cases

Case	2020	2030	2040	2050
No Program				
Gasoline ICE	80	55	54	33
Diesel ICE & HEV	0.3	0.2	0.3	0.3
HEV gasoline	7	11	12	18
PHEV gasoline	13	33	33	48
BEV	0.1	0.2	0.3	0.4
FCV	0.0	0.1	0.1	0.1
Target				
Gasoline ICE	38	23	22	19
Diesel ICE& HEV	0.7	0.4	0.3	0.3
HEV gasoline	23	19	17	17
PHEV gasoline	38	56	58	60
BEV	0.3	1.9	2.8	3.2
FCV	0.2	0.3	0.3	0.4

Differences in market penetration are strongly influenced by differences in purchase price and operating costs, which depend on fuel costs and amortized battery replacement costs for PHEV and BEVs. These influences indicate 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 7 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 8 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.

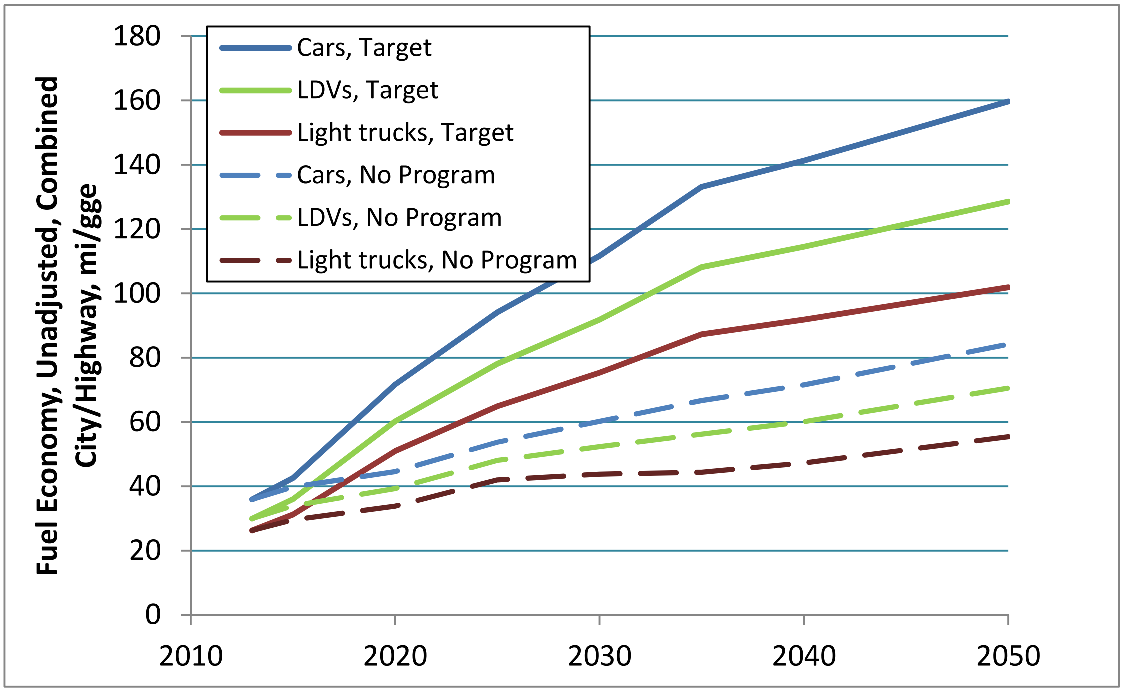

FIGURE 7 Fleet-Average Fuel Economy of New Cars, Light-Duty Trucks, and LDV Fleet for the No Program Case (dashed lines) and Target Case (solid lines)

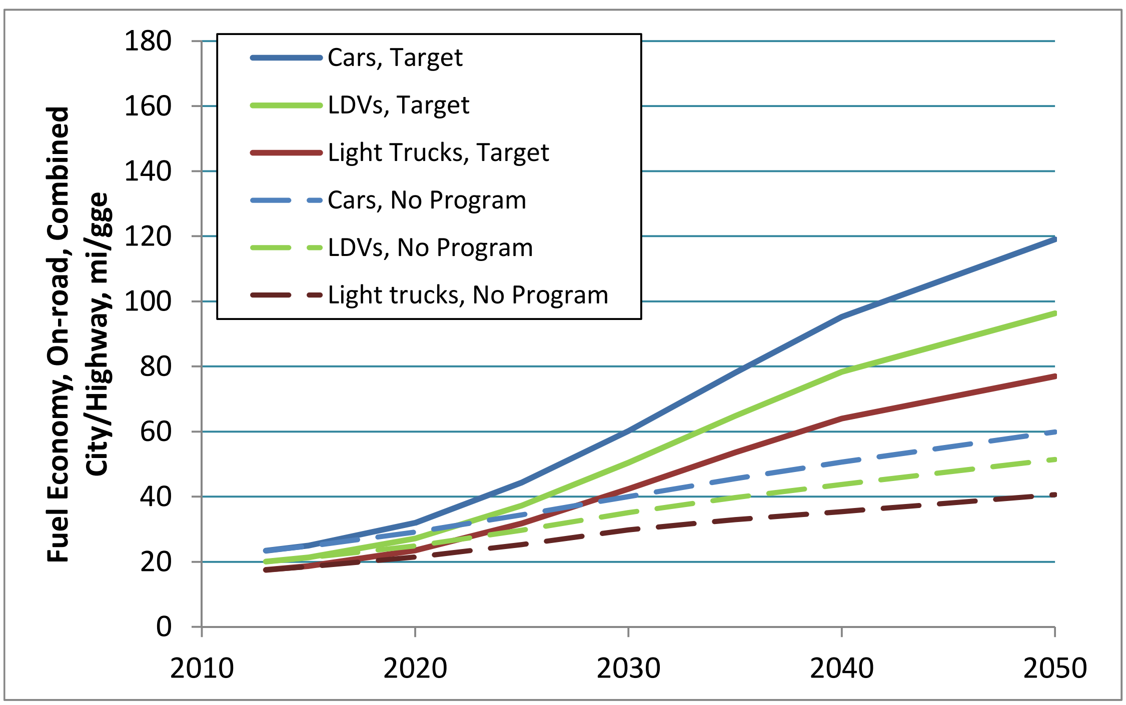

FIGURE 8 Average On-Road Fuel Economy of Cars, Light-Duty Trucks, and LDV Fleet for the No Program Case (dashed lines) and Target Case (solid lines)

Levelized cost of driving (LCD) was estimated for future LDVs with different drivetrains for the No Program and Target cases. The LCD 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 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, 2013). The LCD estimated for the year 2025 is shown in Figure 9 for midsize cars with several of the drivetrains analyzed, in 2010 dollars per mile. The analogous LCD in the year 2035 is shown in Figure 10. These LCD values were calculated assuming that vehicles were driven 13,500 mi/year. Fuel prices (in 2010 dollars per gge) in the year 2025 were assumed to be \$4.28/gal for gasoline, \$4.35/gge for diesel, \$2.21/gge for compressed natural gas (CNG), and \$4.28/gge for hydrogen for the No Program case and \$2.74/gge for the Target Case. Fuel prices for the year 2035 were assumed to be \$5.05/gal for gasoline, \$5.19/gge for diesel, \$2.38/gge for compressed natural gas (CNG), and \$4.23/gge for hydrogen for the No Program case and \$2.35/gge for the Target Case.

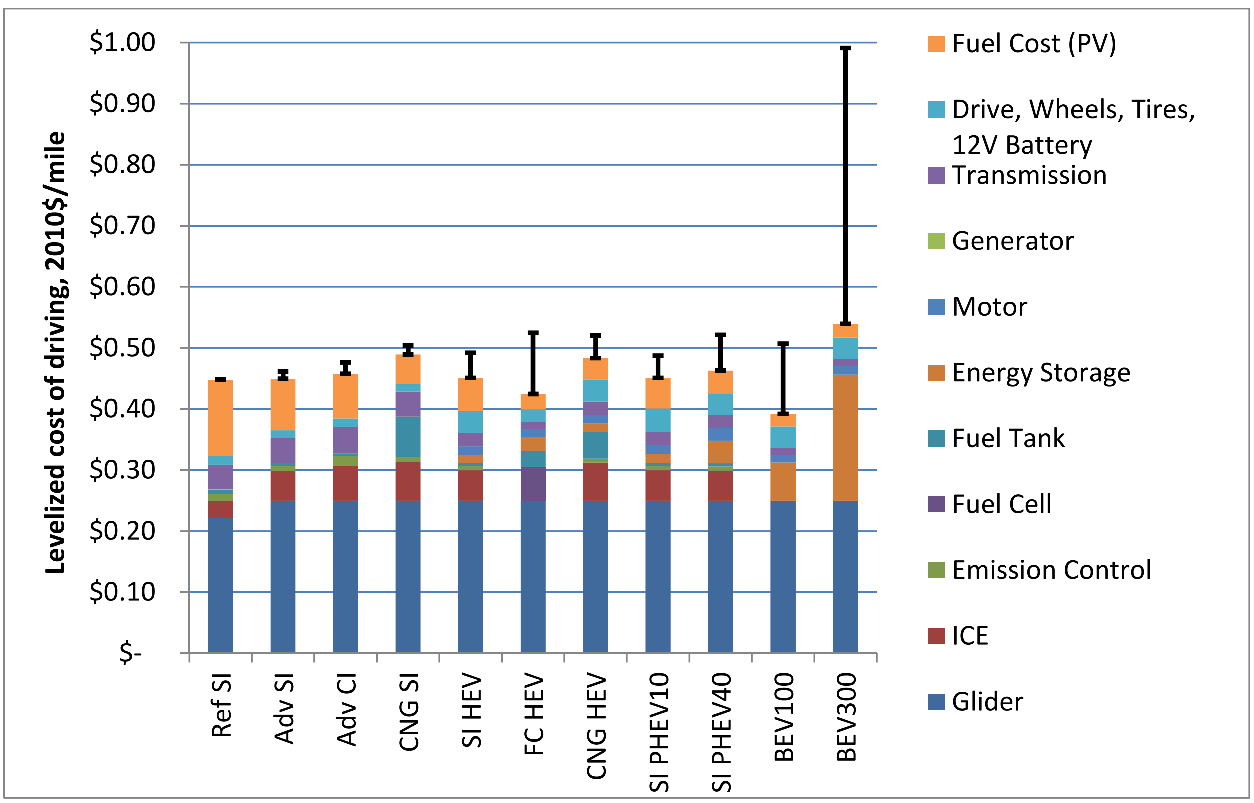

FIGURE 9 Projected Levelized Cost of Driving (LCD) of LDVs in the year 2025. The bars show the LCD of the Target Case, and the upper ends of the error bars show the LCD of the No Program Case. Present value (PV) of fuel cost is shown assuming a 7% discount rate.

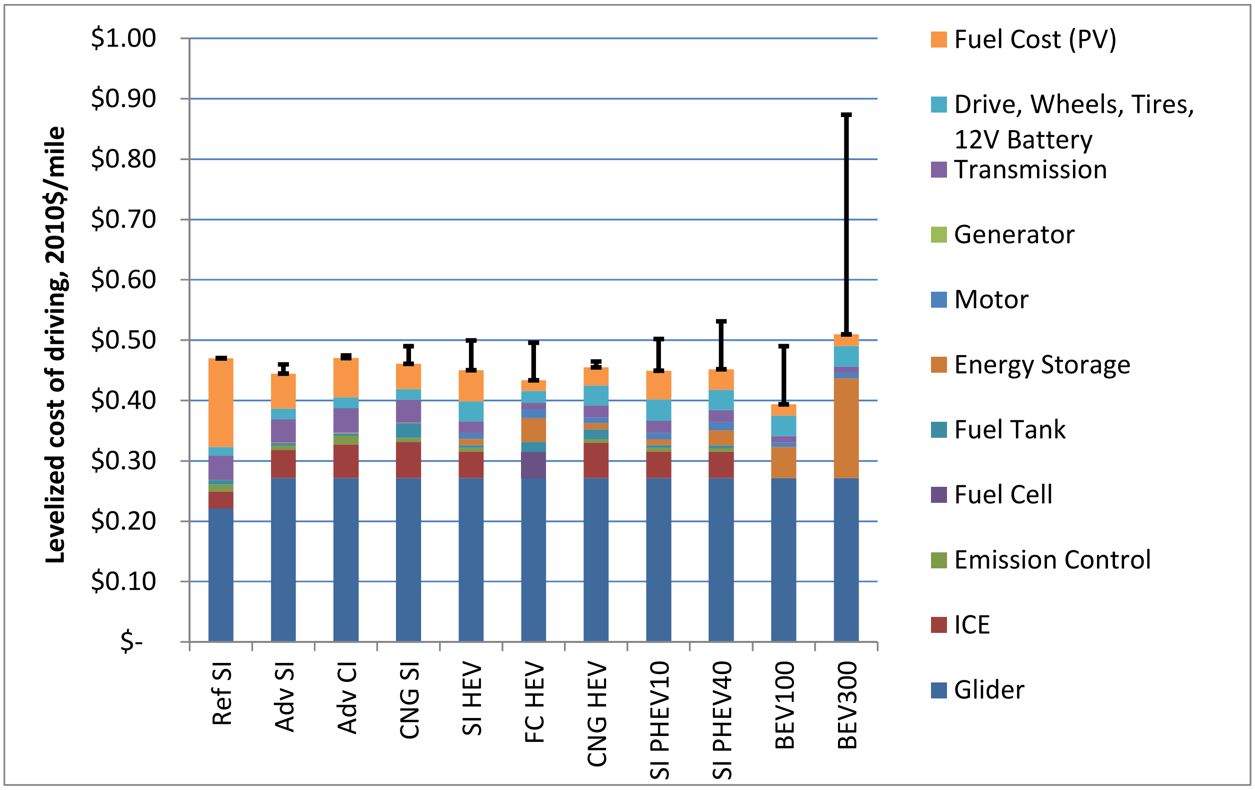

FIGURE 10 Projected Levelized Cost of Driving (LCD) of LDVs in the year 2035. The bars show the LCD of the Target Case, and the upper ends of the error bars show the LCD of the No Program Case. Present value (PV) of fuel cost is shown assuming a 7% discount rate.

Figures 9 and 10 show the total LCD as the sum of costs of fuel and vehicle, by component, and the present value of fuel costs. 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, even as conventional vehicles achieve higher fuel economy in the future. The LCD of BEVs and FCVs are projected to be quite low, and that of CNG vehicles is fairly 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.

The new vehicle fleet fuel economy values for medium- and heavy-duty trucks are shown in Figure 11 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 and 8 trucks is projected to reach 1.47 times that of the baseline truck in 2030 and 1.52 times in 2050. Because of the lower annual usage of class 4-6 trucks, the market penetration and resulting impact of DOE-funded technologies are smaller in these vehicles, with a fuel economy ratio of 1.14 in 2030 and 1.23 in 2050.

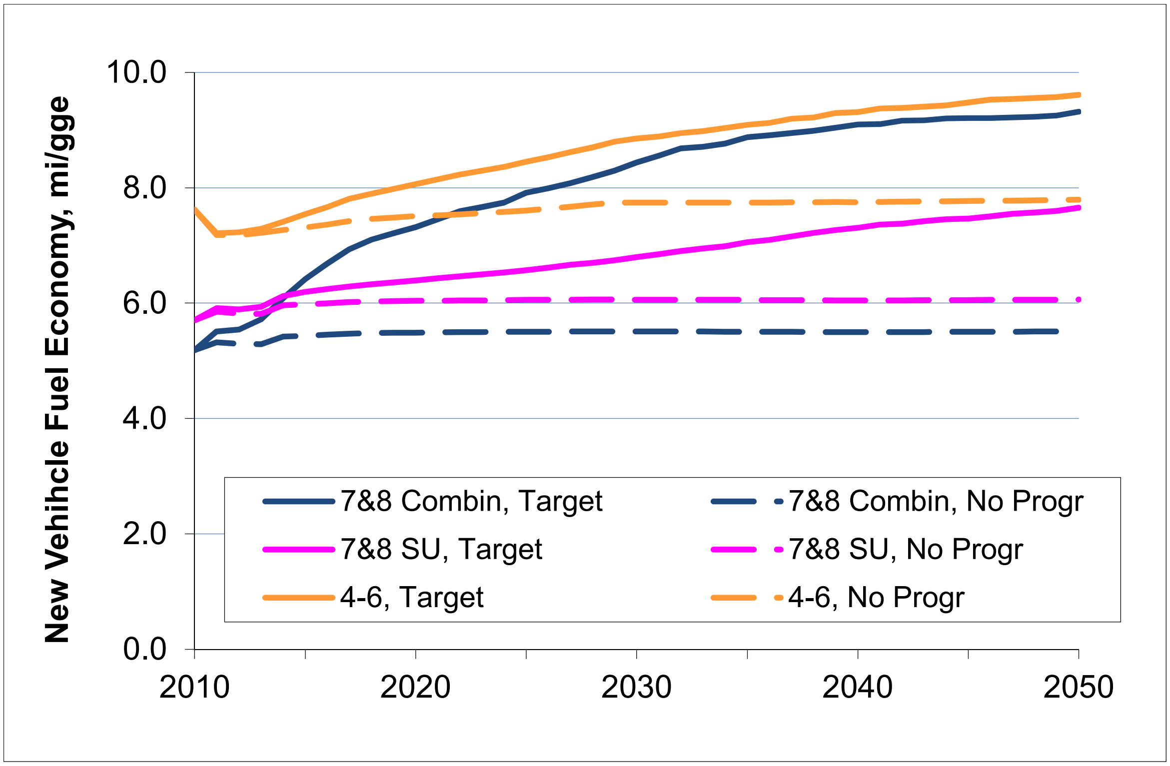

FIGURE 11 Fleet-Average Fuel Economy of New Medium- and Heavy-Duty Trucks for the No Program Case (dashed lines) and Target Case (solid lines)

The average fuel economy of the on-road stock of medium- and heavy-duty trucks of each range of size class analyzed are shown in Figure 12. The on-road fuel economy increases for each size class range, but increases more rapidly for the Class 7 and 8 combination units, since advanced technologies are adopted more extensively in these trucks than in other trucks, and the class 7 and 8 combination unit trucks are replaced at an earlier age, leading to more rapid penetration into the on-road fleet of advanced technologies.

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 incremental cost of the technology—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. In later years, this platform is projected to lose market share as more advanced technologies become more cost-competitive.

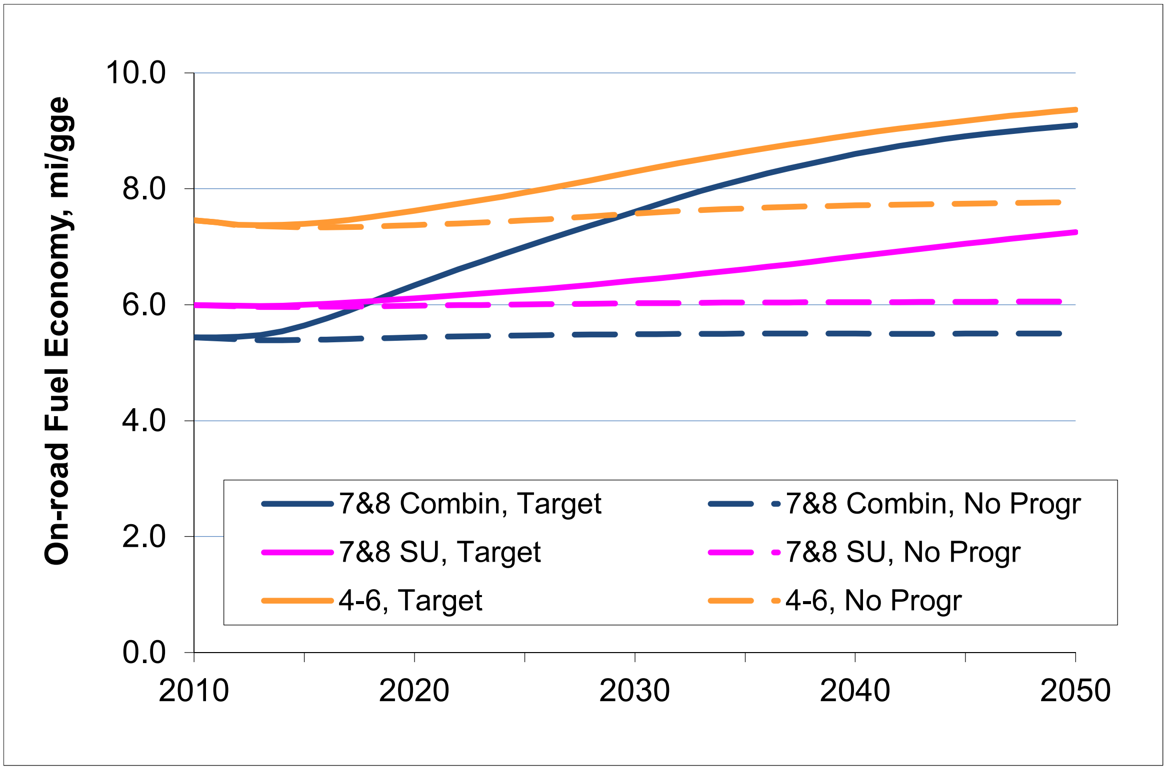

FIGURE 12 Average On-road Fuel Economy of Medium- and Heavy-Duty Trucks for the No Program Case (dashed lines) and Target Case (solid lines)

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

Vehicle	2015	2020	2030	2040	2050
Medium (Class 4–6) diesel					
Baseline	79.6	70.9	56.4	43.5	37.2
BIC Conventional	20.4	17.7	20.6	25.8	28.4
Advanced conventional	0.0	11.3	20.1	24.2	26.3
Diesel HEV	0.0	0.2	2.8	6.5	8.2
Heavy (Class 7, 8) combination unit					
Baseline diesel	47.8	33.0	21.6	14.0	11.2
BIC Conventional	52.2	43.1	35.1	35.0	35.5
Advanced conventional	0.0	20.5	27.2	29.1	29.7
Diesel HEV	0.0	3.5	16.1	21.9	23.7
Heavy (Class 7, 8) single unit					
Baseline diesel	88.4	84.9	74.8	61.2	53.4
BIC Conventional	11.6	11.6	15.1	21.7	25.1
Advanced conventional	0.0	3.1	7.0	10.7	13.3
Diesel HEV	0.0	0.4	3.1	6.3	8.2

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, the advanced conventional technology package becomes less expensive but also more efficient, and it steadily gains market share and share of VMT, growing from 20.5% of VMT in 2020 to 29.7% 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-by-doing) and increasing production volumes. By 2020, the hybrid platform achieves a 3.5% share of vehicle miles in the combination unit class. This grows to 23.7% by 2050. The total share of alternative vehicles reaches about 88.8% of vehicle miles by 2050.

The results for class 7 and 8 single-unit trucks are different, owing to the lower annual miles traveled by trucks in this class. The BIC platform initially captures 11.6% of VMT, which increases to 25.1% by 2050. The advanced conventional truck platform achieves only 3.1% of VMT by 2020 and reaches 13.3% in 2050. Although the hybrid drivetrain provides more fuel consumption benefits over the vocational drive cycle, the low annual mileage of single-unit trucks results in longer payback periods. As a result, the hybrid platform achieves a maximum share of 13.3% of VMT.

Overall, the advanced technology platforms achieve VMT shares within the class 4-6 truck market that are intermediate between the class 7 and 8 combination unit trucks, and the class 7 and 8 single unit trucks. The BIC platform represents 20.4% of VMT in 2015, ceding a few percent to the advanced conventional platform in 2020, but grows to 28.4% by 2050. The advanced conventional platform grows from 22.3% of VMT in 2020 to 26.3% of VMT by 2050, while the hybrid platform penetrates only slowly, reaching 8.2% by 2050.

5 RESULTS OF MODELING: OVERALL BENEFITS OF 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.

TABLE 12 Vehicle Technologies Program Benefits Metrics[a]

Impact	Metric	Year 2020	2030	2050
Energy security	Oil savings, cumulative (billion bbl)	1.0	7.7	31.1
	Oil savings, annual (million bpd)	0.9	2.4	3.5
	New vehicle mpg improvement (percent)[a]			
	LDVs	53	75	82
	HTs	25	39	43
	On-road mpg improvement (percent)			
	LDVs	9	44	87
	HTs	12	27	36
Environmental	CO_2 emissions reduction,[b] cumulative (million t $CO_{2\ eq}$)	450	3,500	14,000
	GHG emissions reduction, annual (million t $CO_{2\ eq}$/yr)			
	LDVs	85	259	350
	HTs	64	142	235
	Total	149	401	585
Economic	Primary energy savings,[b] cumulative (quads)	7	53	218
	Primary energy savings, annual (quads/yr)	2.2	6.2	9.0

[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 2015.

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 2.4 million bpd (barrels or bbl per day). These oil savings amount to over 12% of the total U.S. petroleum consumption in the year 2030 as projected in the AEO2013 Reference case.

The estimated cumulative GHG emission benefit in 2030 is 3,500 million metric tons (t) of carbon dioxide equivalent ($CO_{2\ eq}$), as 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 (IWG, 2013). Assuming CO_2 values ranging from $10 to $100 per metric ton, these estimated VTO Program carbon reductions would range in value from 35 billion to $350 billion (not discounted).

Improving fuel economy offers benefits to consumers, who pay lower prices for fuel and transportation-dependent commodities. The fuel economy improvements shown in Table 12 are large. LDV fuel economy increases of 75% in 2030 and 82% by 2050 (over the No Program case) imply greatly reduced consumer spending on fuel. Likewise, the improvements in HT fuel economy imply savings in goods transported by truck. In addition to these savings, increased 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 both electricity and petroleum.

Oil security remains important to the U.S. even with increased domestic oil production. 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 prices and the amounts of oil supplied. 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. The EPA and NHTSA (2011) have published estimates of disruption costs, based on work by Leiby (2008). Estimates of these costs range from $10-30 per barrel. At the 2.4 million barrel per day reduction estimated in 2030, this would imply a decrease in the disruption cost ranging from $24-72 million per day, or $9-26 billion per year. Even if U.S. oil imports decrease, through reduced consumption and increased domestic production, and the disruption costs decrease as much as a factor of two, the value derived from the decreased oil consumption due to VTO technology programs would be substantial.

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.

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Energy Systems Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439-4815

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