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Examining the Costs and Benefits of Technology Pathways for Reducing Fuel Use and Emissions from On-road Heavy-duty Vehicles in California

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Examining the Costs and Benefits of Technology Pathways for Reducing Fuel Use and Emissions from On-road Heavy-duty Vehicles in California

by

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DISSERTATION

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ABSTRACT

In California and many places around the world, exhaust from heavy-duty (HD) diesel vehicles accounts for a major fraction of criteria pollutant emissions such as particulate matter (PM) and nitrogen oxides (NOx), and HD vehicles are a significant consumer of petroleum-based fuels and a growing contributor to greenhouse gas (GHG) emissions. California has been a leader in implementing a broad range of policy measures that promote the development and deployment of fuels and technologies to reduce fuel consumption and emissions from HD vehicles. This dissertation formulates an analytical method to investigate the costs and benefits of various technology pathways for HD vehicles that result in drastic reductions in criteria pollutant and GHG emissions.

Though there are several studies that estimate the fuel use and emissions contribution of HD vehicles in California and the implications of accelerated advanced technology adoption over time, no studies investigate both the end-user and externality cost impacts of these sweeping technology changes to the HD fleet. This dissertation begins to fill this research gap. Taken together, private and external costs represent an approximation of total societal costs, which is used in a cost-benefit framework to explore the impact of various scenarios for introducing advanced fuel and technologies in the HD vehicle fleet out to 2050. The primary objective of this research is to examine the comparative emissions, fuel use, and total societal costs of six discrete technology adoption scenarios for California HD vehicles between 2010 and 2050.

The results indicate that, compared to the Baseline, the five remaining scenarios provide net present value (NPV) savings between roughly 5% and 10% and significant reductions in emissions and fuel use. Total costs are dominated by vehicle retail, fuel, and maintenance expenses, and monetized externalities generally account for less than 5% of total costs.

Compared to the Baseline, reduced petroleum-based fuel use makes up roughly 90% or more of the cost savings for each of the non-Baseline scenarios.

For the HD fleet, reaching an 80% reduction in GHG emissions versus 1990 levels by 2050 requires that vehicle sales shift almost completely to zero tailpipe emission technologies by 2030, annual fuel consumption reductions in new vehicles are between 2% and 4% per year, and fuel feedstocks transition to low-carbon pathways. Results from this research suggest that if California is to dramatically transform the HD vehicle fleet over such a short timeframe, a combination of strong incentive programs and technology-forcing regulations are required.

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LIST OF ACRONYMS

AB	Assembly Bill
ABT	Averaging, banking, and trading
AFV	Alternative fuel vehicle
AMT	Automated manual transmission
ANL	Argonne National Laboratory
APS	Auxiliary power system
APU	Auxiliary power unit
AQIP	Air Quality Improvement Program
AQMD	Air Quality Management District
ARB	California Air Resources Board
AT	Automatic transmission
ATRI	American Transportation Research Institute
AV	Advanced vehicle
AVCEM	Advanced Vehicle Cost and Energy Use Model
BACT	Best available control technology
BAU	Business-as-usual
BC	Black carbon
BEV	Battery electric vehicle
BTU	British thermal unit (energy unit)
CA	California
CARB	California Air Resources Board
CEC	California Energy Commission
CEF	Carbon dioxide equivalency factor
CFD	Computational fluid dynamics
CH_4	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
C_{RR}	Coefficient of rolling resistance
CTL	Coal-to-liquids
DBG	Dairy biogas
DGE	Diesel gallon equivalent
DMV	Department of Motor Vehicles
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
DRRP	Diesel Risk Reduction Plan
EC	Elemental carbon
ECU	Engine control unit
EF	Emission factor
EGR	Exhaust gas recirculation
EIA	Energy Information Administration
EISA	Energy Independence and Security Act
EMFAC	EMission FACtor Model
EPA	Environmental Protection Agency

EPD	Environmental Product Declaration
EV	Electric vehicle
FC	Fuel consumption
FCV	Fuel cell vehicle
FHWA	Federal Highway Administration
FT	Fischer-Tropsch
GEM	Greenhouse gas Emission Model
GGE	Gasoline gallon equivalent
GHG	Greenhouse gas
GPS	Global positioning system
GVWR	Gross vehicle weight rating
GWP	Global warming potential
HC	Hydrocarbon
HCM	Hybrid control module
HD	Heavy-duty
HDDV	Heavy-duty diesel vehicle
HEV	Hybrid electric vehicle
HFC	Hydrofluorocarbon
HHV	Hydraulic hybrid vehicle
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
ICE	Internal combustion engine
IPCC	Intergovernmental Panel on Climate Change
IPVT	Initial production volume threshold
LCA	Lifecycle analysis
LCFS	Low Carbon Fuel Standard
LEM	Lifecycle Emissions Model
LETRU	Low-Emission Truck Refrigeration Unit
LFG	Landfill gas
LH	Long-haul
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LRR	Low rolling resistance
MBRC	Miles between road calls
MJ	Megajoule
MMBtu	Million British thermal units
MMT	Million metric tonnes
MOVES	MOtor Vehicle Emissions Simulator
MS	Market share
MSRP	Manufacturer suggested retail price
MSW	Municipal solid waste
MT	Manual transmission
MTA	San Francisco Municipal Transportation Authority
MY	Model year
NAS	National Academy of Sciences
NG	Natural gas
NHTSA	National Highway Traffic Safety Administration

NMHC	Non-methane hydrocarbon
N_2O	Nitrous oxide
NO	Nitrogen oxide
NO_2	Nitrogen dioxide
NOx	Nitrogen oxides
NPV	Net present value
NREL	National Renewable Energy Laboratory
OC	Organic carbon
OEM	Original equipment manufacturer
PAH	Polycyclic aromatic hydrocarbons
PFF	Partial flow filter
PFT	Partial flow technology
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
$PM_{2.5}$	Particulate matter with a diameter less than 2.5 microns
PR	Progress ratio
PTO	Power take-off
RFS	Renewable Fuel Standard
SCAQMD	South Coast Air Quality Management District
SCF	Square cubic feet
SCR	Selective catalytic reduction
SH	Short-haul
SOF	Soluble organic fraction
SOx	Sulfur oxides
SUV	Sport utility vehicle
SWCV	Solid waste collection vehicle
TOP-HDV	Technology Options and Pathways for Heavy-Duty Vehicles Model
TRU	Truck refrigeration unit
TSE	Truck stop electrification
UL	Useful life
ULETRU	Ultra-low emission truck refrigeration unit
ULSD	Ultra-low sulfur diesel
US	United States
VB	Visual Basic
VIUS	Vehicle In-use Survey
VMT	Vehicle miles traveled
VOC	Volatile organic compound
VTA	Santa Clara Valley Transportation Authority
WF	Work factor
WTT	Well-to-tank
ZEB	Zero emission bus

1 INTRODUCTION

Heavy-duty vehicles (HD) are a significant consumer of petroleum-based fuels and a growing contributor to carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions. Historically, diesel engines have been the dominant power plant for HD vehicle applications. In California and many places around the world, exhaust from HD diesel trucks and buses accounts for a major fraction of criteria pollutant emissions such as particulate matter (PM) and oxides of nitrogen (NOx), which contribute to poor air quality and both chronic and acute health effects. Moreover, black carbon, which is the light-absorbing component of PM, is a potent climate-forcing aerosol. These environmental and public health challenges will prove more daunting as reliance on HD vehicles for goods and passenger movement increases.

The State of California has been a leader in implementing policy measures to combat the negative impacts posed by the criteria pollutant and GHG emissions from the transportation sector, including HD trucks and buses. The California Air Resources Board (ARB) has introduced a number of voluntary and mandatory programs targeting PM and NOx from HD vehicles since 2000 as a part of the Diesel Risk Reduction Plan. In 2006, the state passed the Global Warming Solutions Act (Assembly Bill 32), which requires the state to return to 1990 GHG emission levels by 2020. Assembly Bill 32 ("AB 32") affects every sector of the California economy, and there are rules in place targeting fuel use and GHGs from a subset of HD vehicles. In addition to the mandatory 2020 provisions, California has a long-term target set by an Executive Order of then Governor Schwarzenegger [1] to reduce GHG emissions to 80% below 1990 levels by 2050.

Though conventional diesel vehicles have made tremendous strides in terms of reduced emissions and improved efficiency over the past two decades, previous studies have shown that California's aggressive emissions mandates require widespread adoption of non-conventional ("advanced") fuels and technologies for the HD vehicle fleet. There are a number of advanced technology and alternative fuel options currently available and under development that are examined in this dissertation. This research explores various engine and driveline options such as NG, hybrid-electric, hybrid-hydraulic, full battery electric, and hydrogen fuel cell vehicles. For fuels, in addition to conventional (i.e. fossil-based) sources of liquid fuels and NG, the fuel feedstocks analyzed in this research include lower carbon substitutes from natural and municipal waste streams.

The technology pathways for HD vehicles that are required to achieve the ambitious California goals for drastic reductions in criteria pollutant and GHG emissions provide a unique research opportunity. The intent of this dissertation is to use a scenario approach to explore the costs and benefits of strategies for reducing emissions from on-road HD vehicles in California. This project builds on previous studies of long-term emission reduction strategies for the California HD vehicle sector [2-4] by utilizing a total social cost framework to investigate the net impacts of various pathways for advanced technology deployment in the HD fleet. This total social cost methodology estimates both the direct costs incurred by HD vehicle users as well as the monetized externality costs imposed by HD vehicles, including air pollution, climate change, noise, and the military expenditures required to secure energy resources abroad. These social cost estimation methods have been developed and utilized by others to study various research topics within the transport sector [5-8].

Though there are several studies that estimate the fuel use and emissions contribution of HD vehicles in California and the implications of accelerated advanced technology adoption over time, no studies investigate both the end-user and externality cost impacts of these sweeping technology changes to the HD fleet. This dissertation begins to fill this research gap. To examine the total societal cost implications of various fuel and technology options for HD vehicles, six discrete HD fleet evolution scenarios were created that look out to 2050. None of the six scenarios represent forecasts for fuel and technology penetration with the California HD vehicle fleet. Rather, each of the scenarios is intended to illustrate the total costs and benefits of a future that is premised on a particular set of assumptions about vehicle technologies and fuels. The six scenarios are as follows:

- *Baseline*: status quo fleet turnover and technology adoption; modest annual improvements that are assumed to match historical rates in new vehicle fuel consumption reduction
- *High Efficiency*: accelerated adoption of hybrid vehicles; increased annual improvements in new vehicle fuel efficiency
- *Plug-in Hybrids and Electric Vehicles (“PHEVs+EVs”)*: identical advanced vehicle adoption rate and annual new vehicle efficiency improvement assumptions of the High Efficiency scenario; hybrids, plug-in hybrids, and electric vehicles are the dominant technologies
- *Fuel Cell Vehicles (“FCVs”)*: identical advanced vehicle adoption rate and annual new vehicle efficiency improvement assumptions of the High Efficiency scenario; hybrids and hydrogen fuel cell vehicles are the dominant technologies

- *Alternative Fuels*: identical advanced vehicle adoption rate and annual new vehicle efficiency improvement assumptions of the High Efficiency scenario; NG vehicles are the dominant technology, and lower-carbon fuels eventually replace fossil-based fuels
- *80% Reduction in CO_2-equivalent Emissions by 2050 ("80in50"[1])*: adoption rates of all advanced technology and low-carbon fuel options that are necessary to achieve an 80% reduction in lifecycle CO_2-equivalent emissions from the HD vehicle fleet in California compared to estimated 1990 levels

The primary contributions of this dissertation generally fall into three categories:

1) Estimating the lifecycle end-user and externality costs associated with HD vehicles in California and understanding how each of these cost components compare to one another
2) Analyzing how each of the six long-term scenarios compare in terms of lifecycle costs, emissions, and fuel use
3) Investigating the comparative impacts of a) annual efficiency improvements in new vehicles, b) the rapid introduction of advanced (i.e. non-conventional diesel or gasoline) technologies, and c) the transition to lower-carbon fuel feedstock

Several research questions emerge in each of these three areas, including:

- *How do the six scenarios differ in terms net present value (NPV)?*
- *How do the costs breakdown in each of the six scenarios?*
- *What are the NPV, emissions, and fuel use impacts of annual efficiency improvements of new vehicles compared to the influence of the rapid adoption of advanced vehicles? What*

[1] Yang et al. (2008, 2009) deserve credit for the "80in50" term, which refers to California target of reducing GHG emissions by 80% lower than 1990 levels by 2050.

is the impact of transitioning to lower-carbon fuels and electricity?

- *How do the scenarios compare in terms of emissions trends for each of the emitted species, CO_2-equivalent emissions, and fuel use?*
- *What is the net effect of non-CO_2 emissions on CO_2e?*
- *For each emitted species, what is the emissions contribution from each of the four lifecycle phases (i.e. vehicle use, upstream fuel production and transport, vehicle manufacturing, and end-of-life vehicle scrappage) included in the analysis?*

The dissertation is organized into five remaining chapters. Chapter 2 provides an overview of the fuels and technologies that are available and under development that reduce criteria pollutant emissions and/or fuel use and CO_2 from HD vehicles. Chapter 3 describes the cadre of incentive-based and mandatory regulatory programs aimed at HD vehicles that the ARB and the federal government have enacted in their ongoing efforts to promote technologies that lead to improved air quality and reductions in fuel consumption and climate-forcing emissions. The methodological and empirical contributions of the research are contained in the second part of dissertation. The analytic model used for the project is the Technology Options and Pathways for Heavy-Duty Vehicles (TOP-HDV) model. The data, assumptions, and methods employed in TOP-HDV are detailed in Chapter 4. Each of the six scenarios is described in detail in Chapter 5, and the results are presented in this chapter as well. Chapter 6 present a summary of the work in the context of the above research questions as well as directions for future work.

2 HEAVY-DUTY VEHICLE TECHNOLOGIES

This chapter reviews the literature on HD vehicle technologies that reduce criteria pollutant emissions and/or petroleum consumption and GHG emissions. The chapter begins by describing the diesel engine, the nature of diesel engine exhaust, and strategies and technologies for reducing emissions. The subsequent sections describe NG, hybrid, plug-in hybrid, electric, and fuel cell HD vehicles, which each offer fuel and emissions benefits compared to conventional vehicles. After the technology overview, the next section summarizes the various vehicle technology options that are available in the near-term to provide fuel consumption benefits. The chapter closes by reviewing three studies that also look at long-term fuel and technology transformations for the HD vehicle sector in California.

2.1 Heavy-duty Vehicle Technology Overviews

2.1.1 Diesel Engines and Exhaust Emissions

Diesel engines have a long-standing history as the dominant power pack for commercial transport and other HD (HD) applications in both land and sea. Due to its inherent efficiency and durability advantages over other internal combustion engines, the diesel engine is ubiquitous in transportation and other HD operations, including on-road passenger and freight transportation by commercial vehicles.

The diesel engine is a compression-ignition internal combustion engine, where air and diesel fuel injected into the engine cylinder are compressed, heated under compression, and auto-ignited in the absence of a spark. Diesel engines typically require higher compression ratios than gasoline engines; producing more work per stroke and lower exhaust temperatures so less energy is wasted, and, thus, thermal efficiency is greater. In addition, diesel fuel has higher energy content per unit volume than gasoline fuel, resulting in better fuel efficiency. At full load, the diesel engine uses only about 70% of the fuel that a comparable gasoline engine consumes for the same power output, and at partial load conditions, the diesel's advantage is even greater [9]. This helps to explain the diesel engine's dominance in the HD vehicle sector.

The benefits of the diesel engine are balanced by the following limitations. To endure the diesel cycle's high working pressures (roughly 1.5 times higher than those of gasoline engines of comparable power), heavier and more costly engine components are required. The diesel's lean combustion characteristics produce less power than a comparable gasoline engine produces. Because of the weight, compression ratio, and diffusion flame combustion process, diesel engines tend to have lower maximum operating speed (i.e., rotations-per-minute, RPM) ranges than gasoline engines. This makes diesel engines high torque rather than high horsepower, and that tends to make diesel vehicles inherently slower in terms of acceleration, which is one of the primary reasons why gasoline vehicles have historically dominated the passenger vehicle market.

Despite the versatility and high efficiency of the diesel engine, the compression-ignition combustion process results in relatively high levels of pollutant emissions—particularly emissions of particulate matter (PM) and nitrogen oxides (NOx). Diesel exhaust is a complex mixture of hundreds of gas-phase, semi-volatile, and fine particles that are produced through the combustion of diesel. The gaseous portion is comprised of typical combustion gases such as nitrogen, oxygen, carbon dioxide (CO_2), and water vapor. However, as a result of incomplete combustion, the gaseous fraction also contains air pollutants such as carbon monoxide (CO), sulfur oxides (SOx), and NOx, as well as volatile organic compounds (VOCs), alkenes, aromatic hydrocarbons, and aldehydes, such as formaldehyde and 1,3-butadiene and low-molecular weight polycyclic aromatic hydrocarbons (PAH) and PAH-derivatives. The exact break down of these various substances in diesel exhaust depends heavily on operating parameters such as engine and vehicle type, speed, load, fuel composition, and ambient conditions [10].

In general, diesel combustion design involves an inherent trade-off between NOx and PM emissions. Most engine modifications that decrease NOx have a tendency to increase PM, and conversely, in-cylinder strategies to reduce PM tend to increase NOx production. Both are linked by combustion temperatures: as in-cylinder temperatures increase, PM levels decrease but NOx increase; the opposite is true as temperatures decrease [11].

One distinct feature of diesel engines is a markedly greater emission rate of solid phase PM than that of spark-ignited engines, on an equivalent fuel energy basis. Particulate emissions are not significant in spark-ignition (e.g. conventional gasoline) engines due to homogenous mixing of air and fuel before combustion starts, but PM is much more prevalent from compression-ignition engines where the fuel is non-homogeneously distributed before ignition, and fuel rich regions in the fuel spray lead to the formation of PM. Diesel exhaust particles are comprised mostly of inorganic solid carbonaceous material[2] and ash, sulfur compounds, and VOCs that have condensed onto the soot. In a comprehensive review of size and composition of PM from diesel engines, Kittelson [12] describes that the inorganic portion primarily consists of solid (or elemental[3]) carbon particles that are formed during combustion in locally fuel rich regions and are typically ultrafines—less than 0.1 microns (μm) in diameter. The soluble organic fraction consists of organic compounds such as aldehydes, alkanes and alkenes, PAH, and PAH-derivatives that arise due to small portions of fuel and evaporated lube oil that have escaped

[2] This solid carbonaceous material is often times referred to colloquially as 'soot.'
[3] Sometimes in literature, the term 'elemental carbon' is used interchangeably with 'black carbon.' To be more precise, black carbon refers to the all of the carbonaceous aerosols (including elemental carbon) that are strongly light absorbing.

oxidation. Sulfur compounds are created as most of the sulfur, which is inherent to the fuel, is oxidized to SO_2. A small percentage of sulfur is transformed into SO_3, which leads to sulfuric acid and sulfate aerosols.

As shown in Figure 2-1 from Kittelson's review of engines and particle matter emissions [12], almost all of the exhaust particles—by mass and number—are less than 10 microns in diameter (PM_{10}), and a large majority are fine particles, which have diameter less than 2.5 microns ($PM_{2.5}$). The emitted species in the so-called nuclei mode, that is, on the smaller side of the spectrum—VOCs, sulfates, and elemental carbon (EC)—are mainly nanoparticles, having diameters less than 50 nm (0.05 μm). While typically only 1-20% of exhaust mass is nanoparticles, these particles in the nuclei mode represent 90% or more of the particle number. Carbonaceous agglomerates, which make up the majority of the mass fraction but a very small part of the number, are the accumulation mode in the 0.1-0.3 μm diameter range. PM size distribution usually follows a lognormal bimodal distribution, with the first peak in the nucleation mode and the second peak at the accumulation mode. Particle size is one of the most salient factors in determining health consequences because as particles decrease in size, there is greater opportunity for deep deposition in the small airways and the alveolar regions of the lungs [13].

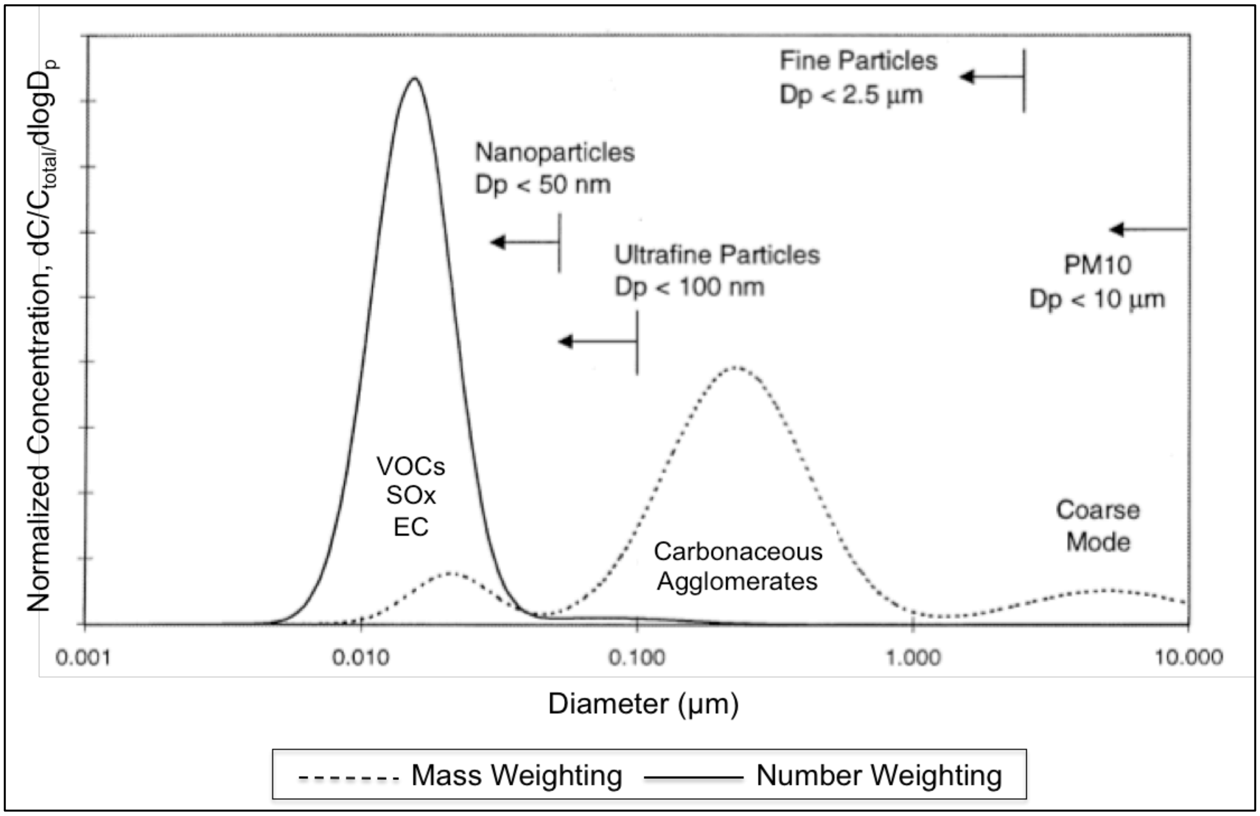

Figure 2-1: Typical engine exhaust particles size distribution (Figure 3, page 577 in [12])

Diesel engine exhaust contains a number of substances that have been deemed as hazardous by the US Environmental Protection Agency (EPA) and the California ARB. Some of these substances are carcinogenic, including acetaldehyde, arsenic, benzene, formaldehyde, mercury compounds, PAHs, styrene, and others. In addition, There is consensus within the scientific community that ambient concentrations of respirable particulate matter are associated with a wide variety of both acute and chronic health effects [14]. Diesel vehicles—particularly HD (HD) vehicles without particulate control aftertreatment devices—are a significant source of PM, so many urban areas, which are home to potentially high emitters such as transit buses and refuse trucks, have 'hot spots' of elevated PM concentration in high traffic areas. Many studies have shown that roadways and adjacent pedestrian facilities such as sidewalks, bus stops, and bike lanes are areas where PM exposure can be very high [15-19]. Epidemiological studies have linked this traffic-related pollution to increased hospitalizations, emergency rooms visits, and reports of asthma symptoms. Moreover, PM is strongly associated with increased mortality due to lung cancer and cardiopulmonary diseases [20, 21]. And not only are exposure risks high for pedestrians, but some of the highest PM concentrations have been recorded inside diesel buses in urban areas, which indicates that the realm of urban PM exposure can be quite extensive [16].

2.1.2 NOx and PM Trends in California

Heavy-duty diesel vehicles (HDDVs) are a major contributor to on-road emissions in California—particularly NOx and PM. According to the ARB's 2008 statewide emissions inventory [22], HDDVs accounted for roughly 61% and 59% of mobile source NOx and $PM_{2.5}$ emissions respectively. Figure 2-2 shows NOx and $PM_{2.5}$ emissions trends for HDDVs and the entire on-road transportation sector. Significant progress has been made as a result of state and federal regulations that have addressed emissions from HDDVs, but while the percentage of $PM_{2.5}$ from HDDVs has been decreasing since 1990, the HDDV contribution to NOx has been steadily increasing over time. As discussed in Section 2.3, policymakers in California are currently weighing options for reducing NOx from HD vehicles in the state and particularly the South Coast and San Joaquin Valley air basins, which will require significant reductions in NOx and other ozone precursors in order to meet federal ozone standards.

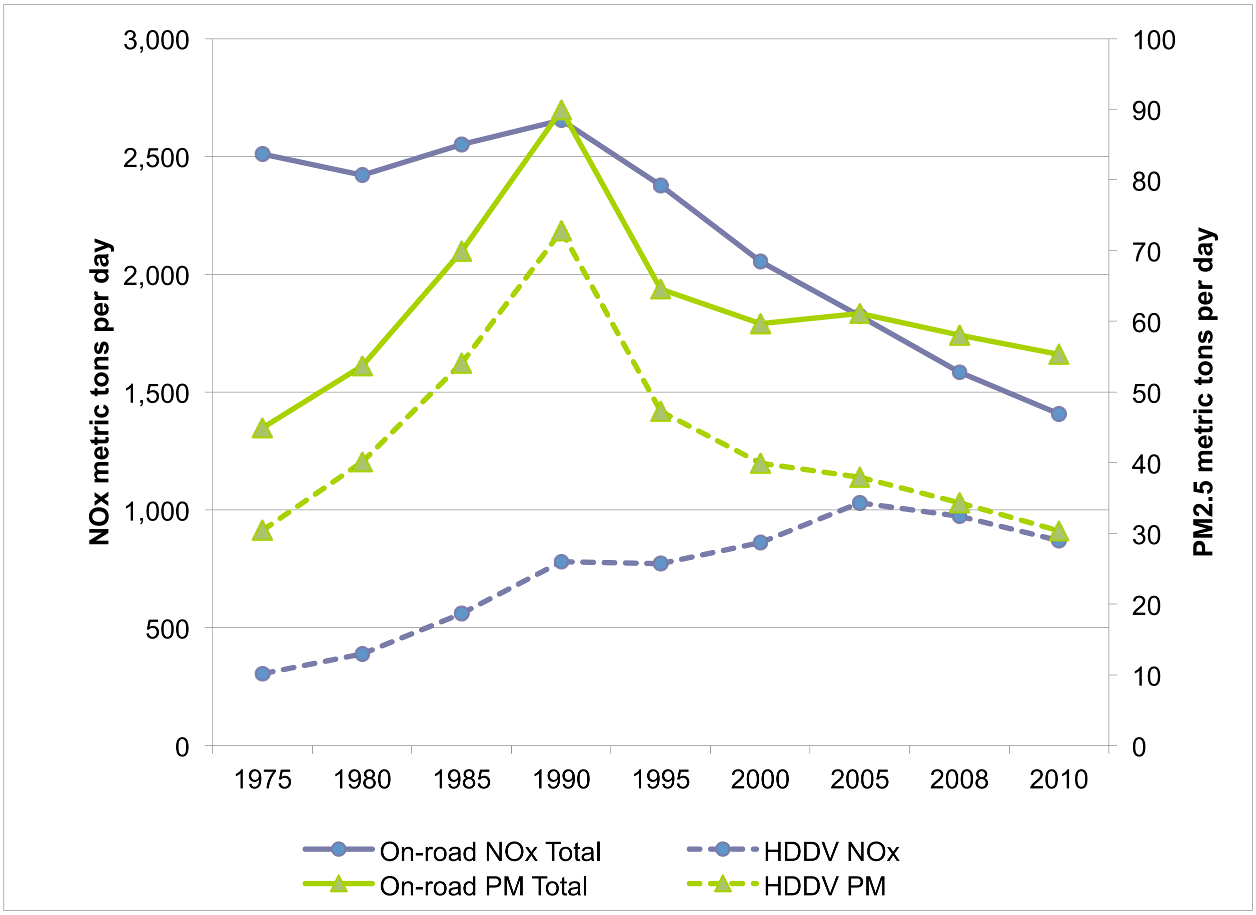

Figure 2-2: NOx and PM emissions trends from on-road vehicles in California (created using data from [22])

2.1.3 Diesel Emission Control Technologies

Pollutant emissions from HDDVs are a complex function of engine technology, engine condition, fuel specifications, and operating patterns. Engine and aftertreatment improvements as well as regulation have been responsible for driving technology developments in emission control. Engine manufacturers have achieved a great deal of sophistication with fine-tuning and controlling in-cylinder combustion in an effort to reduce engine-out emissions. The advent of electronic Engine Control Units (ECU) has greatly improved the fuel efficiency and emissions performance of HD diesel engines.

One of the primary concerns with diesel engines are PM and NOx emissions. As aforementioned, there is an inherent trade-off between NOx and PM, and as a consequence, controlling both species simultaneously during combustion presents a distinct challenge for manufacturers, who must comply with increasingly stringent standards that have tightened by 90% in recent years.[4] The following section discusses the various technologies for reducing HDDV emissions, including engine controls and aftertreatment devices.

2.1.3.1 PM Control

There are three strategies for controlling mobile source PM emissions: in-cylinder combustion management, catalytic and/or physical filtration devices in the exhaust stream, and reductions to fuel (and lube oil) sulfur levels. In most of the developed world and in places with stringent vehicle emissions standards, using only one of these options is typically not sufficient to achieve the necessary PM reductions. To comply with the increasingly stringent PM limits of the modern era, near-zero sulfur diesel fuel must be utilized, and manufacturers must employ engine controls and aftertreatment devices in synergistic fashion.

In-cylinder PM control is achieved by carefully regulating the combustion process, which involves matching the air management and fuel injection systems. Improvements in fuel injection systems involve fuel injection pressure, injection timing and duration, nozzle geometry and opening pressure. The main goal is to carefully control the local concentration of fuel and air

[4] In the US, HD engine emission limits for PM and NOx were cut by 90%, starting in model years 2007 and 2010 respectively.

inside the combustion chamber and avoid the conditions that lead to PM formation. Advanced engine calibration techniques and the implementation of electronic controls have improved air/fuel mixtures and reduced in-cylinder formation of both PM and NOx.

Aftertreatment devices utilized on HDDVs include diesel oxidation catalysts (DOCs), a flow-through catalytic converter composed of a monolith honeycomb substrate (high contact surface area) coated with platinum group metal catalyst. As the exhaust passes over the catalyst, these devices oxidize pollutants such as CO, HC, unburned fuel and oil, toxics, and the soluble organic fraction of PM to carbon dioxide (CO_2) and water (H_2O) in the oxygen-rich diesel exhaust stream. Reductions of CO and HC range from 50 up to 90% [10]. A DOC is very effective at oxidizing the SOF and gaseous CO and HC but does not reduce the number of exhaust soot particles. The SOF portion of PM can vary from 10-90%, depending on the engine and operating conditions, but values are typically on the order of 20-40% [10, 23, 24]. As a result, reductions in overall PM emissions (mass basis) from DOCs are typically cited at 20-50% [10, 25, 26]. Although DOCs are effective at reducing the total PM mass, because they do not collect or burn the soot portion of the exhaust, they do not significantly reduce the particle number [10]. In general, technologies that lower the overall particle mass do not necessarily reduce the number of particles—particularly ultrafines [27-29]. DOCs are a proven low-cost technology that do not require any maintenance or near-zero (“ultra-low”) sulfur diesel and have been utilized in a wide range of original equipment manufacturer (OEM) and after-market (i.e. retrofit) applications. However, while DOCs are attractive in terms of their versatility and costs, compared to the other two aftertreatment options discussed below, DOCs are the least effective technology at reducing PM mass and number and generally do not control the smallest, most harmful, particulate emissions from diesel vehicles.

A partial flow technology (PFT) system is an emission reduction device comprised of a DOC and a flow-through filter element. The DOC functions as described above, and then the soot component is captured and combusted in the filter element. In a PFT system, the filter element can be made up of a variety of materials and configurations such as sintered metal, metal mesh or wire, or a ceramic foam structure. Whatever the material/design combination may be, the exhaust gasses and PM follow a circuitous path through a relatively open network. The partial filtration occurs as particles collide with the rough surface of the mesh or wire network of the filter. If temperatures are sufficiently high, the soot trapped in the filter is continuously combusted by the NO_2 generated by the upstream DOC and thus the filter is regenerated, allowing for additional soot collection. However, if temperatures are too low to sustain regeneration, the filtration efficiency will continue to decrease and the media will become loaded with soot up to its full capacity. In a soot-saturated condition, the filtration efficiency will eventually either drop to zero or oscillate between positive and negative values caused by particle accumulation and blow-off (uncontrolled release of soot) cycles. While PFT systems are generally more effective than the DOC in lowering PM mass—reductions are typically cited as being greater than 50% [30]—the technology is relative new, and their performance and durability have yet to be fully characterized in published literature. Some of the issues include performance deterioration in soot-saturation conditions, intermittent blow-off events, and unproven long-term durability [31].

A diesel particulate filter (DPF) is a wall-flow PM control device. These filters are usually comprised of either cordierite (a clay-derived material) or sintered silicon carbide. Figure 2-3 illustrates how exhaust gases are re-directed by impenetrable barriers and channeled through the porous walls as they escape to the filter exit. After the PM is trapped in the filter, the next stage is to combust these carbonaceous particles, since the filter would quickly become blocked otherwise. There are two basic methods for combusting the captured PM: passive and active regeneration.

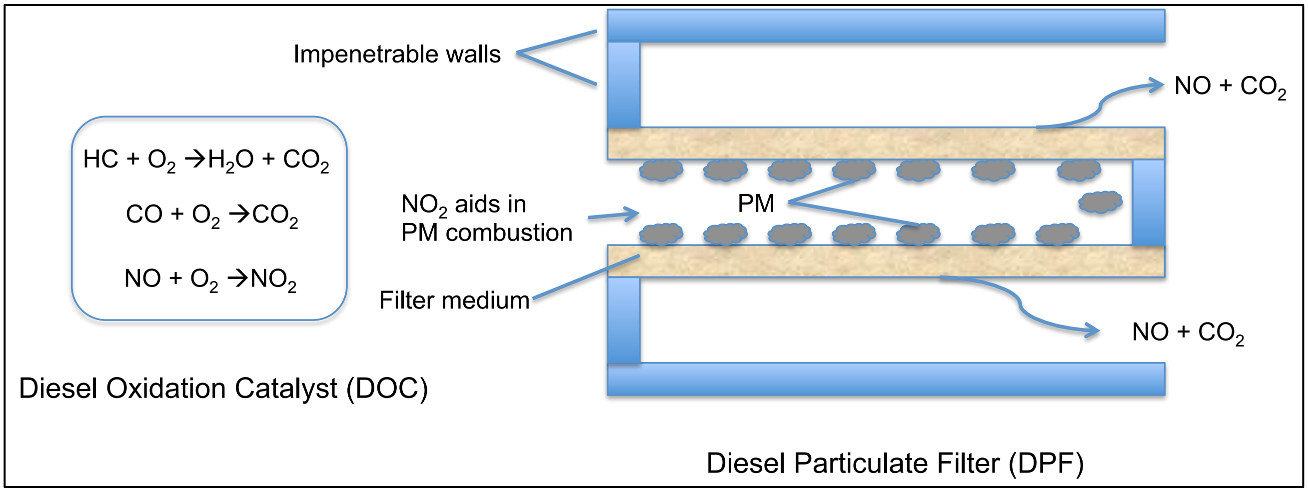

Figure 2-3: Operating principle of a diesel particulate filter

In passive regeneration, trapped PM is combusted during the normal operation of the vehicle—neither the vehicle operator nor the engine management system needs to induce the regeneration process. To facilitate combustion under normal operating temperatures (200-400°C for most HD vehicles), nitrogen dioxide (NO_2) can be introduced. The majority of NOx emissions from diesel vehicles are in the form of nitrogen oxide (NO), so an oxidation catalyst is used to convert NO to NO_2 [32]. This oxidation can be done upstream of the filter in a DOC or a catalyst can be coated onto the DPF itself. The former DPF technology is called a continuously regenerating DPF, and the latter a catalyzed DPF.

Some vehicles that have urban, low-speed driving profiles do not have exhaust temperatures high enough for passive regeneration, and active regeneration is required. In active regeneration, sophisticated engine controls measure back pressure in the filter (which increases as PM levels increase), and when pressure reaches a certain level, fuel injection is modified to increase the temperature of the exhaust gas. The added injection of fuel ensures sufficiently high temperatures in the oxidation catalyst to combust the HC and CO. The resultant heat causes the DPF temperatures to rise, leading to a rapid combustion of PM.

Of the three particulate control technologies, the DPF is the most efficient, with PM mass reductions typically cited between 85% and 95% [26, 33]. Moreover, in addition to effectively filtering and combusting PM mass, the number of particles reduced can be on the order of 99.5% or more as compared to engine-out emissions [26, 27]. The durability and long-term performance of DPF systems is well established for a wide variety of HD vehicle types. Hundreds of thousands of DPFs have been installed on new vehicles as well as in retrofits [34].

2.1.3.2 NOx Control

Devices for PM control are not typically effective for reducing NOx emissions and vice versa [32]. Nitrogen oxides are created as a by-product of combustion. Air contains primarily nitrogen (N_2) and oxygen (O_2). The heat generated during combustion causes these to merge to form NO and, to a lesser extent, NO_2 (both of these species are classified as NOx). NOx formation is directly proportional to peak combustion temperature and pressure. It can be mitigated with engine controls that decrease combustion temperature and/or catalytic aftertreatment. Controlling NOx emissions from diesel vehicles is particularly challenging because NOx must be reduced to N_2 and O_2, unlike PM, HC, and CO, which must be oxidized. The diesel engine inherently runs lean (i.e. less fuel-to-air ratio than stoichiometric conditions), and there is always excess oxygen in the exhaust, which makes it difficult to create a reducing environment that facilitates the separation of NOx into N_2 and O_2. In general, increases in combustion temperature result in increases in NOx emissions. Two types of technologies for controlling NOx—one engine-based and one tailpipe-based—are discussed below.

Exhaust gas recirculation (EGR) is an engine-based technology designed to reduce NOx emissions by recirculating exhaust gases into the engine intake manifold. EGR's ability to reduce NOx is based on its dilution effect, which works in two ways: 1) by reducing the peak temperatures during combustion, thus avoiding the high temperatures where NOx is formed, and 2) by reducing the concentration of O_2 available for NOx formation. In compression-ignition engines the EGR fraction is tailored during engine calibration at specific engine operational conditions. In HD diesel applications, EGR has been used since 2000, especially in North America where it is combined with a DPF to meet the EPA engine NOx limits for model years (MYs) 2007 to 2009 [35]. In Europe, North America, and Asia, EGR has been used in a wide variety of applications (transit buses, refuse trucks, LH (LH) etc.) for retrofit systems as well. EGR is effective in limiting NOx formation at the expense of a small increase in fuel consumption—NOx reductions are typically on the order of 20-50% [10, 35].

Selective catalytic reduction (SCR) has been used in stationary application for decades and has come into increasing prominence in mobile applications. In this type of system, an aqueous, non-hazardous solution of urea, which contains ammonia (NH_3), is injected into the exhaust stream, and the hydrogen from the ammonia reduces NO and NO_2 to N_2 and water. There are various different SCR catalysts that may be used depending on the vehicle application—they are either vanadium-based or zeolite-based catalysts mounted on a ceramic monolith. SCR can be used in combination with EGR, which is typically the case for engines that are certified to the MY 2010 US EPA and ARB HD engines standard for NOx (0.2 grams/hp-hr) [36].

While SCR systems can currently achieve NOx reduction efficiencies on the order of 70-90% [10, 37], its use in vehicles presents two key challenges. Given the variable power requirements of vehicle systems, it can be difficult to achieve precise dosing of urea. Consequently, either very precise urea measuring systems with a downstream sensor and a feedback loop must be used; or an ammonia slip oxidation catalyst must be placed downstream of the SCR device to prevent the unreacted urea from being emitted as ammonia, which is a toxic pollutant with severe human health impacts. SCR systems can vary in many design parameters, including urea mixers, injection strategy, and choice of catalyst. Due to the variability between different types of SCR and the inherent complexity of these systems, there is a wide range of quality and NOx reduction efficiencies in the SCR market. There is evidence that certain SCR types of SCR systems can have elevated NOx emissions during in-use driving, particularly when operating in urban conditions, where exhaust temperatures may not be high enough to facilitate catalyst activity [38]. A significant factor for elevated NOx emissions during urban operating is engine certification procedures that do not require sufficient engine operation in low-load areas or provisions for in-use compliance [39]. Moreover, another challenge is that urea (often called "diesel emission fluid" or "DEF") availability and infrastructure must be considered when assessing the viability of emissions standards that require SCR systems. In addition, HD vehicle operators must refill urea tanks at regular intervals or failsafe measures on the vehicle are in place to guard against operating the vehicle with adequate supply of urea solution. Despite these challenges, SCR has emerged worldwide as a viable technology for reaching stringent NOx emissions levels for HD engines.

2.1.4 Natural Gas Vehicles

Natural gas (NG) is an abundant fossil fuel primarily composed of methane (CH_4), varying quantities of non-methane hydrocarbons (NMHCs), water vapor, hydrogen sulfide and other gases. As with other fossil fuel sources, the exact chemical make-up of NG depends on the location where the gas is produced. At ambient temperatures and pressures, NG is in gaseous state and must be stored onboard a vehicle as either a compressed NG (CNG) at high pressures (3000 to 4000 psi) or as a liquid (LNG) at temperatures around -260°F [40].

There are a number of reasons for adopting NG vehicles. In the commercial sector, perhaps the biggest motivation is the potential fuel savings of using NG. As shown in Figure 2-4 [41, 42], NG is nearly half the cost of diesel fuel on an energy-equivalent basis, and the Energy Information Administration projects that this difference in retail price will grow over the long-term [43].[5] Figure 2-4 shows average monthly retail transportation fuel prices in the US from 2000 to 2012. The price of petroleum-based fuels (i.e. gasoline and diesel) is the primary driver of overall fuel prices. As petroleum prices rise, so does demand for alternative fuels, thereby driving their prices upward as well. However, NG prices have been shielded from this effect, because its primary market is electric power generation, industrial, commercial, and residential uses [44] as well as the fact that recently there have been increases in domestic NG production [45]. This abundant supply in North America makes NG very attractive in terms of increasing US energy security by reducing our dependence on imported petroleum products.

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[5] In the Early Release of the EIA's Annual Energy Outlook for 2013, diesel and NG prices (2011$) are forecasted to grow between 2011 and 2040 at an annual rate of 1.1% and 0.9% respectively.

Another motivation for increased NG use in the transportation sector is the potential for reduced GHG emissions. As compared to other hydrocarbon fuels, NG has a lower carbon-to-hydrogen ratio, so its combustion typically produces less CO_2 per unit of energy. However, methane is a potent greenhouse gas, so increased fugitive emissions of CH_4 resulting from increased use of NG can offset the reduced CO_2 in the vehicle exhaust.

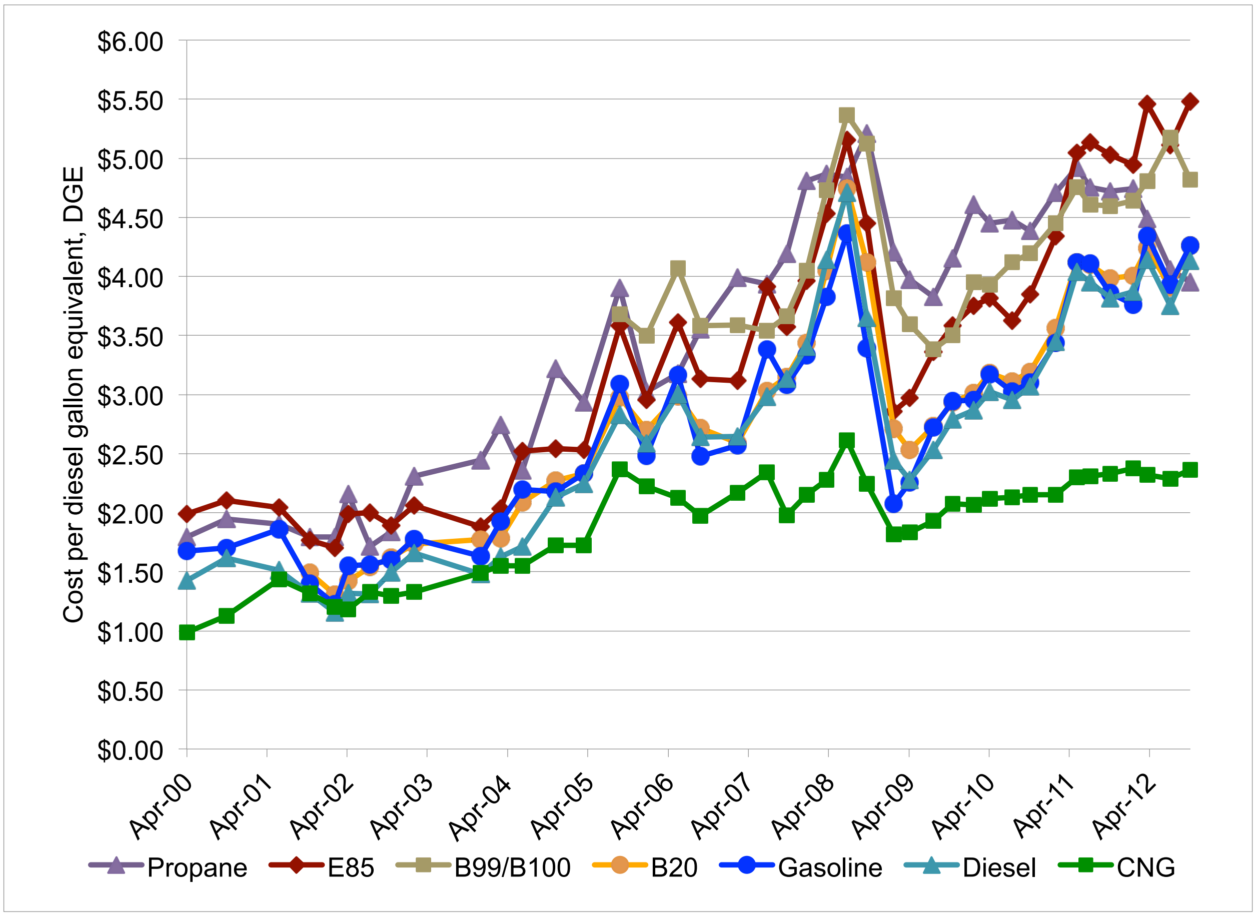


Figure 2-4: Average retail fuel prices in the US for conventional and alternative fuels (created using data from [42] and [41])

In addition to fuel cost savings, energy security benefits, and GHG reductions, one of the original reasons for that policymakers promoted NG vehicles in favor of diesels was the greatly reduced particulate emissions. Over the past two decades, tests of comparable NG and diesel HD vehicles demonstrate that NG engine emissions can be much lower than diesel engine emissions [46-56]. Much of this testing research was done prior to model year 2007, when diesel particulate filters were first introduced on diesel engines in the US and Canada. If a diesel engine does not have a DPF, one of the primary advantages of choosing a NG over diesel for HD applications is that NG engines produce very few PM emissions due to the almost homogeneous combustion of the air-gas mixture and the absence of large hydrocarbon chains [57].

Table 2-1, which is a synthesis of the data presented by Hesterberg et al. [51], roughly estimates how HD NG vehicles perform relative to their diesel equivalents in terms of 1) engine-out emissions and 2) emissions downstream of a best available control technology (BACT). For NG vehicles, the BACT is assumed to be a three-way catalyst, and for diesel vehicles, a catalyzed DPF and high-rate EGR and/or SCR. While manufacturers are able to produce both NG and diesel HD engines that comply with the most stringent standards in the US and Japan (and upcoming in the European Union with the implementation of Euro VI in 2013 [58]), Hesterberg et al.'s comparative review shows that with the BACTs, NG vehicles tend to have higher CO and NMHC emissions, but NOx and PM emissions are generally comparable between the two technologies.

Table 2-1: Qualitative emissions comparison of NG engines versus diesel engines (based on data from [51])

	CO	NMHC	NOx	PM
Engine-out	~ 2 times higher	~ 2 times higher	~ equivalent	~ 4-10 times higher
BACT	~ 10 times higher	~ 5-10 times higher	~ equivalent	~ equivalent

In the late 1980's and early 1990's, the first generation of NG engines used either stoichiometric or lean combustion based on modified spark-ignited engines [59]. Stoichiometric combustion is defined as the theoretical process where the fuel and oxygen are completely combusted, and no unburned fuel or oxygen remains in the exhaust. Lean combustion, on the other hand, occurs under excess air. Ignition is accomplished through a spark plug in both cases, but the configuration of the lean combustion is more complex. In the first-generation NG engines for mobile applications, the lean burn approach became the dominant technology for the commercial vehicle market due to its higher fuel efficiency, superior torque and power, better reliability and durability, and lower heat rejection as compared to stoichiometric engines. Fuel and ignition systems of this generation of NG engines were borrowed from stationary application engines [60].

By the mid 1990's the second generation of engines utilized electronic controls to reduce the sensitivity to the operating environment, offering an integral design with improved reliability at lower costs. In subsequent generations, manufacturers made improvements to this lean-burn design, but in order to achieve the NOx limits that were fully phased-in by model year 2010, NG engine manufacturers adopted a stoichiometric combustion approach that uses cooled EGR. This engine design combines the positive attributes of lean and stoichiometric combustion and allows manufacturers to reach the current criteria pollutant emission limits using a three-way catalyst [59].

In many areas around the world, NG is first introduced as a transportation fuel for transit bus fleets. Urban transit buses normally operate on fixed routes and utilize depot-based refueling, which is ideal for an alternative fuel such as NG that currently does not have nearly as extensive a network of publically available refueling stations as petroleum products do in many regions of the world. According to the US Energy Information Administration (EIA), there were approximately 9,400 CNG buses in-use in California in 2010, which is almost half of the nearly 19,200 HD NG vehicles registered in the state [61]. For the entire country, the EIA estimated fleet total for CNG buses in 2010 is approximately 20,100, and the total number of HD CNG vehicles is roughly 48,500. From these in-use estimates, California represents a disproportionately large share of NG vehicles in the US As discussed in the following chapter, various policy measures that have been implemented over the past decade are one of the primary reasons why California has lead the country in the adoption of NG and other alternative fuel and advanced (i.e. non-conventional) technology vehicles.

For HD vehicles in California, the EIA's Alternative Fuel Data Center has in-use fleet data [61] for CNG, LNG, LPG, and electric vehicles[6], and this data is summarized in the figures below. As shown in Figure 2-5, CNG vehicles make up the majority of alternative fuel HD vehicles in the state, and the CNG share of the alternative fuel market steadily grew between 2003 and 2010. Some examples of HD NG vehicles on the road are shown in Figure 2-8. In 2010, CNG vehicles represented nearly three-quarters of the alternative fuel HD vehicle market in California. The next largest share of the alternative fuel market belongs to LPG vehicles at 17%, followed by LNG at 8%, with electric vehicles taking the remaining 2%. Looking at Figure 2-6, buses account for the nearly half of CNG vehicles, whereas for LNG and LPG, trucks represent 73% and 77% of the total fleet. Figure 2-7 shows that, together, municipal governments and transit agencies own and operate the large majority of HD CNG and LPG vehicles in California.

In certain applications, the greatly increased energy density of liquefied NG (LNG) is advantageous over CNG in order to boost a vehicle's driving range. Because it must be kept at cold temperatures, LNG is stored in double-walled, vacuum-insulated pressure vessels. The

[6] This AFDC database has records for pure electric vehicles but does not have data on hybrid or plug-in hybrids.

complex, heavy, and expensive onboard fuel storage systems make it such that LNG systems are not generally feasible in the passenger vehicle market; however, as shown in Figure 2-6, there are approximately 2,100 LNG vehicles in the California HD fleet. A gallon of LNG only contains about 56% of the energy in a gallon of diesel, so, typically, LNG vehicles are not able to provide equivalent driving range to diesel (or gasoline) vehicles unless their fuel tanks are sized to roughly 1.8 times larger than a fuel storage system for comparable diesel vehicle [62]. As compared to HD CNG vehicles, the LNG fleet in California is dominated by trucks, which account for nearly three-quarters of total in-use vehicles, and buses make up the remainder of the LNG vehicle population.

Liquefied petroleum gas (LPG), also known as propane or autogas, is a byproduct of NG processing and crude oil refining. The atmospheric boiling point of LPG is -44 °F, and it must be stored under moderate pressure (~200 psi) to remain liquid [63, 64]. This pressure is significantly lower than that required for CNG storage, which makes the fuel easier to carry onboard. The volumetric energy content of LPG is approximately two-thirds of diesel, so it requires more volume to store enough fuel for comparable range. Although lower than NG, LPG's octane rating is still high, making its use more suited to spark-ignition engines than to compression-ignition engines [65]. Engine technology for LPG vehicles is very similar to that of NG vehicles, and pollutant emission profiles between the two fuel types are comparable as well [66].

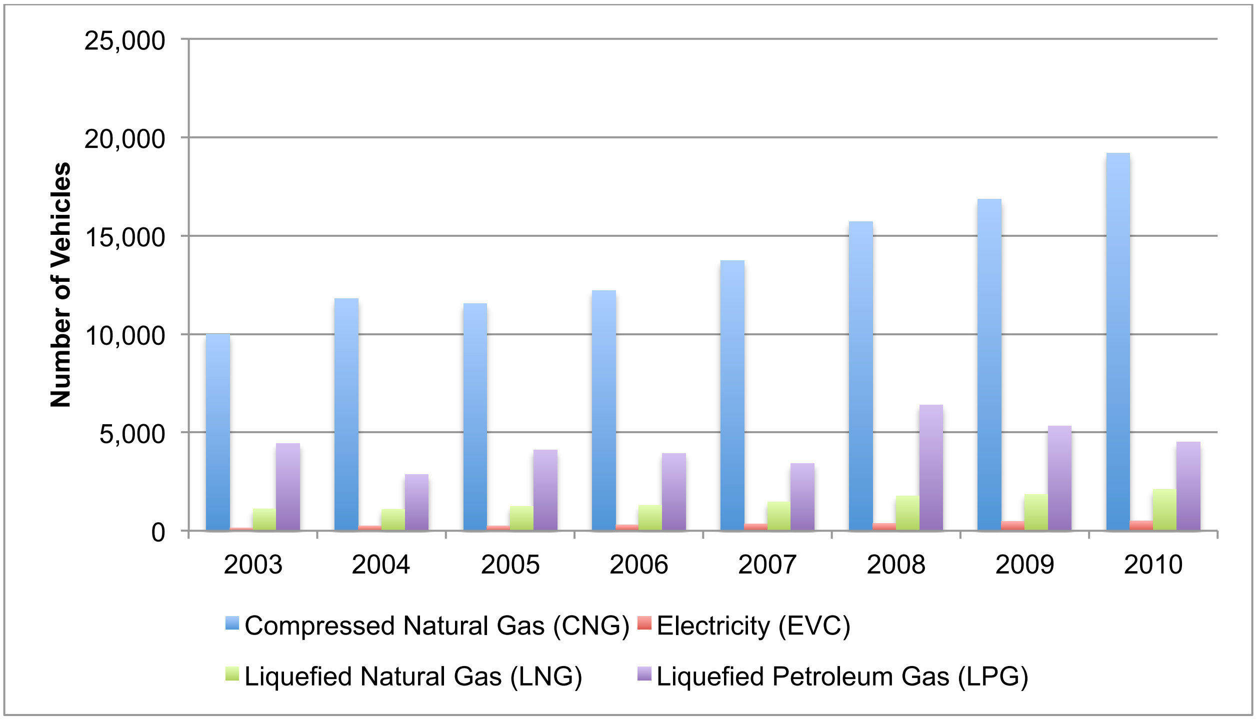


Figure 2-5: In-use alternative fuel HD vehicles in California (created using data from [61])

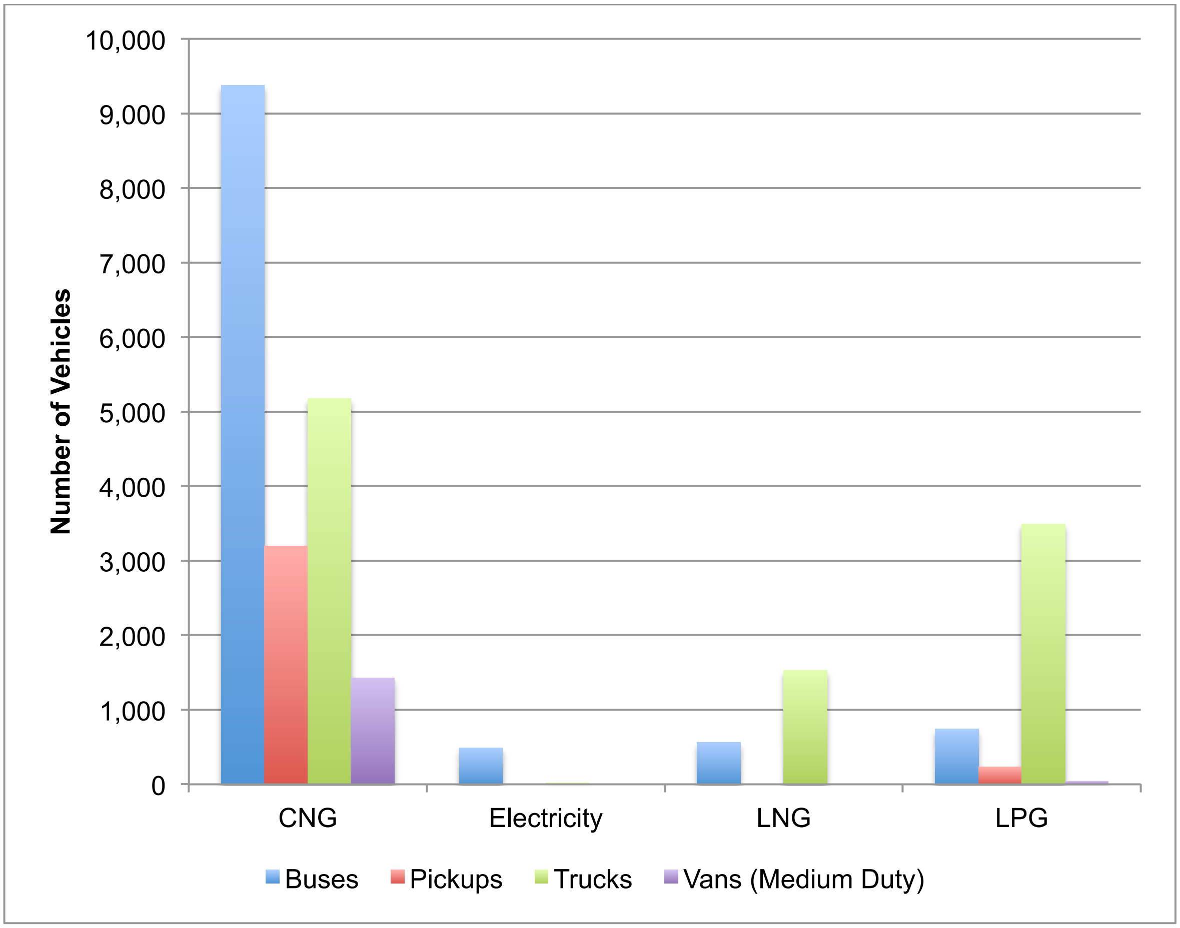


Figure 2-6: In-use alternative fuel HD vehicles in California in 2010 by vehicle type (created using data from [61])

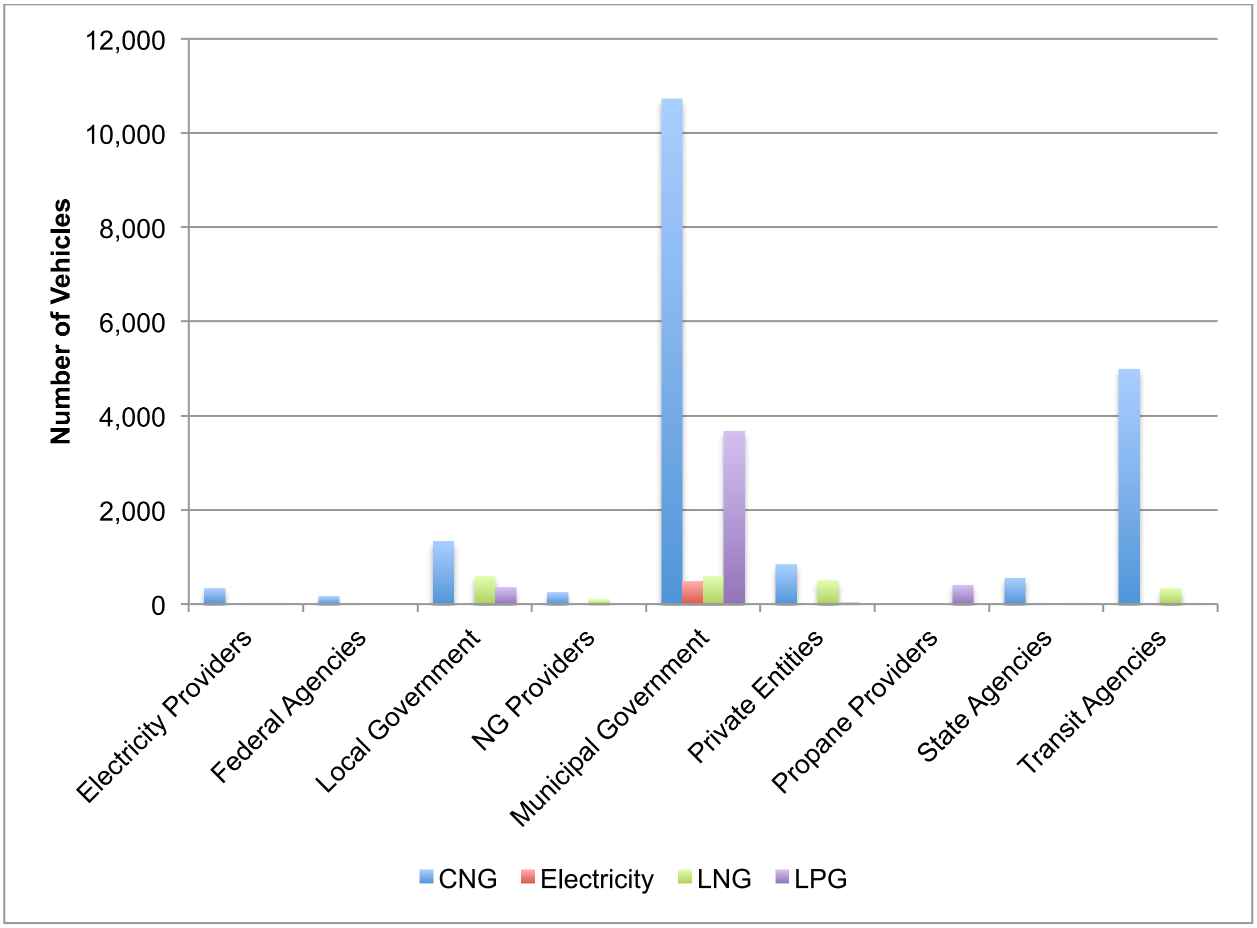


Figure 2-7: In-use alternative fuel HD vehicles in California in 2010 by user group (created using data from [61])

HD Pickup Truck	**Urban Bus**
 http://wheels.blogs.nytimes.com/2012/03/14/driving-rams-natural-gas-pickup-truck/	 http://www.showtimesdaily.com/news-articles/cng-and-beyond-in-los-angeles

<table>
<tr>
<td>Other Bus


http://www.businesswire.com/news/home/20130115005310/en/DesignLine-CNG-Coach-Completes-Altoona-In-Service-Testing</td>
<td>MD Urban Vehicle


http://www.cleanmpg.com/forums/showthread.php?t=28488</td>
</tr>
<tr>
<td>MD Vocational Vehicle

http://www.worktruckonline.com/channel/green-fleet/article/story/2010/03/freightliner-m2-112-goes-all-natural.aspx</td>
<td>HD Vocational Vehicle


http://ecotrope.opb.org/2012/08/garbage-haulers-switch-from-diesel-to-natural-gas/</td>
</tr>
<tr>
<td>LH Tractor

http://bulktransporter.com/2010-emissions/pete_model_lng-1101/</td>
<td>SH Tractor

http://www.fleetsandfuels.com/fuels/cng/2012/12/freightliner-cng-cascadia-trials/</td>
</tr>
</table>

Figure 2-8: Examples of HD NG vehicles

2.1.5 Hybrid Vehicles

Hybrid vehicles employ additional energy storage and delivery in conjunction with an internal combustion engine (or other power plant such as a fuel cell) for motive power. Energy can stored onboard as electricity in batteries (or ultracapacitors), as pressurized fluid in the case of hydraulic (or pneumatic) hybrids, or as kinetic energy in the case of flywheel hybrids.

Internal combustion engines (ICEs) are most efficient at steady loads and with minimum transients and shifting/transmission losses. Hybrids increase the efficiency of the driveline system by helping to cover transients and smoothing the demand loads on the ICE. In addition, the hybrid system can allow the ICE to turn off during idling or low speeds, and, typically, the motor can also run backwards as a generator to capture vehicle braking energy (i.e. regenerative braking). The interactions between the engine and the hybrid components affect criteria pollutant emissions and fuel consumption. Often, an engine installed in a hybrid vehicle operates very differently from the same engine installed in a conventional vehicle driven over the same route. The realized fuel consumption benefits of a particular hybrid technology are strongly dependent on the application and duty cycle.

Generally, passenger cars and light-duty trucks make use of electric hybrid systems, whereas HD vehicles make use of both electrical and hydraulic systems. Due to the large mass of many HD vehicles, certain operations allow regenerative braking systems to capture a significant amount of energy. As a result, power transfer through the hybrid system can be very high, which makes both ultracapacitors and hydraulic storage very attractive since they have very high power density, as shown in Figure 2-9, which compares the power versus the energy density of different energy storage systems. However, the energy density of both ultracapacitors and hydraulic systems is lower than that of batteries and, therefore, energy cannot be discharged over a long duration. The high-power systems are advantageous in driving cycles that have rapid start-stops, as energy can be captured and released quickly. In contrast, batteries have higher energy density and can be used for long energy storage and supply. At present, ultracapacitors, hydraulic accumulators, and advanced flywheels have the highest power density among storage systems, but their energy density is limited significantly.

Hydraulic hybrid vehicles employ the same basic architecture as electric hybrids; however, energy storage in a hydraulic hybrid is achieved with a hydraulic accumulator instead of batteries, and hydraulic motors/pumps take the place of electric motors/generators. In a hydraulic hybrid system, braking energy is used to drive a hydraulic pump that sends fluid from a low-pressure reservoir to a high-pressure accumulator. This energy can then be used to supplement engine power by releasing the fluid in the high-pressure accumulator back to the low-pressure reservoir, driving the motor in the process. One of the principal advantages of the hydraulic systems is the ability to capture more braking energy than in electric systems. Currently, hydraulic hybrids can recover approximately 70% of total braking energy, whereas, electric hybrids are typically only able to capture roughly 25% of braking energy [67]. To date, hydraulic hybrids have been targeted for power-driven applications that have high regenerative braking potential and relative low energy storage requirements. Some early applications for hydraulic hybrids include Class 6-8 (i.e. greater than 19,500 lbs. GVWR) urban commercial vehicles such as refuse trucks and package delivery vehicles [68].

Hybrids first began appearing in transit bus and urban delivery vehicle applications in the early to mid-2000s. Since then, hybridization has spread to virtually every size and vocation within the HD segment, though in some applications such as LH trucking, hybrids are currently in the pre-commercial, proof-of-concept phase. Some examples of real-world hybrid vehicles across various HD vocations are shown in Figure 2-10.

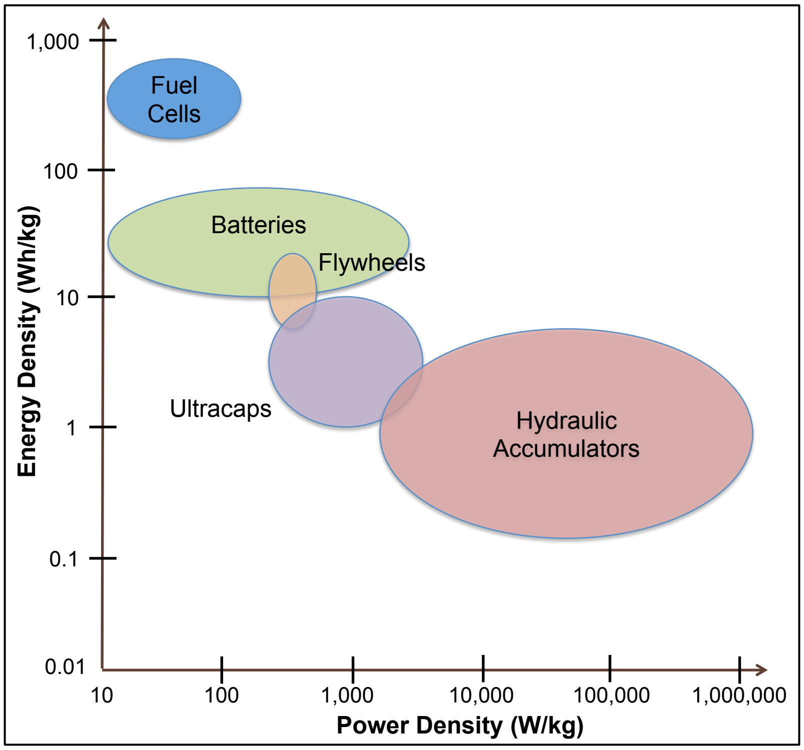


Figure 2-9: Energy density versus power density for various technologies (adapted from [69])

HD Van	Urban Bus
 http://www.fleetsandfuels.com/fuels/hybrids/2012/06/xl-test-results-confirm-21-mpg-gain/	 http://www.greencar.com/articles/buses-green-hybrid-electric-vehicle-technologies.php

Other Bus	MD Urban Vehicle
 http://media.navistar.com/index.php?s=43&item=263	 http://green.autoblog.com/photos/fedex-hybrid-truck/776933/
MD Vocational Vehicle	**HD Vocational Vehicle**
 : http://www.alabamacleanfuels.org/latestarchive.cfm	 http://puregreencars.com/Green-Cars-News/Hybrids/Volvo-Launched-First-Hybrid-Refuse-Truck-in-the-World.html
LH Tractor	**SH Tractor**
 http://www.thedetroitbureau.com/2009/08/heavy-hauling-hybrids/	 http://www.fleetsandfuels.com/fuels/hybrids/2012/09/nrel-confirms-hybrid-truck-savings/

Figure 2-10: Examples of HD hybrid vehicles

2.1.5.1 Hybrid Architectures

There are a great variety of hybrid system sizing approaches and architectures, and the choice of design is largely based on the size of the vehicle and the anticipated operating characteristics. There are three broad categories of hybrid architectures: parallel, series, and series-parallel (or “power-split”). The following section describes some of the possible driveline configurations for each of these three types of hybrid vehicles.

In a parallel hybrid system, both the engine and hybrid components (e.g. in the case of an electric hybrid, this includes the motor/generator, energy storage system, power electronics, and hybrid controls) are capable of delivering power to the engine output shaft to drive, through the transmission, the wheels or auxiliary components. To drive a specific route, a pre-transmission parallel hybrid system would typically provide the transmission the same torque requirements that the engine alone would in a conventional vehicle. The engine and hybrid components are controlled by an engine control unit (ECU) and/or hybrid control module (HCM), which determines the instantaneous proportion of power to be delivered from the engine and the hybrid drive motor to meet the instantaneous power requirement of the vehicle. A schematic of a pre-transmission parallel hybrid system is shown in Figure 2-11.

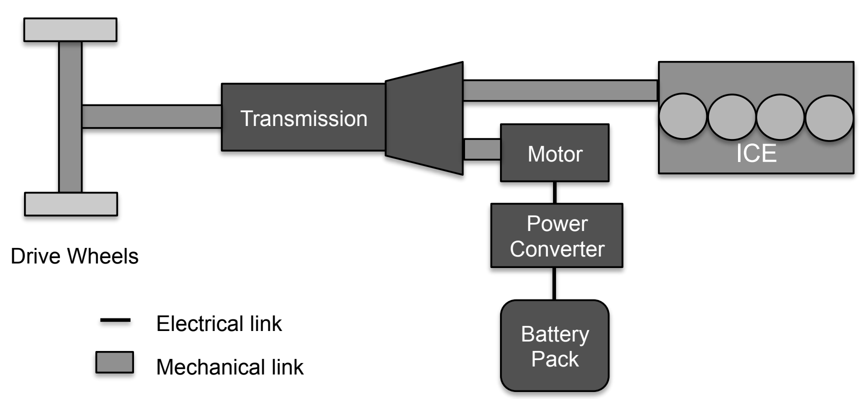


Figure 2-11: Pre-transmission parallel hybrid configuration

In a post-transmission parallel hybrid configuration, one or more electric motors and gearing are combined into a device that takes the place of a conventional automatic transmission and is used to deliver power from the engine output shaft to the wheels. In this configuration the hybrid “transmission” might provide a pure mechanical path, a pure electric path, or a combination thereof to deliver the power produced by the engine and hybrid system battery to the vehicle’s wheels. An example of a post-transmission parallel hybrid system is shown in Figure 2-12.

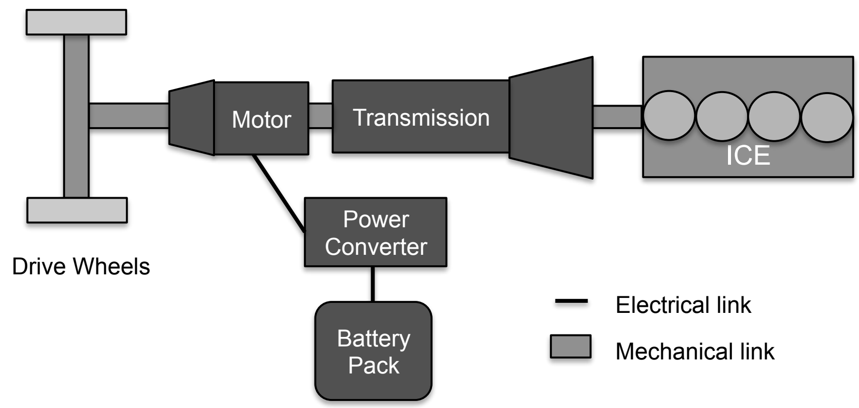


Figure 2-12: Post-transmission parallel hybrid configuration

In a series hybrid there is no mechanical path between the engine and the vehicle wheels. A generator is attached to the engine output shaft, and a separate electric motor is attached to the drive wheels. The engine supplies power to the generator, which produces electricity to power the drive motor to drive the wheels. Series systems typically do not include a conventional transmission, but may include a gear set attached to the drive motor. A schematic of a series hybrid system is shown in Figure 2-13. Series hybrids typically require larger battery packs and are thus heavier and more costly. Series configurations are most common in buses, which are generally less sensitive to weight increases than other HD vehicles. As such, most other HD vehicle types favor parallel type configurations [70].

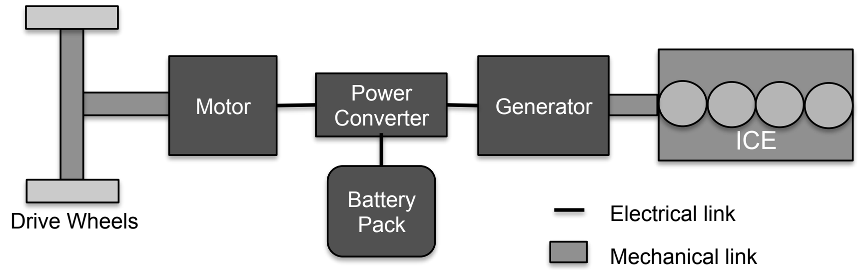


Figure 2-13: Series hybrid configuration

The final broad category of hybrid vehicles is a series-parallel (or "power-split") configuration. This architecture is designed to take advantage of the positive aspects of both the series and parallel configurations. This system divides the engine power along two paths: as shown in Figure 2-14, one goes to the generator to produce electricity and one goes through a mechanical gear system to drive the wheels. One example of this type of architecture in a HD vehicle is the ArvinMeritor Dual Mode Hybrid System, which has been designed for a Class 8 LH tractor truck. In the ArvinMeritor Dual Mode tractor, the vehicle operates in series mode at low speeds and then transitions to parallel operation for speeds greater than roughly 50 mph. In this design, series mode provides maximum efficiency for low speed, transient conditions, and parallel mode offers maximum efficiency at highway speeds while still providing the hybrid benefits of regenerative braking and torque assist [71].

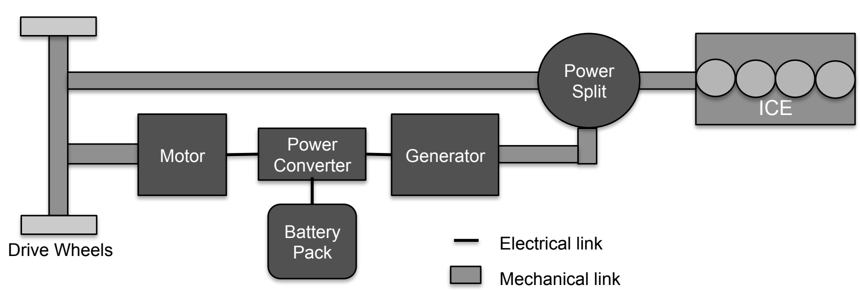


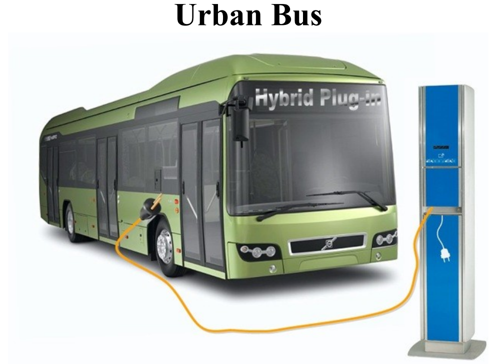
Figure 2-14: Series-parallel (power split) hybrid configuration

2.1.6 Plug-in Hybrids

Plug-in hybrid electric vehicles (PHEVs) have the ability to recharge onboard battery packs by plugging in to the electrical grid, and these vehicles also have an internal combustion engine. As described in **Error! Reference source not found.**, a plug-in hybrid vehicle's ability to utilize grid electricity during charge-depleting mode is one of the key advantages as compared to a conventional, charge-sustaining hybrid. The table shows increased levels of electrification moving from the left to the right, and plug-in hybrids are in-between hybrids and electric vehicles and have characteristics of both conventional hybrids and full electric vehicles. Typically, plug-in hybrids have larger battery packs than conventional hybrids and rely more on the electrical system for motive power, and often times the internal combustion engine can be downsized as compared to conventional hybrid or non-hybrid vehicles. Due to a larger reliance on battery power during charge-depleting mode, PHEVs usually provide additional efficiency gains as compared to charge-sustaining hybrids. For example, if a typical charge-sustaining hybrid were to provide 20 to 35% reduction in primary fuel use (e.g. diesel) gains versus a non-hybrid vehicle, a comparable PHEV might yield primary fuel consumption reductions on the order of 40 to 60% during charge-depleting operation [70].

As with conventional hybrids, PHEVs can be configured as parallel, series, or series-parallel systems. Typically, series or series-parallel PHEVs, which have direct pathways between the battery pack and the drive wheels, are designed to provide all-electric operation. For these PHEVs with all-electric range, often the energy management strategy is to operate in charge-depleting mode until the battery pack reaches a certain state-of-charge, and then after that point, the vehicle runs as a charge-sustaining hybrid until the vehicle is able to recharge its batteries via the grid. For plug-in hybrids that offer all-electric range, the internal combustion engine (or fuel cell) is sometimes referred to as a *range extender*. In these PHEV designs, the vehicle is essentially a battery-electric car with an on-board generator for extending the driving range.

All permutations of plug-in hybrids are in their infancy in the HD vehicle sector. Figure 2-15 shows the proof-of-concept and early generation commercial PHEVs that currently exist in five of the eight broad HD vehicle categories used in this dissertation research. To date, plug-in HD hybrids have been developed for applications that primarily involve urban driving in which vehicles typically return to central depots every day. However, PHEVs have yet to be introduced in segments such as LH tractors and coach buses, where the highway-intensive duty cycles would likely make frequent recharging less feasible given the current lack of extensive recharging infrastructure for HD PHEVs and electric vehicles.

HD Van	**Urban Bus**
 http://green.autoblog.com/2012/11/26/emerald-automotive-bright-idea-phev-delivery-van/	 bus: http://green.autoblog.com/2011/09/02/volvo-will-test-rapid-charge-plug-in-hybrid-bus-next-year/
Other Bus	**MD Urban Vehicle**
No commercial vehicles currently exist	 http://www.odyne.com/

MD Vocational Vehicle	**HD Vocational Vehicle**
 http://www.odyne.com/	 http://ev.sae.org/article/11486
LH Tractor No commercial vehicles currently exist	**SH Tractor** No commercial vehicles currently exist

Figure 2-15: Examples of HD plug-in hybrid vehicles

2.1.7 Electric Vehicles

Full electric vehicles (EVs) derive all of their energy from the electrical grid and store energy onboard via rechargeable batteries. Electricity can be transmitted to the vehicle in a number of ways and can be categorized as either conductive or inductive charging, and both of these methods can occur either while the vehicle is stationary or while the vehicle is in motion.

Conductive charging. Electricity is transmitted from the grid to the vehicle via a physical, wired connection.

- Stationary charging: Currently, this is by far the most common approach for EV recharging. Typically, there are dedicated charging locations that require the vehicle to be parked and taken out of service during the charging event.

- Dynamic (in-motion) charging: In these systems, vehicles connect and derive power from overhead catenary wires. These types of systems have been used in the transit bus sector for many decades [72], but this type of charging approach is currently in the prototype phase for other HD vehicle applications, with one proof-of-concept system currently being demonstrated in Germany [73]. In Siemens' *eHighway* project, the trucks are series hybrid-electric vehicles that have the ability to sense when catenary is overhead, connect, and then operate in full electric mode. In the absence of catenary contact, the vehicle acts as a hybrid. This type of charging approach requires significant infrastructure investments. At present, such a system is under consideration as an option for the overhaul construction of the I-710 freeway in southern California between Long Beach and central Los Angeles [74].

Inductive charging. Electricity is transmitted from the grid to the vehicle via electromagnetic fields that originate from plates that can be embedded in (or on) the road or in overhead charging stations.

- Stationary charging: To date, this type of recharging strategy has been limited to transit buses. The highly repetitive nature of transit service is amenable to this type of system where the vehicle repowers during scheduled downtime while in service. For example, the Proterra Ecoliner electric bus is designed to quickly recharge in less than 10 minutes in the layover time between routes by parking under an overhead charging bay [75].
- Dynamic charging allows the battery of the electric vehicle to be charged while driving over these electrified sections of the road. As with stationary inductive charging, the electrification of roadways is primarily in the demonstration phase for

niche transit applications. For example, recently, Bombardier conducted a pilot project to test dynamic inductive charging for a Van Hool transit bus [76].

For EVs that charge while stationary, all of the vehicle's energy demands during operation must be met solely by the batteries, the therefore battery packs must typically be much larger than that of a charge-sustaining hybrid or a PHEV if the electric vehicle is to provide comparable driving range. Current batteries in electric trucks and bus models are typically able to provide between 50 and 100 miles of driving on a single charge. As such, to date the commercial EV market has mainly been limited to urban applications such as parcel delivery and transit service. Some examples of commercially available HD EVs are shown in Figure 2-16.

Batteries are a critical technology for hybrids, plug-in hybrids, and electric vehicles, and there are a number of different chemistries and technologies available. Choice of battery technology depends on a multitude of factors, including vehicle size and weight, degree of electrification, power and energy requirements, cycle and calendar life, and cost [77]. Within the vehicle sector, there are three predominant battery technologies: lead acid, nickel metal hydride (NiMH), and lithium ion (Li-Ion). Each of these battery technologies has advantages and disadvantages, which are summarized at a high level in Table 2-2. Lead acid batteries are generally attractive for their low costs, but they are inferior in terms of energy density and overall weight. NiMH batteries have good power and energy density but are generally surpassed by Li-Ion for these attributes. Given the superior energy and power density of Li-Ion technologies, Li-Ion are generally expected to the battery technology of choice for light- and HD hybrid and electric vehicles for the foreseeable future [78].

Table 2-2: Qualitative comparison of battery technologies (adapted from Slide 15 in [77]; green = good, yellow = fair, red = poor)

Attribute	Lead Acid	Nickel Metal Hydride	Lithium Ion
Energy density (kWh/kg)			
Discharge power (kW)			
Cold temperature performance			
Deep cycle life (number)			
Calendar life (years)			
Maturity			

As with hybrids and PHEVs, battery costs continue to be the predominant factor behind the large incremental cost of electric vehicles. In recent years as production volumes in both the light- and HD vehicle markets have grown, Li-Ion battery costs have steadily declined [78, 79]. In a series of in-depth interviews with battery suppliers, vehicle OEMs, end-users, and other stakeholders, CalStart found that, on average, respondents expect battery costs for HD vehicles to be roughly cut in half between 2015 and 2025—from $500-600/kwh to $300/kWh [79].

There are many other challenges to increased electric vehicle adoption identified in the CalStart report. Top concerns include high incremental costs; lack of sufficient vehicle quality, warranty, and service availability; lack of performance data to validate the reliability and business case; and unclear expectations about infrastructure requirements [ibid].

HD Pickup Truck	**Urban Bus**
	
http://news.pickuptrucks.com/2011/12/electric-pickup-truck-to-debut-at-2012-detroit-auto-show.html	www.proterra.com

Other Bus  http://www.motivps.com	**MD Urban Vehicle**  http://www.greencarreports.com/news/1043872_fedex-launches-all-electric-trucks-for-urban-parcel-delivery
MD Vocational Vehicle  http://www.government-fleet.com/channel/green-fleet/news/story/2009/06/pg-e-to-test-first-sev-all-electric-utility-truck.aspx	**HD Vocational Vehicle**  http://www.fleetsandfuels.com/fuels/evs/2013/03/motiv-names-chicago-partners/
LH Tractor No commercial vehicles currently exist	**SH Tractor**  http://electriccarsreport.com/2012/05/balqon-introduces-zero-emissions-mx30-electric-tractor/

Figure 2-16: Examples of HD electric vehicles

Table 2-3: Continuum of vehicle electrification (adapted from [70])

	Start/Stop	**Mild Hybrid**	**Full Hybrid**	**PHEV**	**EV**
Features	• Engine start/stop at idle	• Engine off at deceleration and stops • Mild regenerative braking • Mild electric power assist	• Full regenerative braking • Electric launch • Engine cycle optimization • Engine downsizing	• Same as full hybrid plus: • Use of grid electricity during charge depleting mode • Pure electric range during charge depleting mode (range extender only)	• Full electric drive • Full regenerati ve braking
ICE Fuel Savings	2-4%	10-15%	20-35%	• 40-60% in charge depleting mode • 20-35% in charge sustaining mode • No ICE fuel consumed in charge depleting mode (range extender only)	• No ICE fuel consumed

Table 2-4: Commercial status of different hybrid vehicle architectures (adapted from Table 4-5 of [36])

Architecture	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Voc.	HD Voc.	LH Tractor	SH Tractor
Parallel HEV	Yellow	Green	Green *	Green	Green	Green	Yellow	Green
Parallel HEV w/ ePTO	Red	Red	Red	Red	Green	Green	Red	Red
Parallel hydraulic hybrid (HHV)	Red	Red	Red	Green	Red	Green	Red	Red
Series HEV	Red	Green	Red	Red	Red	Red	Red	Red
Series HHV	Red	Red	Red	Yellow	Red	Yellow	Red	Red
Series-Parallel HEV	Yellow	Red	Red	Red	Red	Red	Yellow	Red

Green shading = currently available commercially; yellow = prototype or pre-commercial phase; red = unfavorable application or no models currently under development

* Limited development underway in the coach bus market; hybrids are currently available in the school and shuttle bus market.

2.1.8 Hydrogen Fuel Cell Vehicles

In a hydrogen fuel cell, electricity is generated when hydrogen and oxygen are converted into water. To date, commercial use of hydrogen fuel cells in HD vehicles has been primarily limited to the transit bus industry. A number of different design configurations have been used, including hydrogen in internal combustions engines, and various fuel cell technologies. In addition, fuel cell buses have been designed in both non-hybrid and hybrid-electric configurations. Just as when hybrid components are combined with an internal combustion engine, the hybrid system in a FCV reduces peak loads on the primary power pack (i.e. the fuel cell) and allows for energy recuperation through regenerative braking. Over time, fuel cell bus manufacturers have gravitated to hybrid designs [80]. Similar to the continuum shown in **Error! Reference source not found.**, hybridized fuel cell systems offer trade-offs between energy storage capacity and fuel cell power output, allowing a range of different configurations. For example, at one end of the spectrum, there are fuel cell-dominant designs that rely heavily on the fuel cell for motive power, and the energy storage system makes a relatively minor power contribution. Conversely, in range-extender type designs, the vehicle primarily operates as a battery electric vehicle, and the primary function of the fuel cell is to replenish the energy storage system after the battery pack has dropped below a set state-of-charge.

Similar to electric vehicles, some of the most important hurdles to increased FCV adoption and the development of products across more HD vehicle categories include high capital costs, inferior reliability and durability as compared to conventional vehicles, and lack of widespread maintenance and support infrastructure. Still, hydrogen buses have evolved substantially in the last two decades in terms of performance, reliability, durability, and costs. Though continued improvements are needed for hydrogen fuel cell buses to truly compete with their diesel counterparts, the latest generation of fuel cell systems are smaller and lighter, yield improved fuel efficiency performance and up-time, and their costs have decreased by a factor of four in the past 5 years [81].

As of this writing, the only non-transit bus commercial example of a HD fuel cell vehicle is the Vision Tyrano tractor truck, which first went into revenue service in southern California in 2011 in regionally-based drayage operations [82]. In May 2012, Vision reached a procurement agreement with Total Transportation Services, Inc. to deliver 100 Tyrano trucks [83].

<table>
<tr>
<td>HD Pickup Truck

http://editorial.autos.msn.com/article.aspx?cp-documentid=435410</td>
<td>Urban Bus


http://www.isecorp.com/gallery/album02/AC_Fuel_Cell_Bus_001</td>
</tr>
<tr>
<td>Other Bus
No commercial vehicles currently exist</td>
<td>MD Urban Vehicle


http://www.greencarcongress.com/2005/05/purolator_intro.html</td>
</tr>
<tr>
<td>MD Vocational Vehicle
No commercial vehicles currently exist</td>
<td>HD Vocational Vehicle
No commercial vehicles currently exist</td>
</tr>
</table>

LH Tractor	SH Tractor
No commercial vehicles currently exist	 http://www.fuelcelltoday.com/news-events/news-archive/2012/october/us-doe-to-potentially-co-fund-20-tyrano-fuel-cell-trucks-in-texas

Figure 2-17: Examples of HD hydrogen fuel cell vehicles

2.2 Technologies for Increasing Fuel Efficiency

Over the course of most of the last century and in recent years, there has been a tremendous amount of technology advancement that has resulted in more efficient goods and passenger movement from HD vehicles. These technology improvements over time have occurred in virtually every possible area of vehicle design and construction.

Looking to the future, there is a great deal of work across industry, academia, and government to continuously seek out technology improvements that lead to increased efficiency. Over the past three years, there have been a number of studies that have assessed the technology potential of commercial vehicles out to the 2015 to 2020 timeframe. For the North American HD vehicle market, a National Academy of Sciences (NAS) panel performed the most recent comprehensive literature review of technology potential and costs [36]. In 2007, as part of the Energy Independence and Security Act, Congress charged the NAS panel with conducting a technology assessment for commercial truck and buses. This NAS report that was published in early 2010 formed the technical basis for much of the EPA/NHTSA rulemaking that was finalized in the fall of 2011 to target GHGs and fuel consumption from HD vehicles.

At present there are no comprehensive technology and cost assessments such as the NAS study that look beyond 2020, but there is research currently underway that will likely extend to the 2025 to 2030 timeframe.

This section begins by giving a brief overview of energy balances for some example HD vehicles and then summarizes the key technology developments that are expected over the next decade in the following broad areas: engines, transmissions and drivelines, aerodynamics, tires, weight reduction, and vehicle informatics.

2.2.1 Energy Balances and Areas for Increased Efficiency

In simple terms, a vehicle transforms chemical energy into rotational mechanical energy that is used to move the vehicle over the road or power auxiliary equipment. There are numerous inherent losses that occur during vehicle operation due to unavoidable phenomenon such as aerodynamic drag, rolling resistance, and mechanical friction. In the HD sector, these losses manifest in a number of different ways based on the great deal of variety of vehicle sizes, configuration, and duty cycles. Some examples of how losses can differ based on vehicle type are depicted in Figure 2-18, Figure 2-19, and Figure 2-20, which show the percentage contribution to total losses for the following areas: engine, transmission and drivetrain, auxiliaries, aerodynamics, and rolling resistance. As shown in these figures, loss breakdowns in each of the five areas are generally different for the three vehicle types, with the exception being engines, which are responsible for roughly 60% of total losses in each example. Looking at non-engine areas, aerodynamic losses are the biggest energy consumer for a tractor traveling at highway speeds, whereas, in a city delivery truck, rolling resistance is generally the largest loss category. For transit buses, the loss profile is much different, with auxiliaries being responsible for the majority of non-engine energy consumption, while aerodynamic and rolling resistance losses are relatively minor.

Just as the energy loss profiles vary greatly based on vehicle type, size, and duty cycle, the efficacy of technologies for reducing fuel consumption depends on this same set of factors. For instance, a tractor-trailer operating primarily at highway speeds benefits from technologies that improve aerodynamic performance and reduce rolling resistance, whereas a transit bus operating city routes in stop-and-go driving will likely benefit much less from these technologies.

In the NAS study, a thorough examination of the various characteristics and operating patterns of the different HD vehicle categories revealed that there is substantial potential for technology to play a prominent role in fuel use and GHG reductions across the entire fleet. One of the important findings of the NAS study is how technology potential differs amongst the seven HD vehicle categories that were developed for the analysis. As shown in Figure 2-21, the per-vehicle technology potential for fuel consumption reductions ranges from roughly 30 to 50% depending on the vehicle category. This figure shows that the percentage contribution from each of the six[7] technology areas is fairly different between the seven vehicle types.

[7] In the NAS study, the efficacy of driver management and coaching is only explored for the tractor category.

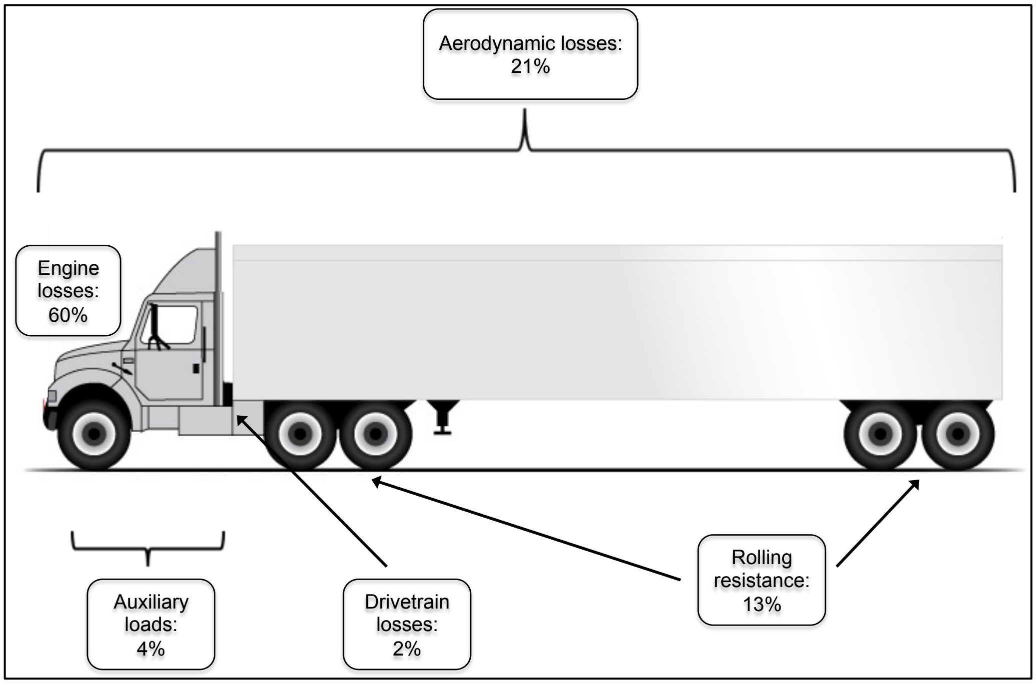


Figure 2-18: Example energy audit of a fully loaded (80,000 lbs. GVWR) tractor-trailer traveling at 65 mph (created using data from Table 3.1 in [84])

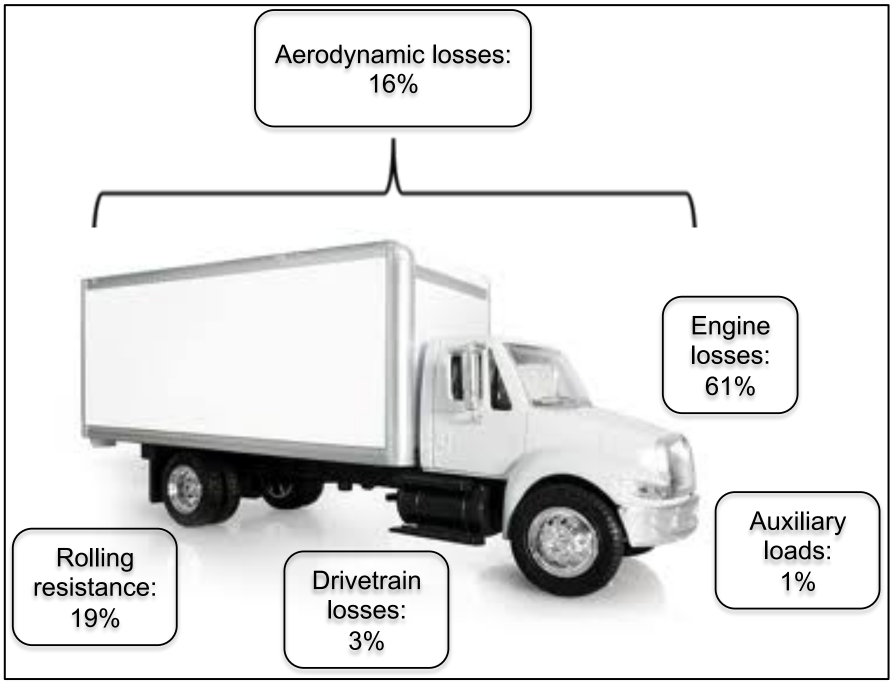


Figure 2-19: Example energy audit for a fully loaded (26,000 lbs. GVWR) MD truck vehicle operating on a level road at 40 miles per hour for 1 hour (created using data from Table 2-4 in [85])

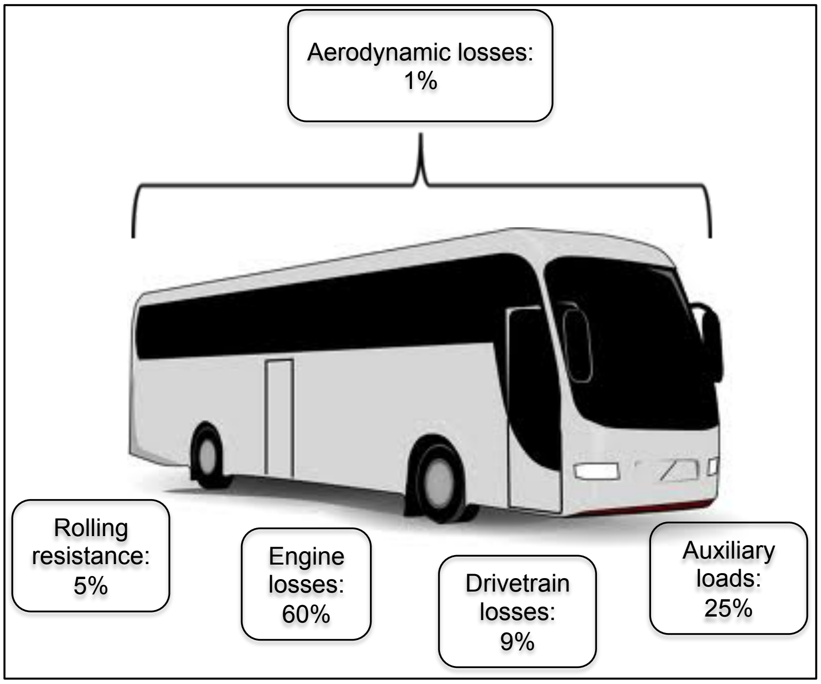


Figure 2-20: Example energy audit for half-seated 40-foot transit bus (32,000 lbs. GVWR) with air conditioning operating over the Central Business District cycle for 1 hour (created using data from Table 2-5 in [85])

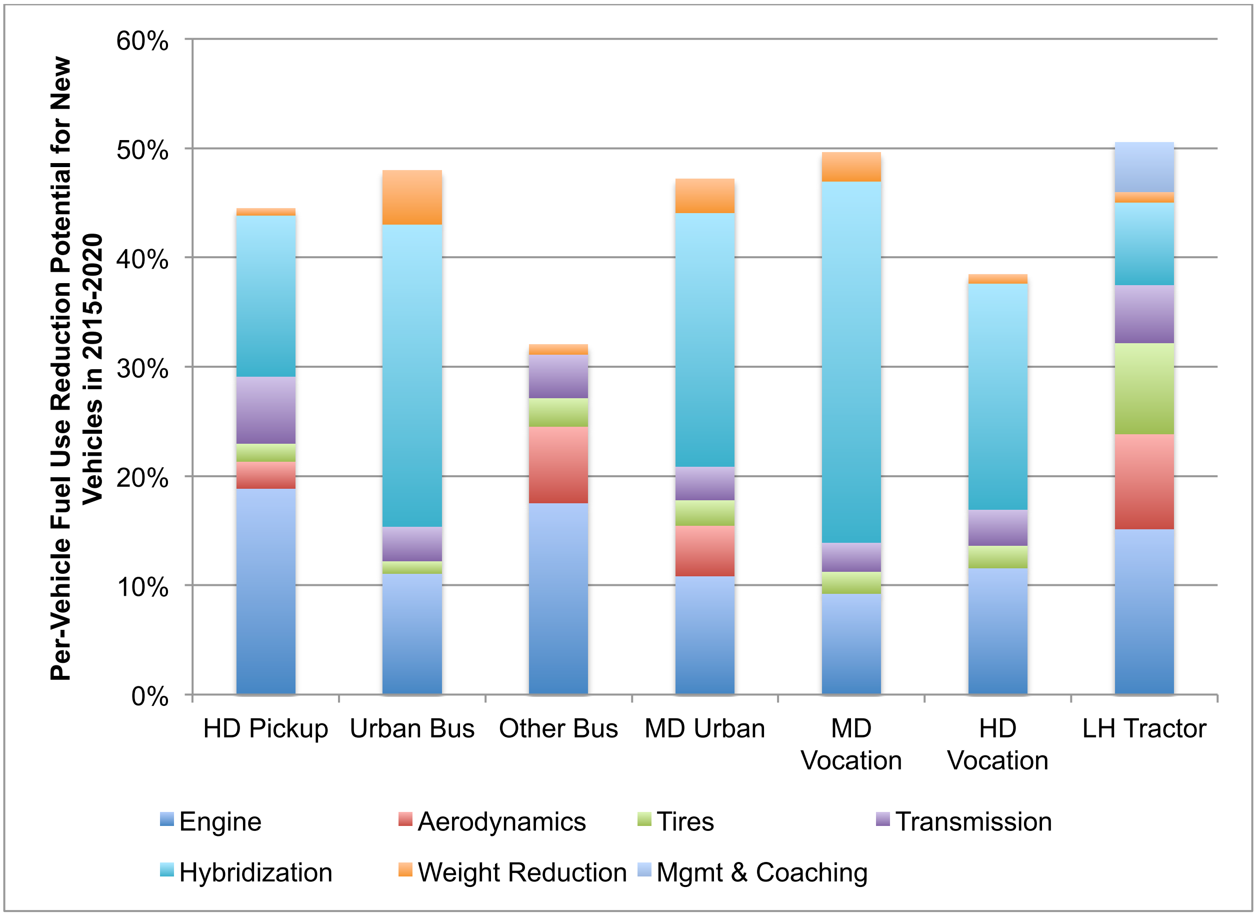


Figure 2-21: Per-vehicle fuel consumption reduction potential in 2015-2020 (created using data from [36])

2.2.2 Engine

As shown in the energy balance figures above, engine losses dominate, representing roughly three-fifths of the total losses for each of the vehicle types. An approximate energy balance breakdown for a typical modern engine is shown in Figure 2-22.

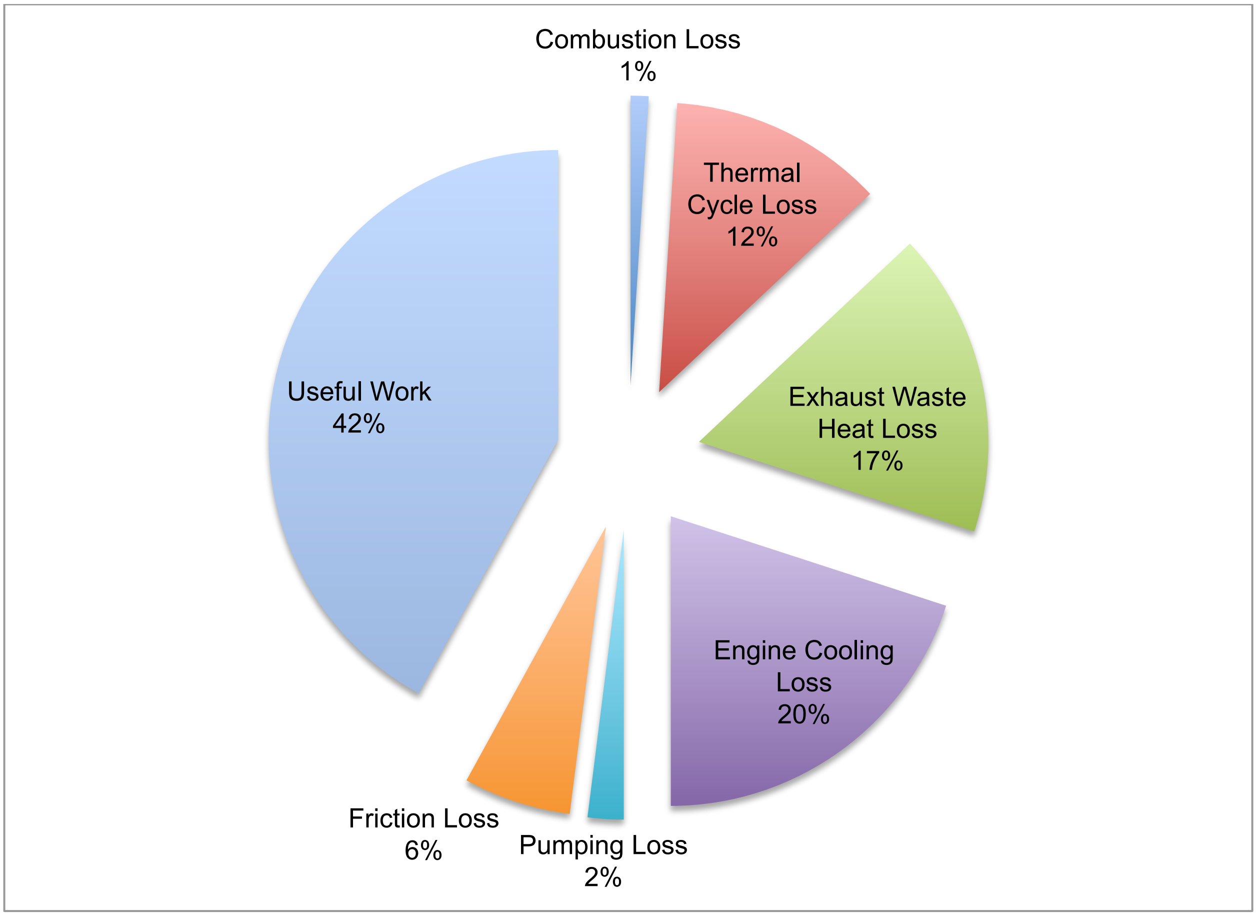


Figure 2-22: Example energy audit for a typical modern diesel engine (adapted from [86])

There are continuous efforts to reduce losses in each of these areas, and some of the fuel-saving technologies and strategies that are currently in production or are soon to be introduced for diesel engines include:

- Enhanced combustion, increased engine-out NOx levels for higher thermal efficiency
- Improved SCR and DPF aftertreatment systems
- Reduced friction via advanced materials and coatings
- Advanced turbocharging
- Reduced parasitics
- Increased engine pressures

- Engine down-speeding
- Waste heat recover systems (turbocompounding, bottoming cycles)

2.2.3 Transmission and Driveline

The transmission and driveline system connect the power pack to the vehicle wheels. As shown in the energy balance figures, losses across the transmission and driveline are relative minor and are generally largest for vehicles such as transit buses that have highly transient driving behavior [85]. Across the HD vehicle sector, there are technology advancements in transmissions aimed at increasing efficiency and improving overall powertrain integration so that the engine can run at more efficient operating points for a higher percentage of the time. Often, increasing overall powertrain efficiency can be as straightforward as having better matching of the transmission gearing and axle ratios to the vehicle's size and duty cycle. However, in addition to developing a proper specification (or "spec") for a vehicle in terms of transmission gearing and axle ratios, there are technology options for transmissions that may lead to increased efficiency.

In the commercial vehicle market, there are three primary types of transmissions, and each has its advantages and disadvantages, which are summarized in Table 2-5. Transmissions at the lighter end of HD spectrum (i.e. Class 3 through 7) typically have between 5 and 8 speeds, whereas the heaviest trucks generally have transmissions with between 9 and 18 speeds. Overall, manual transmissions (MTs) are the most common type of transmission in the HD vehicle sector, making up roughly two-thirds of the total market [36]. In LH trucking, their share is even higher at roughly 80% of the market [ibid]. With a MT, the driver engages the clutch foot-pedal and physical changes gears with the stick shift in order to regulate torque transfer from the engine to the transmission. Automated manual transmissions (AMTs) are based on the platform of the MT, but there are additional actuators and controls that allow the transmission control module to take over the shift activities from the driver. AMTs represent approximately 20% of the LH trucking sector and 10% of the remaining HD vehicle types [ibid]. As opposed to a MT or AMT, where different sets of gears are locked and unlocked to produce various gear ratios, in an automatic transmission (AT), the same sets of gears achieve all of the gear ratios using a planetary gearset. Fully ATs are most popular in urban applications such as transit busing and refuse hauling, where they have nearly a quarter of the market [ibid].

Table 2-5: Comparison of transmission types used in HD vehicles and impacts on fuel consumption (FC)

Transmission Type	Advantages	Disadvantages
Manual Transmission (MT)	• Least mechanical losses	• More work for the driver • Driver-to-driver FC variability is largest for MTs
Automated Manual Transmission (AMT)	• Reduces driver variability • Less driver distraction • Smoother shifts • FC improvements vs. MTs for average drivers	• Higher complexity and cost • Slight weight increase • Best drivers can out-perform AMTs in FC
Automatic Transmission (AT)	• Same as the AMT plus: • Ability to complete upshifts under full engine power	• Much higher complexity and cost, shorter warranty periods • Higher parasitic losses

2.2.4 Aerodynamics

As with any physical body moving through the air, vehicle motion displaces air, thus creating pressure forces at the front of the vehicle and shear forces on the sides that are parallel to the air flow. The net pressure force on a vehicle is customarily approximated as being proportional to the square of the velocity:

$$F = 0.5C_dAV^2$$

where A is the frontal area of the vehicle, V is the velocity, and C_d is a drag coefficient, which is empirically defined by this equation. Aerodynamic drag forces increase with the square of velocity, so vehicles such as LH tractors that spend a large percentage of time at highway speeds are subject to much larger aerodynamic burden than vehicles that have lower average speeds. As such, compared to other HD vehicle applications, there is a great deal of effort focused on improving the aerodynamic performance of LH tractor-trailers.

As shown in Figure 2-23, the total air resistance over the tractor-trailer is roughly split evenly between the front of the tractor, the gap between the tractor and trailer, the side and underbody of the tractor-trailer, and the back of the trailer [87]. For each of these four areas, there has been an increasing amount of effort over the past decade to reduce drag and increase overall vehicle fuel efficiency. For tractors, manufacturers have made great strides to smooth the vehicle profile and avoid protruding features such as exhaust stacks and air cleaners. An example of a tractor with superior aerodynamic performance versus a conventional (or "classic") tractor is shown in Figure 2-24 and Figure 2-25. In addition, both trailer OEMs and a many after-market component manufacturers have developed a number of different technologies to reduce drag. Some examples of these devices are shown in Figure 2-26. Altogether, aerodynamic tractors and trailer technologies are currently available that can provide combined fuel consumption benefits of 10% or more, depending on payload and operating characteristics [36, 85, 88].

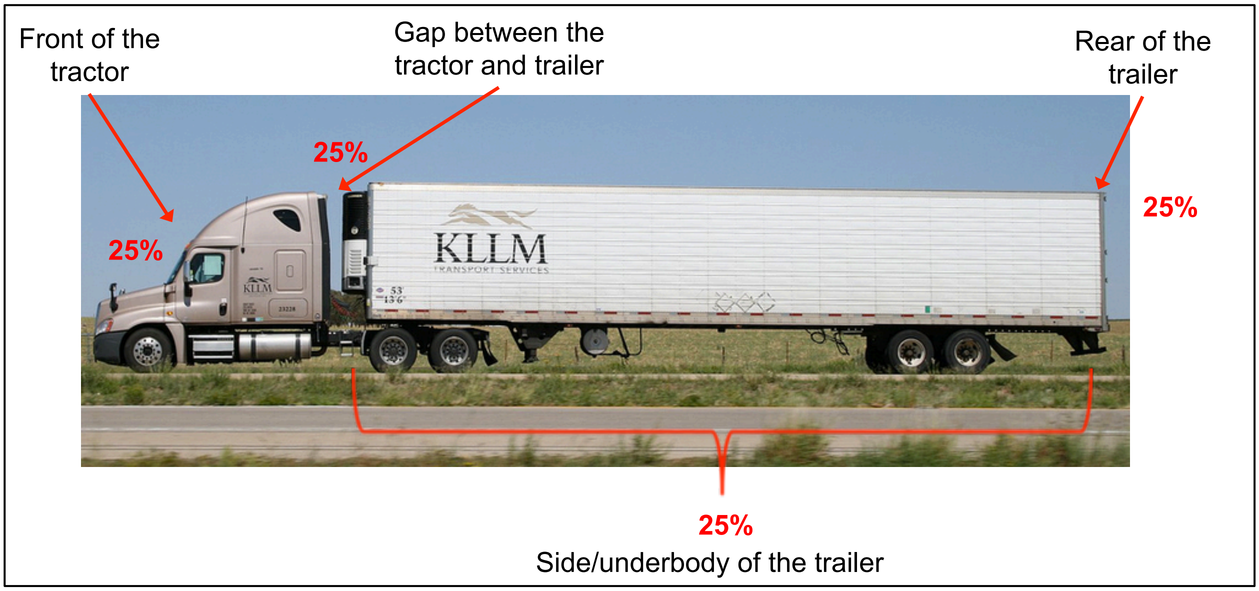


Figure 2-23: Four primary areas of aerodynamic drag on a tractor-trailer (adapted from [87])

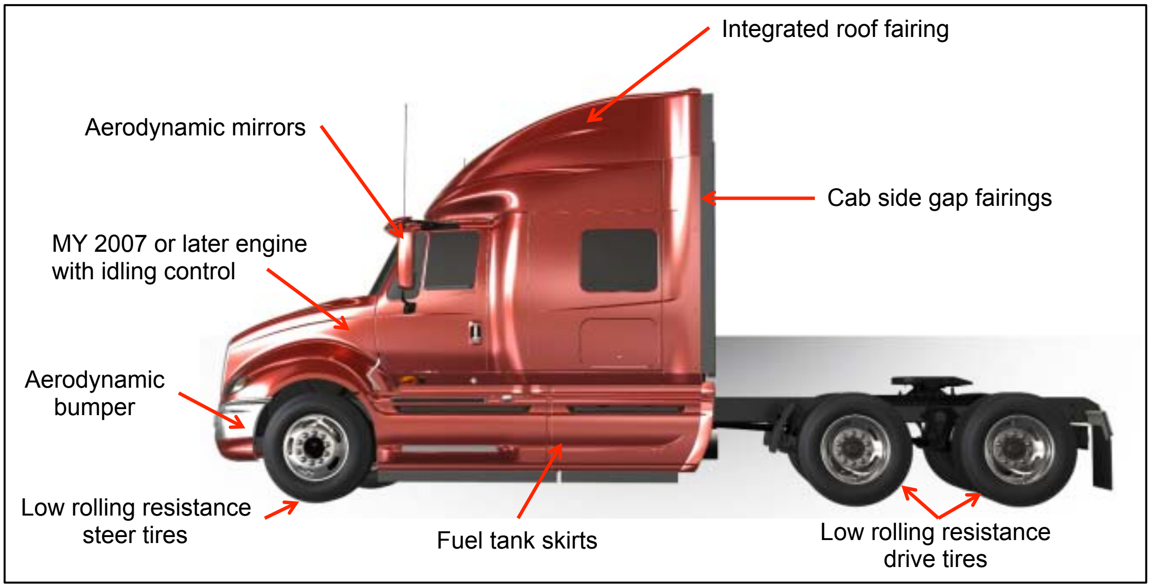


Figure 2-24: Example of a tractor with aerodynamic features[8]

[8] Image of Navistar Prostar tractor from www.internationaltrucks.com

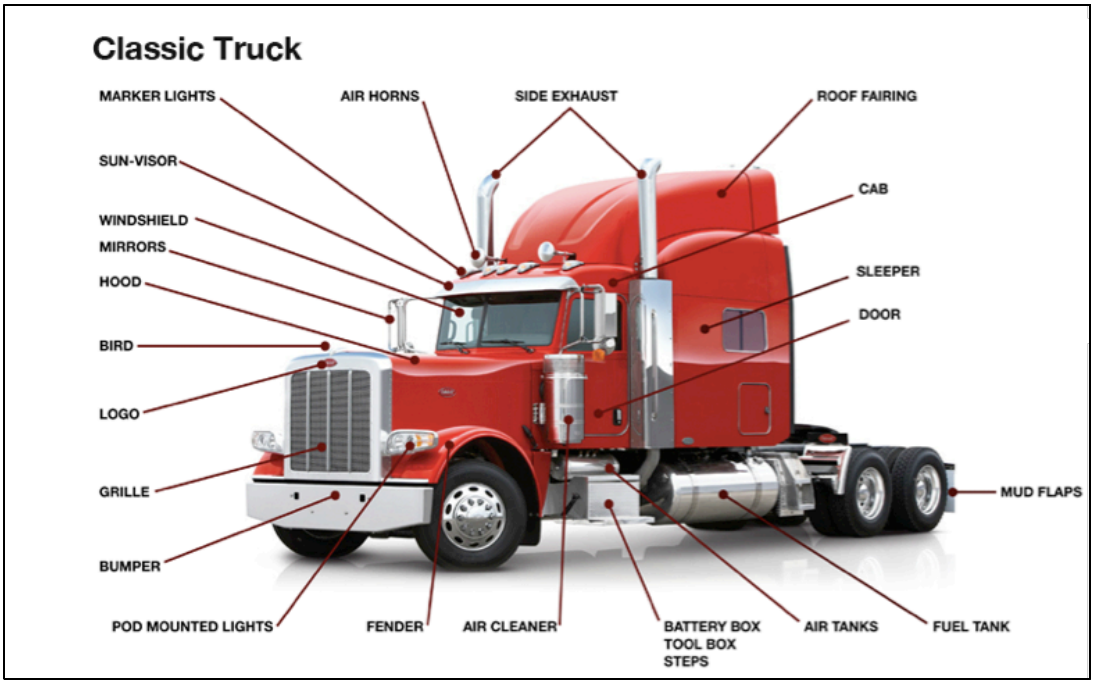


Figure 2-25: Example of a conventional or “classic” tractor[9]

[9] Image of a “classic” Peterbilt tractor from https://forge.localmotors.com/pages/competition.php?co=68&tab=design-brief

Gap Reducer	**Trailer Side Skirt**
 http://freightwing.com/gap_fairing.php	 http://www.silvereaglemfg.com/aero/overview.shtml
Trailer Underbody Device	**Trailer Boat Tail**
 http://smarttrucksystems.com/undertray.php	 http://www.atdynamics.com/trailertail.htm

Figure 2-26: Examples of trailer aerodynamic devices

2.2.5 Rolling Resistance

Rolling resistance forces develop as a tires move over the road surface. The drag force resisting a rolling tire is primarily caused by the constant deformation of the tire when rolling and the shear and compressive forces at the contact surface. Rolling resistance is a function of a number of factors, including tire pressure, tire and surface material, the elasticity of the tire and road surface, speed, and the load on the tire [89]. Rolling resistance forces are greater than aerodynamic forces at lower speeds, and the opposite is true at higher speeds. In describing how the forces present on a tractor-trailer are a function of vehicle speed, Tanguay [90] presents an example in which the rolling resistance forces dominate until roughly 90 km/hr. (~ 55 mph), and at higher speeds, aerodynamic drag is the largest force. As shown in Figure 2-27 [ibid], there is a linear relationship between rolling resistance and velocity, whereas aerodynamic forces grow exponentially with increased velocity.

Lowering the rolling resistance of tires through improved design and inflation reduces the power required to move the truck down the road, directly reducing fuel consumption and GHG emissions. Another development in tire technology for reducing rolling resistance is the wide-base (or single-wide) tire. One wide-base tire takes the place of two conventional dual tires. Not only do wide-base tires reduce rolling resistance, but they offer weight savings as well. In addition, automatic tire inflation and air pressure monitoring systems can also lower the rolling resistance by helping vehicle operators maintain optimum tire pressure. One of the potential downsides of reduced rolling resistance that must be balanced in tire design is the reduced traction and braking performance that is associated with lowering rolling resistance.

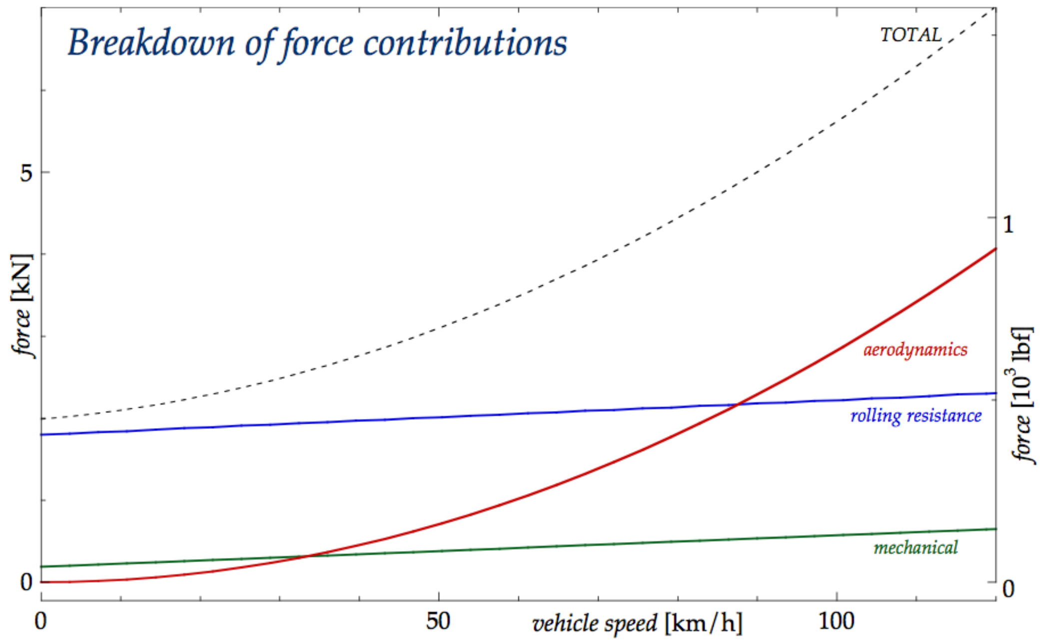


Figure 2-27: Drag forces as a function of vehicle speed for a tractor-trailer (Slide 23 in [90])

2.2.6 Weight Reduction

Decreasing the curb (or empty) weight of a vehicle improves fuel efficiency by reducing the rolling resistance as well as the power required to accelerate and climb grades. In addition, for HD vehicles that operate at maximum payload (i.e. at the gross vehicle weight rating, GVWR), a lighter curb weight allows the vehicle to carry more payload, which increases the freight efficiency of the vehicle (e.g. gallons/payload-ton-mile).

Manufacturers can reduce vehicle weight by introducing lightweight materials such as high-strength steel, aluminum, or composites or eliminating components. The use of wide-base tires is one such example, as the need for two wheels is eliminated, and the wide-base single tire is lighter than the combined weight of two conventional duals. Another component-eliminating example is the 6x2 axle configuration in which a tractor truck has one drive axle instead of two. For both the wide-base tire and 6x2 axle examples, there are potential downsides such as lack of redundancy and reduced traction that must be taken into consideration in the vehicle specification process.

2.2.7 Driver Training and Intelligent Vehicle Systems

Perhaps more so than any one particular technology, a driver's behavior can have a substantial impact on fuel efficiency performance. A main thrust of much of the research and development for commercial vehicles in recent years has been aimed at minimizing driver-to-driver variability and optimizing the vehicle's performance in terms of routing and situation adaptability.

The difference in fuel consumption from a fuel-conscious driver to a very aggressive driver can be significant. Driver training can be a cost-effective tool for increasing fuel efficiency, lowering operating costs, and fostering driver skills. These skills courses can be attractive in terms of their minimal capital requirements and immediate impact on driver behavior. Empirical studies have found that typical fuel savings following a driver training program are on the order of 2 to 4 percent [91, 92]. However, even amongst "good" drivers, variation can be fairly substantial. In a US Department of Transportation-funded project, Con-Way, a large trucking company and logistics provider, tested its most fuel efficient drivers in identical vehicles with manual transmissions for 10 months on highly repetitive routes. The variation between the highest and lowest fuel economy results was up to 30% [93].

In addition to driver training programs, there are a number of technologies currently available and under development for promoting *eco-driving* and/or reducing the ill-effects of poor driving. One strategy for motivating fuel-conscious driving is installing displays that provide drivers with real-time feedback about their fuel efficiency performance. Some companies are taking data from these monitoring devices and linking bonuses and incentives to a driver's fuel efficiency performance [94]. Some devices go a step further and actually limit a vehicle's top speed or acceleration rate. In addition, as discussed in Section 2.2.3, choice of transmission type can also reduce driver variability, as automated-manual and automatic transmissions take the shifting responsibility away from the driver.

Moreover, *intelligent* vehicle technologies can increase efficiency by combining information about the state of the vehicle and environmental conditions, and this information can be provided to the driver and/or used by the vehicle control systems to optimize performance. Global Positioning System (GPS) technology has been a significant enabler for these types of technologies, which include:

- Dynamic routing software
- Adaptive and predictive cruise control
- Look-ahead powertrain management

2.2.8 Costs

Up-front capital costs are a critical factor in the decision to adopt a particular technology or set of technologies. There are many factors that influence the decision to adopt a particular technology, but, typically, HD vehicle owners and operators chose to invest if there is a firm expectation that the technology will yield a return on investment in the form of fuel savings. The additional costs posed by fuel-saving technologies can vary wildly—from a few dollars to many thousands of dollars. The expected fuel savings of a given technology or technology package may or may not be related to the magnitude of its cost. This is evidenced in Figure 2-28, which summarizes the cost and fuel consumption reduction benefits of the technology packages analyzed in the NAS study for the following vehicle areas: engines, aerodynamics, tires, transmissions, hybridization, and weight reduction.

In the figure, the y-axis is the ratio of the percent fuel consumption reduction to the percent increase in vehicle cost: the larger the value, the more cost-effective the technology or technology package. A value of '5' implies that if a technology increases the total vehicle cost by 1 percent, the estimated fuel savings would be 5%. These point values do not necessary imply that all technologies for that vehicle system are at the same level of cost-effectiveness. For example, while low rolling resistance and wide-base singe tires have a very low additional cost and yield fairly sizeable fuel savings, the same is not necessary true for other tire-related interventions such as automatic tire inflation systems.

On average, across all of the vehicle types, low rolling resistance (LRR) tires clearly represent the biggest savings at the lowest cost. Engine, aerodynamics, and transmission improvements are in the next tier of cost-effectiveness, and the least cost-effective technology packages are hybridization and weight reduction.

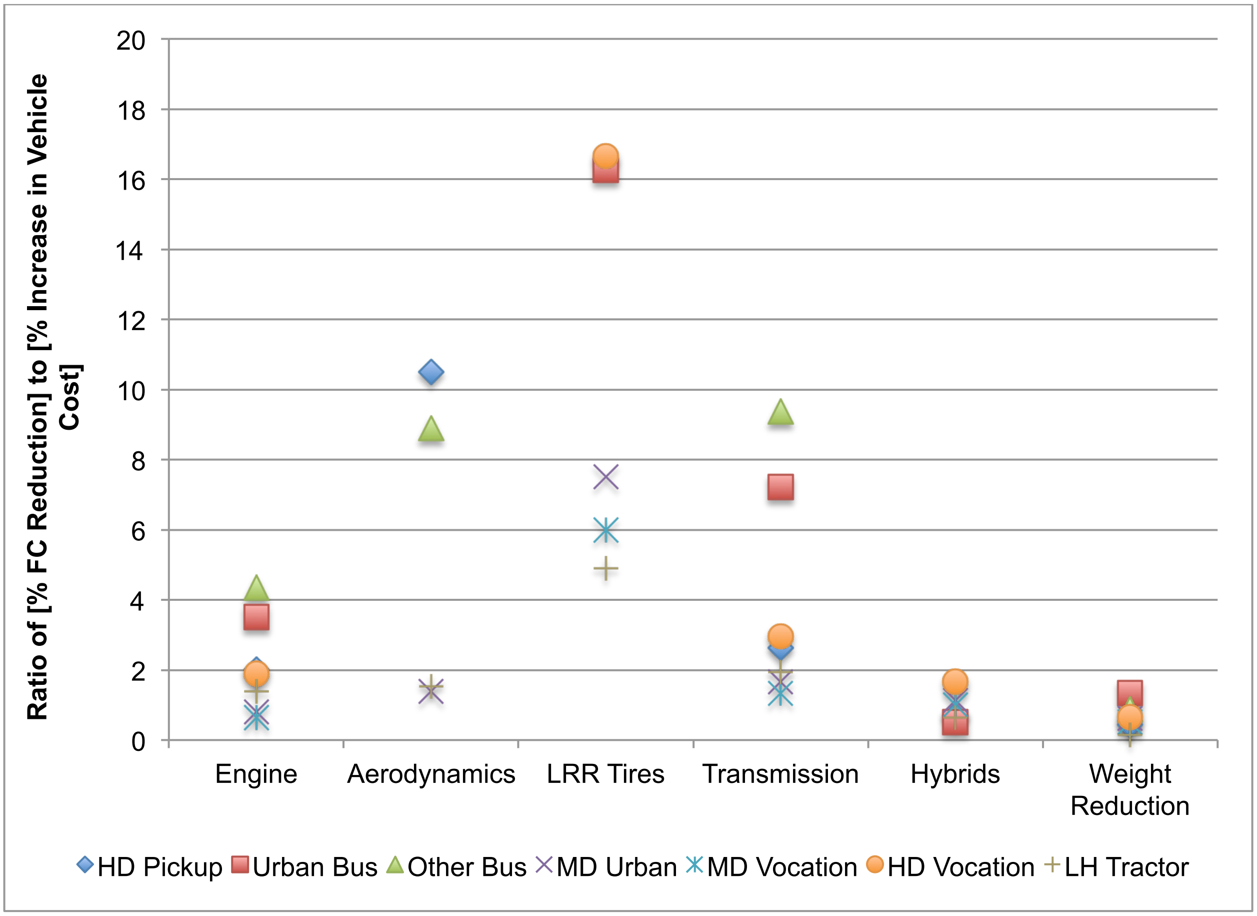


Figure 2-28: Ratio of percent fuel consumption reduction to percent increase in vehicle cost for different technology areas and HD vehicle types (created using 2015 to 2020 technology potential and cost estimates in Chapter 6 in [36])

2.3 Long-term Technology and GHG Inventory Studies of HD Vehicles in California

The aggressive GHG targets and mitigation plans set forth by the state of California have motivated a number of studies examining fuel and technology scenarios for the transportation sector. To date, there have been three published studies that have examined long-term transformation scenarios for the HD vehicle fleet in California.

The first study was conducted by the ARB [2]. The *Vision for Clean Air* report is part of the ARB's ongoing assessment of coordinated strategies to achieve state air quality and climate goals. As part of the state's mission to reach the climate mandates in the Global Warming Solutions Act (AB 32) as well as reduce criteria pollutants emissions enough to meet the federal ozone standards over the next two decades, the planning and action plan outlined in the Vision report touches all sectors of the economy, including HD freight and passenger transportation.

The key GHG-related assumptions for HD vehicle fuel and technology transformations are summarized in Table 2-6. The ARB examined four levers for GHG abatement: 1) vehicle efficiency gains, 2) fuel decarbonization through the increasing use of low-carbon diesel substitutes, 3) wide-spread advanced technology adoption, and 4) infrastructure and operational improvements.

Figure 2-29 shows the GHG impact of each of these measures as well as the effect of combining measures. In the figure, each bar represents GHG emissions of that scenario as compared to 2010 levels. Business-as-usual (BAU) emissions in 2050 are estimated to be 73% higher than 2010 emissions, which is more than 10 times higher than the 2050 target for the HD sector (i.e. 85% lower than 2010 levels, which is equivalent to 80% lower than 1990 levels). Of the four individual GHG mitigation measures, biofuels and advanced technology adoption provide the largest benefit in 2050, roughly 90% and 70% reductions respectively versus BAU levels. ARB staff estimates very large benefits from low-carbon, low-impact diesel drop-in fuels—primarily Fischer-Tropsch diesel made from forest residue or municipal solid waste. For the advanced technology scenario, full electric and hydrogen fuel cell vehicles are assumed to make up roughly 90% of vehicle sales by 2050, with hybrids and PHEVs representing the remaining 10%.

By itself, an approximate doubling of vehicle fuel economy over the study period is estimated to reduce GHGs by about 35% versus BAU levels in 2050, but emissions are still over 10% higher than 2010 levels in this scenario. Gains in logistical efficiency are projected to yield just over 20% in reductions in 2050, but GHGs remain 35% over 2010 levels. None of the strategies applied individually achieve all of the needed reductions. However, as shown in the second column from the right, when aggressive biofuel penetration is combined with advanced technology proliferation and increased vehicle efficiency, the total GHG reductions surpass the 2050 target. Adding operational improvements to this multi-strategy scenario results in another few percentage points of reduction.

In addition to the analyzing the GHG reductions of targeted action for HD vehicles, the Vision report also estimates emissions impacts of current programs and regulations to control HD vehicle criteria pollutants and the additional measures that are necessary to meet federal air quality standards. As described in the report, the South Coast and San Joaquin Valley air basins are the only areas in the country that are designated as being in "extreme nonattainment" of the federal ozone standard. The severity of the air quality challenges facing these areas—particularly for NOx, which is an ozone precursor—determine the degree of transformation that is required statewide. In both the South Coast and San Joaquin Valley air basins, diesel-powered trucks represent the largest share of NOx emissions [22]. Despite the suite of regulations that have been implemented to control emissions from HD vehicles statewide, ARB projections indicate that a significant amount of NOx reductions are still needed in the South Coast and San Joaquin Valley air basins. Broad deployment of zero emission and "near-zero" emission HD vehicles are required, but especially in these two regions. "Near-zero" refers to the assumed introduction of a new NOx emission standard in 2025 at 80% lower levels than the current standard of 0.2 g/hp-hr.

Even with the widespread adoption of zero and near-zero emission vehicles, the ARB estimates that NOx emissions will exceed allowable levels in 2023 and 2032, the attainment deadlines for the federal ozone standard. One of the key findings of the report is that adoption rates of advanced technology and low-emission vehicles must be more aggressive to achieve NOx targets than the adoption rates needed to reach GHG targets alone.

The second study comes from Yang et al. [95], who investigate how California can reduce GHG emissions from transportation to 80% below 1990 levels by 2050 in their *80in50* scenarios. The transport modes analyzed include light- and HD vehicles, aircraft, rail, marine, and agricultural/off-road equipment. Similar to the ARB analysis, the mitigation measures examined for trucks and buses are increased vehicle efficiency, transitions to low-carbon fuel feedstocks, and rapid introduction of hybrid, electric, and fuel cell vehicles. The study's three most aggressive scenarios lead to 80% reductions in GHGs from the transport sector as a whole as well as from HD vehicles in particular. Two of these 80in50 scenarios, the *Efficient Biofuels 80in50* and *Electric-drive 80in50*, are summarized in Table 2-6, and the third, which primarily emphasizes reducing passenger-miles traveled from automobiles and aircraft, is omitted from this comparison.

The main feature of the Efficient Biofuels 80in50 scenario is a large uptake of renewable fuels that results in an overall fuels mix that has an 85% lower carbon intensity as compared to baseline petroleum-based fuels. By 2050, this fuel feedstock transformation is coupled with an 80% increase in average fuel economy along with the complete turnover of the truck fleet to hybrids and a bus fleet consisting of 75% hybrids and 25% plug-in hybrids. These scenario results show a large reliance on fuel decarbonization to provide GHG reductions. However, compared to the ARB study, a smaller percentage of the overall GHG reductions come from transitioning to lower carbon fuels. In the ARB modeling, the lowered carbon content of biofuels results in practically all of the reductions needed in 2050, but in the Efficient Biofuels 80in50 scenario, GHG reductions are split almost evenly between fuel decarbonization and vehicle efficiency, which, in the Yang et al. analysis, includes the adoption of advanced technology vehicles.

The second scenario of interest, Electric Drive 80in50, assumes the rapid introduction of zero tailpipe emission vehicles such that by 2050 the truck fleet is comprised of 90% FCVs and 10% EVs, and the bus fleet is split evenly between these two technologies. Also, the average fuel economy for the HD fleet nearly triples over the study, primarily due to the superior efficiency of electrified drivelines. With these parameters, two-thirds of the GHG reductions of this scenario are due to increased vehicle efficiency, with the remaining third coming from the lowered carbon intensity of fuels.

The third and final study examining long-term fuel and technology transformation for HD vehicles in California comes from the CalHEAT Research Program, which is a California Energy Commission (CEC)-funded research effort led by CalStart that is tasked with developing a technology transformation roadmap for the state's commercial vehicle fleet that will ultimately inform the CEC's investment portfolio for the sector. A draft version of the CalHEAT Technology Roadmap report was released in early 2013.

Compared to the ARB and Yang et al. studies, the CalHEAT research is more detailed in terms of vehicle segmentation and breaks the HD fleet into six segments based on vehicle type, size, and vocation:

- Class 7/8 over-the-road tractors
- Class 7/8 short- and regional-haul tractors

- Class 3-8 urban trucks and buses
- Class 3-8 rural and intercity trucks and buses
- Class 3-8 worksite support trucks
- Class 2B/3 pickup trucks and vans

CalHEAT researchers developed a distinct technology evolution pathway for each of these six vehicle types. Fuels and technologies analyzed include conventional diesel and gasoline, electric and hydraulic hybrids, alternative fuel platforms (e.g. NG vehicles), hydrogen fuel cell vehicles, and electric vehicles. As of this writing, the final report is still forthcoming; however, the draft report depicts the market evolution for each of the six segments, and the overall technology breakdown of the fleet is fairly diverse, with each of the aforementioned fuels/technologies represented in 2050. Altogether, advanced vehicles make up nearly two-thirds of the total vehicle population in 2050. In addition, CalHEAT researchers assume that fuel feedstocks become increasingly low carbon. Unlike the previous two studies, which assume a fairly substantial decrease in average fuel carbon content, the carbon intensity reduction due to biofuels in the CalHEAT study climbs to 20% by 2035 and holds steady out to 2050. For hydrogen and electricity, the renewable percentage of the feedstocks grows from roughly 30% in the first half of the study period to 95% by 2050. Altogether, these vehicle and fuel transformation parameters lead to approximately a 50% cut in CO_2 emissions versus a 2010 baseline. The draft report acknowledges the gap in reaching 80% reductions in GHG emissions by 2050 versus a 1990 baseline for the on-road HD fleet.

Table 2-6: Key assumptions and results for three studies looking at long-term transformation of the HD vehicle sector [2, 4, 95, 96]

Study	Select Fuel and Technology Assumptions	Key Findings for HDV Sector
ARB's Vision for Clean Air (2012)	• By 2050 avg. fuel economy of trucks doubles • 60% of HD and 75% of MD vehicle sales are zero emission by 2050 • In the long-term, hydrogen fuel cell trucks dominate LH sector • Diesel used is 100% renewable by 2050, predominantly Fischer-Tropsch diesel from forest residue and municipal solid waste	See Figure 2-29. Combination of fuel eff. gains, biofuels, and adv. tech adoption needed to reach 2050 target.
Yang et al. (2008, 2009)	*Efficient Biofuels 80in50 scenario*. In 2050: • ~ 80% increase in avg. HDV fuel economy • 85% reduction in carbon intensity of fuels • Trucks: 100% HEV; buses: 75% HEV, 25% PHEV *Electric Drive 80in50 scenario*. In 2050: • ~ 170% increase in avg. HDV fuel economy • 77% reduction in carbon intensity of fuels • Trucks: 90% FCV, 10% EV; buses: 50% FCV, 50% EV	By 2050 both scenarios yield 80% reductions in HD sector GHG emissions vs. 1990 levels.
CalHEAT Roadmap (2012)	• By 2050, ~ 50% of HD fleet is HEV or EV, ~ 25% are HHVs, FCVs, or NGVs, and ~ 25% are conventional diesel or gasoline • Carbon intensity reduction by 2050: 20% for diesel (biofuels), 95% for H_2 and electricity	By 2050 ~ 50% reduction in CO_2 vs. 2010 levels

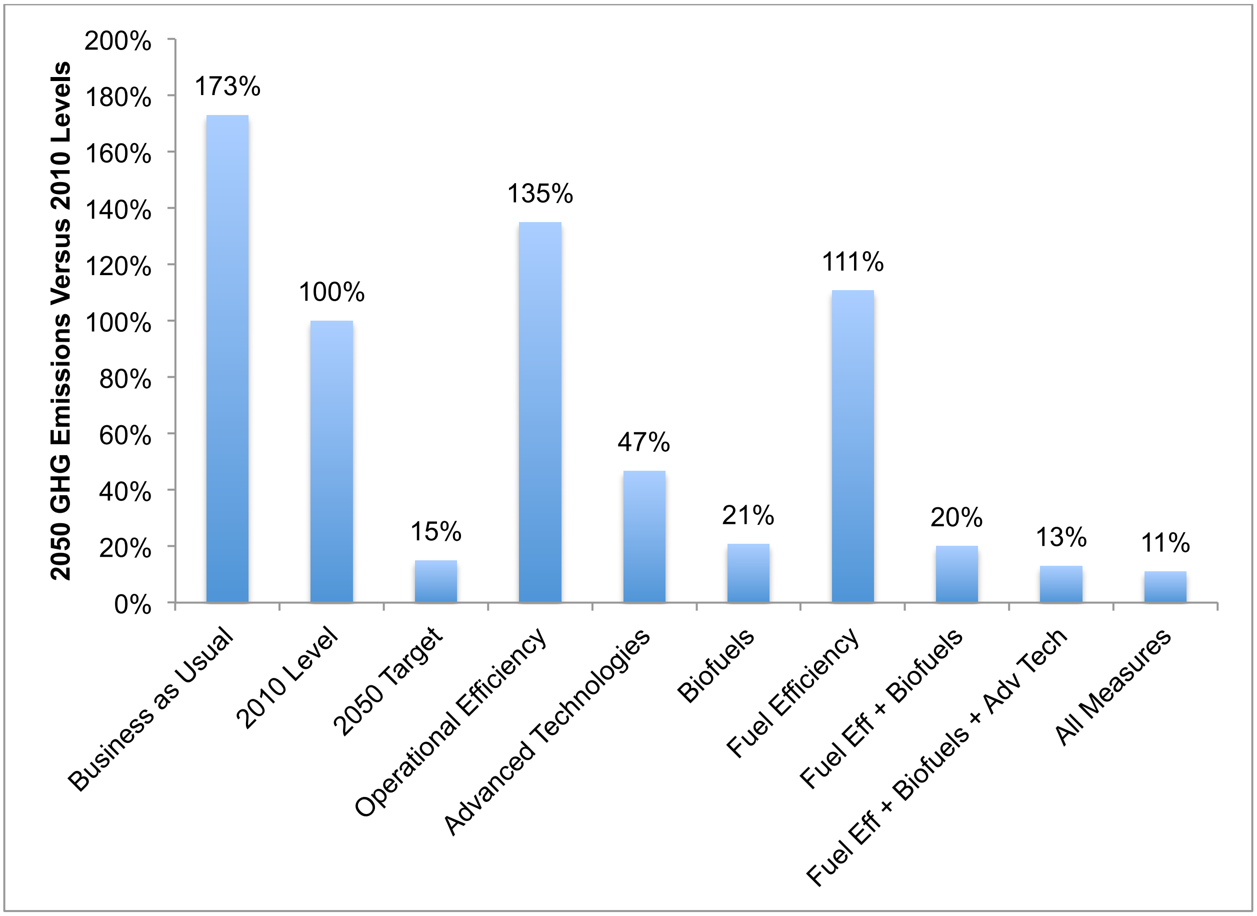


Figure 2-29: Estimated GHG results in 2050 for the HD vehicle sector from the ARB Vision for Clean Air report (created using data from Figure 19 and Table 1 in [2])

3 POLICIES AFFECTING HEAVY-DUTY VEHICLES IN CALIFORNIA

California has a long history of innovation in developing programs to improve air quality and mitigate climate change. The series of policies the state has implemented to reduce criteria pollutant and GHG emissions from HD vehicles is emblematic of the significant efforts being made across the entire transportation sector and economy as a whole and make California particularly interesting for this research, which examines future technology transformation pathways of the HD fleet.

This chapter describes the various incentive-based and mandatory regulations enacted to promote the development and deployment of technologies that reduce fuel use and emissions from the on-road HD vehicle fleet in California. The chapter begins by describing the policies enacted in California in the context of the suite of measures available to policymakers to stimulate the adoption of HD vehicle technologies to reduce emissions and fuel use. After the broader policy discussion, the chapter describes the specific incentive-based programs and regulations enacted to reduce criteria pollutant emissions from HD vehicles in California, and the final sections describe the policies implemented primarily to promote greater fuel efficiency and lower GHG emissions from commercial trucks and buses operating in the state.

3.1 Policy Options for Promoting Reduced Emissions from Heavy-Duty Vehicles

There are three general ways for curtailing criteria pollutants and/or GHGs from vehicles: 1) improving vehicle technology, 2) changing fuel feedstocks or fuel characteristics, and 3) modifying vehicle operating patterns. There are a number of different policy options that target emissions and fuel use from HD vehicles in each of these three areas, which are discussed in more detail in the following sections. After describing policy options in each of the three areas, Section 3.1.4 briefly outlines the portfolio of incentive-based and regulatory policies that have been implemented in California and at the federal level to decrease HD vehicle emissions.

3.1.1 Technology-Focused Policies

Many of the technologies for lowering criteria pollutants and/or GHGs from commercial trucks and buses are described in Chapter 2, and there are various ways that policy can encourage the adoption of these technologies in both new and in-use vehicles. In general, a policy targeting vehicle technologies typically impacts either one of two distinct sets of entities: the technology producer or the technology consumer. The former encompasses vehicle and component developers, manufacturers, and suppliers, while the latter includes any company, organization, or individual that owns or operates a vehicle. Another distinction is whether a policy is aimed at new vehicles or in-use vehicles. These two policy dimensions are summarized in Table 3-1. Each quadrant of the table has examples of incentive-based and mandatory regulations for promoting vehicle technology uptake.

Looking at the left-hand side of Table 3-1, there are a number of types of policies targeting manufacturers within the HD vehicle sector. One example of a manufacturer incentive is government funding for research, development, and demonstration. This type of financial support can aid in the development of products for both the new and in-use HD vehicle markets. Another type of incentive can exist in regulatory programs that allow manufacturers to comply based on averaging over their entire set of regulated products. In these types of regulatory compliance schemes, each product is not required to meet a designated emission (or fuel consumption) limit, but, instead, the average of all products must meet the emission standard. In regulations with this type of compliance flexibility, provisions can exist in which manufacturers can earn additional compliance credits for selling certain types of technologies. One such example is in the US fuel efficiency and GHG regulation for HD vehicles (see Section 3.3.4), where manufacturers can earn credits with a 1.5 multiplier for selling hybrids, zero emission vehicles, or engines that have a Rankine cycle waste heat recovery system.

In addition to incentives, manufacturers in the HD vehicle sector are generally subject to both environmental and safety regulations for their products. Examples of environmental regulations include engine emission standards (which often contain provisions for onboard diagnostics, durability and warranty) and technology performance requirements.

At the other side of the policy impact spectrum, there are also incentive-based programs and regulations for end-users to promote technology adoption. For new vehicles, these measures include vehicle purchase grants and tax credits as well as technology purchase requirements. Some examples of policies targeting in-use vehicles include incentives or requirements for vehicle scrappage or retrofit. California has arguably the most extensive set of end-user HD vehicle policies in the world, which are chronicled in this chapter starting in Section 3.2.

Table 3-1: Policies for promoting HD vehicle technology adoption

Market	**Point of Policy Impact**	
	Manufacturers	**End-Users**
New vehicles	• Research, development, and demonstration funding • Engine emissions standards • Onboard diagnostics (OBD) requirements • Durability and warranty requirements • Sales-weighted performance standards • Regulatory crediting programs	• Purchase grants, vouchers • Tax credits • Purchase requirements
In-use vehicles	• Research, development, and demonstration funding • Technology certification requirements • Durability and warranty requirements	• Vehicle scrappage incentives or requirements • Retrofit incentives or requirements

3.1.2 Fuel-Focused Policies

A fuel's feedstock and characteristics have important impacts on both criteria pollutant and GHG emissions. The use of higher quality conventional fuels or certain alternative fuels with lower carbon content and/or embodied GHG emissions can be an effective strategy to control vehicle emissions. The following section describes the criteria pollutant and GHG impacts associated with the choice of fuel as well as policy measures that have been implemented to promote emission reductions.

3.1.2.1 Reducing Diesel Sulfur Levels

Fuel quality—particularly the amount of sulfur present in the diesel—is a significant parameter that affects the composition of tailpipe exhaust as well as the performance of emissions control technologies. Sulfur is a naturally occurring component in crude oil, and its content can vary based on the location where the oil is produced and is typically classified as "sour" (1% to 5% sulfur content by weight) or "sweet" (less than 1% sulfur) [97]. Most of the sulfur in the fuel is oxidized to SO_2, but a small portion is oxidized to SO_3 that leads to sulfuric acid and sulfate aerosols. The concentration of sulfates in the exhaust is roughly proportional to the fuel sulfur content, which is why the benefits of reducing sulfur levels in fuel are evident even without emissions control equipment. Elevated fuel sulfur levels increase the number and mass of PM emissions, as well as the quantities of other conventional air pollutants [10, 98, 99]. Moreover, sulfur inhibits the proper function of many catalytic emissions control devices, including passively regenerating diesel particulate filters and selective catalytic reduction (SCR) systems, in some cases permanently damaging their effectiveness. Accordingly, many countries and regions around the world, including California and the US, have implemented fuel quality regulations requiring reduced diesel sulfur content to near-zero levels in order to enable the adoption of the most effective emission control technologies.

3.1.2.2 Reducing the Embodied GHG Content of Fuels

Extracting a raw energy source and the processing steps required to transform an energy source such as crude oil into refined transportation fuels like gasoline and diesel requires input energy and materials. There are emissions associated with the production of these energy and materials inputs that are part of the fuel production process as well as energy and emissions resulting from the refining process itself. Thus, there are *embodied* upstream emissions associated with each finished fuel that is delivered to end-users for consumption. Often in lifecycle analysis, each of a fuel's embodied emissions is converted into CO_2-equivalent emissions (see Section 4.3.8.2 for a more detailed discussion of CO_2-equivalency determination) so that fuels and vehicle systems can be evaluated in terms of their lifecycle climate impacts.

There are two major low carbon fuel policies in the United States: the US EPA's Renewable Fuel Standard (RFS) and the California ARB's Low Carbon Fuel Standard (LCFS) [100, 101]. The RFS program was created under the Energy Policy Act of 2005 and established the first nationwide renewable fuel volume mandate. The original RFS program required 7.5 billion gallons of renewable fuel to be blended into gasoline by 2012, and under the 2007 Energy Independence and Security Act (EISA), the RFS program was expanded to include diesel substitutes, updated volumetric mandates, and other new provisions. The RFS regulates renewable biofuels in the entire US, while the LCFS covers both renewable and conventional fuels in California. The LCFS is a carbon intensity-based, fuel neutral standard that aims to reduce GHG emissions from transportation fuels in California by 10%, and the ARB estimates that on a full lifecycle basis, the regulation will result in CO_2-equivalent reductions of 23 million metric tons per year in 2020 (see Table VII-2 in [102]). Both the RFS and LCFS rely on lifecycle analysis for determining each fuel's GHG intensity in terms of CO_2-equivalent emissions per unit of energy of fuel (e.g. grams CO_2e/MJ).

3.1.3 Vehicle Operation-Focused Policies

Along with technology and fuel improvements, changing vehicle operating patterns is the third broad area of strategies for decreasing fuel use and emissions. Within this area, there are two general types of changes to vehicle operating behavior that can lead to lower emissions and/or fuel consumption: 1) reducing the total amount of vehicle activity and 2) operating a vehicle in a more fuel-efficient manner.

3.1.3.1 Reducing Levels of Activity

In the HD vehicle sector, the most targeted policy measures to reduce vehicle activity have been the efforts to limit extended idling. An effective technology for restricting idling is an engine automatic shut-off control, which is typically programmed to activate after a few minutes (e.g. 5 minutes) of idling. Vehicles with automatic shut-off engines must use auxiliary power units to meet cabin space heating and cooling loads as well as other electricity demands for times that require power during extended stationary operation (e.g. for overnight 'hoteling' in a tractor truck with a sleeper cab). In addition to California, 27 states have extended idling regulations for HD vehicles [103].

Apart from anti-idling regulations, there only other policies that have aimed to decrease the total activity of HD vehicles have been market-based measures. Examples of market-based disincentives for freight movement by truck include road charging fees and tolls that are levied against HD vehicles. An example of a government that has encouraged the implementation of such modal-shift policies is the European Commission, which, in its 2001 Eurovignette

Directive, stated that road charging and tolls are a "polluter pays" way in which E.U. member states are able to charge HD vehicle end-users for the externalities resulting from vehicle emissions. However, in 2006 the Commission revised its stance on modal shift policies in response to the fact that road charging and toll fees across the E.U. had virtually no effect in driving down the trucking sector's market share of freight movement [104]. To date, no such policies with the direct objective of decreasing truck market share have been adopted in California or the US

In addition to mode-shift to rail or shipping, another method to reduce the energy use and emissions per unit of freight transported is to simply allow HD vehicles to carry more payload, which, in turn, decreases the number of vehicles needed to move the same amount of freight. Increased gross vehicle weight rating (GVWR) can be achieved by allowing any of the following or combination thereof: higher axle weights, longer trailer length, or greater use of two- and three-trailer combinations. The benefits of such a policy change would need to be weighed against potential dis-benefits from reduced safety and increased damage to roadways [105]. Another barrier to the increased proliferation of heavier tractor-trailers is the non-uniform nature of dimension and weight regulations, which vary from state-to-state. Nominally, federal law limits the GVWR of a tractor-trailer to 80,000 pounds, but states are allowed to set unique weight limits based on *grandfathering*. In addition, regulations on trailer length and the number of trailers that a tractor can pull also vary amongst the states [106].

3.1.3.2 Operating Vehicles in a More Fuel-Efficient Manner

As discussed in Section 2.2.7, a driver's manner of operating a vehicle can have significant impacts on fuel efficiency, and there are a number of technologies available that either provide real-time feedback to the driver, limit the vehicle's response to the driver's throttle commands, or use environmental data (e.g. GPS) to better optimize the powertrain for better fuel efficiency. Of this set of technology options, to date only speed limiters (which control a vehicle's maximum speed) have been promoted in a regulatory program. As part of the US fuel efficiency and GHG standards for HD vehicles, setting a maximum speed lower than 65 mph is a regulatory compliance option for tractor trucks to reduce fuel use and CO_2 emissions.

Another factor that has an important influence on vehicle operating patterns is road infrastructure. Roadway improvements such as increased capacity or truck-dedicated lanes can reduce congestion and lead to more efficient vehicle operation. At the federal, state, and local level, governments are continuously funding and executing infrastructure improvement projects to increase the level of service and safety for all types of vehicles, both light- and HD.

3.1.4 US and California Policies Targeting Emissions from Heavy-Duty Vehicles

California, which has arguably the world's oldest and most comprehensive motor vehicle emission control program, has implemented HD vehicle policies related to all three of the broad impact areas discussed above. Figure 3-1 depicts the suite of incentive-based and regulatory policies at the state and federal level that affect vehicles operating in California. The policies above the arrow are measures that primarily target criteria pollutant abatement, and those below the arrow are policies for fuel consumption and GHG reductions. The "carrot" policies on the left of the figure are voluntary, incentive-based programs, while the "stick" policies on the right are mandatory regulations. *Carrots* generally include subsidies for research and development and vehicle purchase, and *sticks* range from emission standards to fuel sulfur level regulations to California's extensive series of end-user fleet rules. Across the vehicle technology and fuels realms, there have been numerous policies enacted in California (green and red), at the federal level (black), and in collaborative, harmonized efforts between the state and federal governments (dotted-line). The only policy measure that has been implemented to directly change vehicle operating patterns is the ARB's anti-idling regulation.

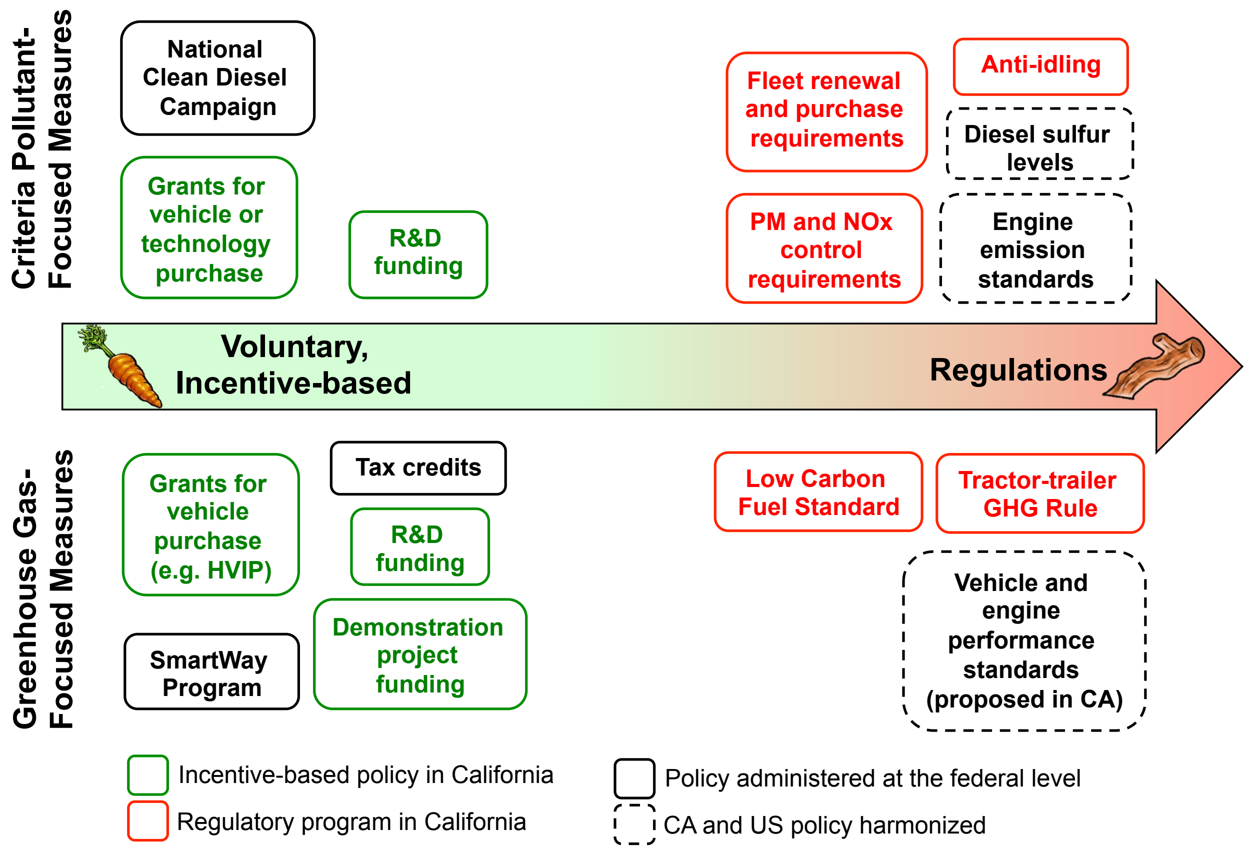


Figure 3-1: Policies affecting HD vehicles in California

The following sections provide an overview of the incentive-based programs and regulations that have been put in place to reduce criteria pollutant and GHG emissions in California. Many, if not all, of the policy measures described in the remainder of the chapter are dynamic and are continually updated and revised in response to ever-changing technology, state emission reduction needs, economic factors, and stakeholder concerns. In light of the fluid nature of policy development for the HD vehicle sector in California, the subsequent sections aim to provide a snapshot of the current policies as well as brief summaries of how the policies have evolved over time.

3.2 Criteria Pollutant-Focused Policies

In August 1998, after a ten-year review process, the ARB identified diesel exhaust as a toxic air contaminant [107]. The growing body of knowledge surrounding both the ozone-depleting characteristics and the human health risks associated with the exhaust from HD diesel engines provided policymakers in California the impetus for developing the Diesel Risk Reduction Plan (DRRP) in 2000. The DRRP is a portfolio of incentive-based and mandatory programs aimed at accelerating the adoption of cleaner diesel and alternative-fuel technologies. The DRRP's overarching goal of an 85% reduction in PM from diesel exhaust by 2020 was the driving force behind a host of vehicle programs and the transition to ultra-low sulfur (15 parts per million) diesel fuel statewide.

Another reason that California regulators have sought out aggressive measures for curbing criteria pollutants is that many air basins in California are in non-attainment for federal ozone standards [34]. Ground level ozone, or "smog" is created by a chemical reaction between NOx and volatile organic compounds in the presence of sunlight and is linked to a number of serious health risks [108]. While multiple areas across the state exceed federal air quality standards, the air quality in the South Coast and the San Joaquin Valley air basins, which are extreme non-attainment areas, poses the greatest challenge [34]. The South Coast Air Quality Management District estimates that changes to meet the new lower ozone levels will require a reduction in oxides of nitrogen (NOx) of 88 to 91% by 2030 [3]. Heavy-duty vehicles are significant producers of NOx—particularly in the San Joaquin Valley and South Coast air basins, where HD vehicles represent 84% and 61% respectively of total on-road NOx emissions as well as 49% and

34% of overall state NOx emissions [109, 110]. Without substantial reductions from these commercial trucks and buses, especially in the South Coast and San Joaquin Valley, the state would be unable to attain federal ambient air quality standards.

3.2.1 Incentive-based Programs

Through the legislative process, California policymakers and voters have made a substantial commitment to funding programs that support improved air quality. The following three sections described the primary funding sources at the state level that, amongst other things, have dedicated funds for incentive programs for cleaner and more efficient HD vehicle technologies. The three funding programs include the Carl Moyer Program, the Air Quality Improvement Program (Assembly 118), and the Goods Movement Emission Reduction Program (Proposition 1B). Combined, these funding sources are fairly significant, surpassing $500 million in 2013. However, as shown in Figure 3-2 [111], the majority of funds for these three programs are set to sunset over the next few years.

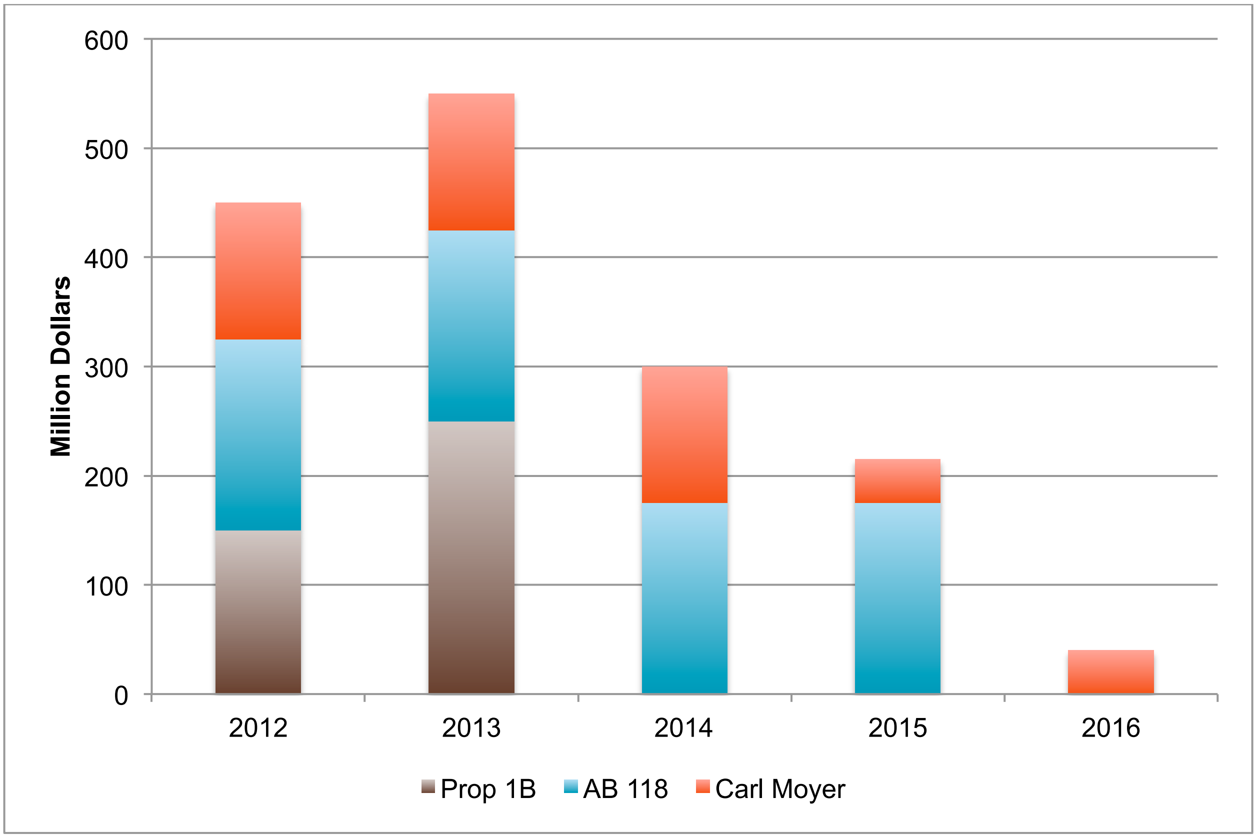


Figure 3-2: California air quality incentive funding (created using data from [111])

3.2.1.1 Carl Moyer Program

The Carl Moyer Program was created by the California state legislature in 1998 to provide monetary grants to help businesses and public agencies clean up their HD diesel engines beyond what is required by air pollution regulations. It was one of the first incentive programs for clean vehicles in the state and has set the foundation for other programs such as the Air Quality Improvement Program (AB 118) and the Goods Movement Emission Reduction Program (Prop 1B) that are discussed in subsequent sections. The Moyer Program continues to drive the early adoption of clean technologies that reduce the emissions of NOx, PM, and reactive organic gases from the combustion of diesel fuel in HD engines. The grants cover a percentage of the project costs for engine retrofits and replacements and are available to a wide range of public and private sector fleets, including on-road trucks and buses, off-road and agricultural equipment, locomotives, and marine vessels. The mission of the program is to drive emission reductions in surplus of regulations, and the grants are not designed to fund compliance with regulatory deadlines. As of 2011, the Moyer Program has provided $680 million in funding for roughly 24,000 projects, which are distributed amongst the various transportation modes as shown in Figure 3-3. Funding for on-road HD vehicles has primarily gone to transit bus and refuse truck projects and accounts for roughly one-fifth of total program spending since its inception [112].

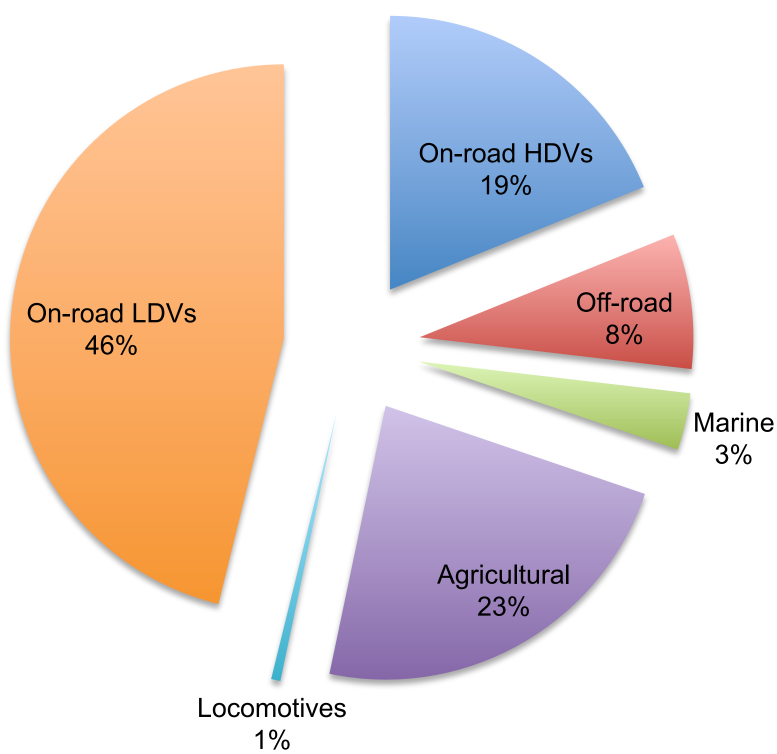


Figure 3-3: Funding summary to date (as of April 2011) for the Carl Moyer Program (created using data from [112])

Program administration is a partnership between the Air Resources Board (ARB) and each of the state's 35 Air Quality Management Districts (AQMDs). The ARB's function is to provide general oversight, set guidelines, and allocate funding within the state, and the AQMDs are responsible for selecting, funding, and monitoring each project as well as training vehicle and equipment dealers who sell certified products. Projects are evaluated using cost-effectiveness (i.e. $/ton-abated) metrics and environmental justice criteria as stipulated by AB 1390, which requires that 50% of funds must be spent in communities with the greatest air pollution impacts. Each AQMD ensures that fleet operators are in compliance by collecting detailed project cost estimates (from at least two engine/emission control dealers), receipts, annual fuel use records, and by conducting field audits. These implementation safeguards are vital for certifying actual emissions reductions and require considerable staff resources for both the AQMDs and the ARB.

Each AQMD must match funding—$1 for every $2 of Moyer funds received from the ARB. For the fiscal year 2010/2011, current funding levels for the Carl Moyer Program are approximately $70 million and are comprised of appropriated funds from Senate Bill (SB) 1107 and Assembly Bill (AB) 923. Enacted in September 2004, AB 923 created substantial new funds for the Moyer Program from a combination of smog-check exemption fees that new-vehicle owners pay, a new fee on tires, and an addition to the vehicle registration fee. A key component of the 2004 expansion was the addition of PM and hydrocarbons into the program landscape.

3.2.1.2 Air Quality Improvement Program (AB 118)

In 2007 the California Alternative and Renewable Fuel, Vehicle Technology, Clean Air, and Carbon Reduction Act (Assembly Bill (AB) 118) established the Air Quality Improvement Program (AQIP), which is administered by the ARB to fund clean vehicle and equipment projects, biofuels research, and workforce training. The AQIP supports three distinct projects, the

Clean Vehicle Rebate Project, the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program, and Advanced Technology Demonstration and Testing Project. The funding summary from the most recent fiscal year (2012-2013) is shown in Table 3-2 [113].

Table 3-2: Funding allocation for the AQIP for fiscal year 2012-2013

Project Category	**Funding Amount**	**Potential Vehicles**
Clean Vehicle Rebate Project	\$21 M	10,700
Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project	\$14 M	500
Advanced Technology Demonstration and Testing Project	\$5 M	N/A

The Clean Vehicle Rebate Project provides rebates to California residents, businesses, nonprofit organizations and government entities that purchase or lease a zero (or partial zero) emission vehicle such as a battery electric, plug-in hybrid electric, or fuel cell electric vehicle. This program is focused on passenger vehicles, while the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) and Advanced Technology Demonstration and Testing Project are aimed at on-road HD vehicles and off-road equipment respectively. The HVIP program is discussed in Section 3.3.2.

3.2.1.3 Goods Movement Emission Reduction Program (Prop 1B)

Proposition 1B (Prop 1B) was approved by California voters in 2006 and authorized \$1 billion in bond funding to the ARB to reduce emissions in four key trade corridors: the Los Angeles and Inland Empire areas, the Central Valley, the Bay Area, and the San Diego and California-Mexico border region. The Prop 1B program provides financial assistance to owners of HD trucks, freight locomotives, and marine cargo vessels to upgrade to technologies that decrease PM and NOx emissions as well as GHGs in some cases. Funding is also available for cargo handling equipment and the electrification of truck stops and distribution centers. The funds are designed to partially offset the costs of upgrading equipment. To date, approximately $570 million in funds have been allocated as summarized in Figure 3-4 [114]. Combined, port truck and HD vehicles projects represent the large majority of the overall program budget at roughly 80% of funding.

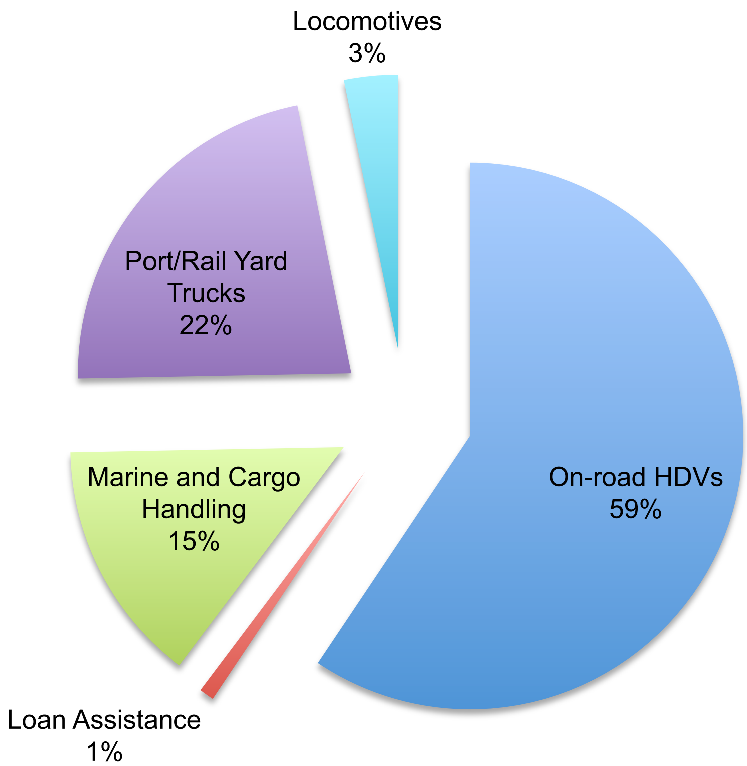


Figure 3-4: Funding summary to date (as of January 2013) for the Prop 1B Program (created using data from [114])

The ARB distributes program funds to local air districts and ports, which then use a competitive process based on emission reductions and cost-effectiveness to allocate awards to equipment owners for clean technology upgrades. As with the AQIP, Prop 1B funding must be used to provide emission reductions above and beyond what is required by regulation.

Thus far, over 10,700 cleaner diesel and advanced technology trucks have been funded or partially funded by Prop 1B. From the January 2013 presentation to the Board by ARB staff, there are proposed changes to the program that are largely based on the Statewide Truck and Bus Regulation and the Drayage Truck Regulation due to the fact that funds cannot be allocated to assist in compliance with existing regulations. Based on phase-in schedules for each of these regulations, the ARB Prop 1B program administrators have proposed that only the projects shown in Table 3-3 be eligible for funding [114]. Key proposed changes include removing PM retrofits from project eligibility due to compliance deadlines of the Truck and Bus Rule as well as requiring that new truck replacements have engines meeting model year 2010 NOx (0.2 grams/hp-hr) and PM levels (0.01 grams/hp-hr) [114].

Table 3-3: Proposed eligible projects under the Prop 1B program

Eligible Vehicles	Replacement Requirement	Maximum Funding
Class 8 truck w/ MY 1994-2006 engine	Truck w/ MY 2013 or newer engine	$50,000
	Truck w/ MY 2010-2012 engine	$40,000
Class 7 truck w/ MY 1994-2006 engine	Truck w/ MY 2010 or newer engine	$35,000
Class 6 truck w/ MY 1996-2006 engine	Truck w/ MY 2013 or newer engine	$25,000
Class 6-8 truck w/ MY 1994-2006 engine	Zero emission truck	$65,000 - $105,000
Class 7-8 truck w/ MY 1994-2006 engine	MY 2010 or newer engine (engine replacement only)	$20,000
Class 6 truck w/ MY 1994-2006 engine	MY 2010 or newer engine (engine replacement only)	$10,000

3.2.2 Mandatory Programs

In assessing the Moyer Program's contribution to the overall Diesel Risk Reduction Plan (DRRP), which was developed in 2000, the ARB recognized the need for mandatory in-use regulations to compliment the Moyer Program in ratcheting down NOx, PM, and other pollutant emissions. The DRRP's overarching goal of an 85% reduction in PM from diesel exhaust was the driving force behind a host of vehicle programs and the transition to ultra-low sulfur (15 parts per million) diesel fuel statewide in the early-to-mid 2000s [115]. In accordance with DRRP goals, the ARB began adopting fleet-specific regulations in 2000, methodically phasing-in different vehicles and equipment in subsequent years. Table 3-4 [116] provides a timeline for in-use regulations in California. In the table, the fleet rules in bold font apply to on-road HD vehicles and will be discussed in more detail in Sections 3.2.2.1 through 0.

Table 3-4: Timeline of California HD fleet regulations and the approximate number of vehicles affected when each respective rule was passed

Type of Fleet	Regulation Adopted	Approx. Number of Vehicles Affected
Urban Buses	2000	50,000 (total[10])
Solid Waste Collection Vehicles	2003	
School Bus Idling	2003	
Stationary Engines	2004	
Truck Refrigeration Units	2004	
Truck and Bus Idling	2004	
Portable Engines	2004	
Transit Fleet Vehicles	2005	
Public Fleets and Utilities	2005	
Cargo Handling Equipment at Port and Rail Yards	2005	
Off-Road Vehicles	2007	200,000
Port Trucks	2007	20,000
Statewide Trucks and Buses	2008	900,000

The off-road vehicle and the statewide truck and bus standards were motivated by the aggressive NOx and PM targets set in the State Implementation Plan and represent a momentous increase in the breadth of in-use diesel vehicles subject to regulation. Details of the Statewide Truck and Bus regulation are outlined in section 0.

[10] This value excludes the Truck Refrigeration Unit and Truck and Bus Idling regulations, which are fleet-wide measures that affect both public and private entities.

3.2.2.1 Urban Buses

In 2000, the ARB adopted a new urban transit bus emission regulation to be phased-in beginning in 2002, affecting about 8,500 urban buses at roughly 80 California transit agencies [115]. This urban bus rule was the first measure of the ARB's Diesel Risk Reduction Plan. An urban bus is defined in the regulation as any HD vehicle with the capacity to carry 15 or more passengers, is 35 feet or longer, has a GVWR of greater than 33,000 pounds, and is owned or operated by a public transit agency and primarily intended for city operation. Under this rule, bus fleet operators have two compliance options for their future bus procurements: a diesel pathway or an alternative fuels pathway. The alternative fuel path requires that 85 percent of buses purchased or leased each year through MY 2015 are alternative fuel vehicles. Examples of alternative fuels include NG, propane, methanol, ethanol, hybrid-electric (gasoline hybrid-electric only), electricity, hydrogen, or any other technology that does not rely on diesel fuel. Transit operators who stay on the diesel path can purchase diesel-fueled buses, but are required to follow a more aggressive emission reduction schedule. Table 3-5 summarizes the average fleet PM emission reduction requirements for each compliance pathway compared to the fleet baseline for diesel buses as of January 1, 2002 [117]. Moreover, as of October 1, 2002, all transit bus fleets had to have an average NOx level of no greater than 4.8 g/hp-hr. Average fleet emission levels are determined by summing the certification standard for each engine and dividing by the number of buses in the fleet. Every January 31st between 2003 and 2016, transit agencies are required to report the number of buses owned, operated, and under contract as well as the model year and fuel type of each bus [ibid].

In addition to the ARB regulation, another policy that shaped the transit fleet in California was the South Coast Air Quality Management District's (SCAQMD) Rule 1192, which stipulated that all transit agencies had to purchase non-diesel alternative fuel buses starting in

June 2000 [118]. As a result of the rule, all agencies operating within the SCAQMD's five-county southern California jurisdiction began to adopt alternative fuel buses—primarily NG buses.[11]

Table 3-5: Fleet average PM emission reductions required by the Urban Bus rule

Year	Diesel Path	Alternative-fuel Path
2004	40%	20%
2005	60%	40%
2006	-	-
2007	85%*	60%
2008	-	-
2009	-	85%*

* The sum of certified emission levels may not exceed 0.01 g/hp-hr times the total number of diesel buses in the fleet.

In addition to the ARB vehicle purchase and fleet average emission requirements, diesel-fueled, dual-fuel, and bi-fuel engines in urban buses were subject to more stringent exhaust emission standard between October 1, 2002 and the 2006 model year, after which, starting with the 2007 model year, the standard aligned with the California (and federal) HD engine exhaust emission standard [119].

In the original version of the regulation in 2000 [120] and in the amendments that were adopted in 2006 [72][12], the final components of the urban bus regulation were a mandatory

[11] The SCAQMD fleet rules include seven measures requiring fleet operators of transit buses, school buses, refuse trucks, airport shuttles and taxis, street sweepers, and HD utility trucks to buy alternative fuel models when replacing or adding vehicles to their fleets. This purchase mandate was in effect from 2000 to mid-2004, when the US Supreme Court overturned portions of the fleet rules. Subsequently, in March 2005, a US District Court in California issued a ruling that SCAQMD's fleet rules are indeed applicable and, in general, its requirements are in full force.

demonstration project as well as purchase requirement for zero emission buses (ZEBs). This portion of the urban bus rule was designed to catalyze ZEB demonstration projects and spur larger-scale adoption. A ZEB is defined as a bus that produces zero exhaust emissions of any pollutant under any possible operation conditions. Types of ZEBs include hydrogen fuel cell buses, electric trolleys, and battery electric buses. As originally envisioned, agencies with an active fleet of 200 or more buses (i.e. "large" fleets) would be required that at least 15% of new bus purchases would be ZEBs for both the diesel pathway beginning in MY 2008 and in MY 2010 for the alternative fuel pathway. In the 2006, these purchase requirements were pushed back to MY 2011 for diesel pathway agencies and MY 2012 for the alternative fuel agencies. The large fleet designation applies to 10 transit agencies in California, as summarized in Table 3-6 [121]. The transit service operating territory covered by these large fleets are made up of five agencies in northern California and five in southern California, as shown in Figure 3-5. Together, these fleets represent roughly half of the total transit buses in the state.

Table 3-6: Large transit agencies in California

Transit Agency	**Pathway**	**Approx. Number of Buses in 2011 [121]**
Los Angeles Metro. Transportation Authority	Alternative Fuel	2,700
San Francisco Municipal Transportation Authority	Diesel	800
Orange County Transit Authority	Alternative Fuel	730
Alameda-Contra Costa Transit	Diesel	630
San Diego Transit Corporation	Alternative Fuel	490

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[12] The Transit Fleet Rule revisions that were adopted in 2006 also expanded the scope of the regulation to include "transit fleet vehicles," which are defined as any HD vehicles with a GVWR greater than 8,500 pounds that is operated by a transit agency and is not an urban bus.

Santa Clara Valley Transportation Authority	Diesel	440
San Mateo County Transit District	Diesel	330
Foothill Transit	Alternative Fuel	320
Sacramento Regional Transit District	Alternative Fuel	220
Golden Gate Transit	Diesel	210

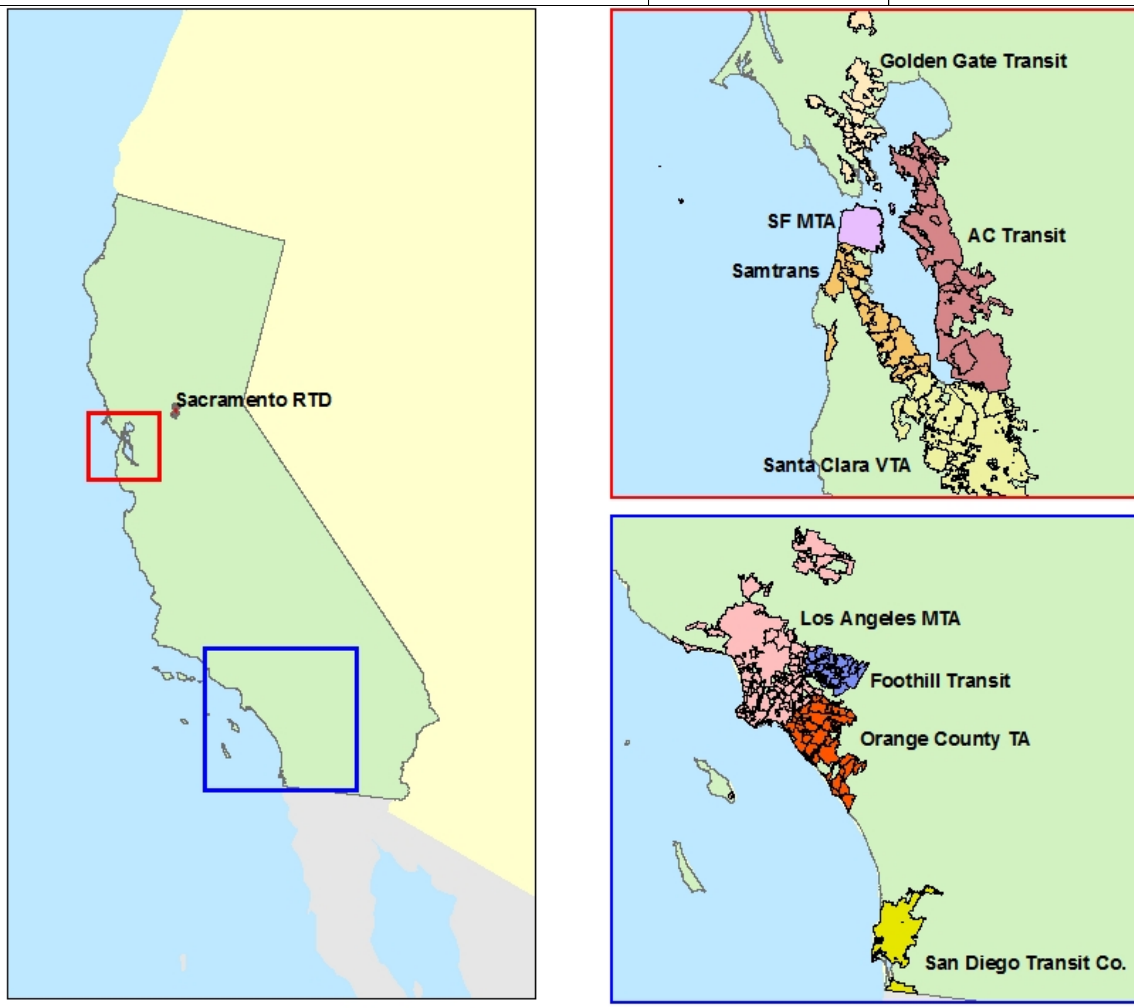

Figure 3-5: Service territories of the transit bus fleets affected by the Zero Emission Bus program (Slide 10 in [122])

As required by the ZEB provisions, a Phase 1 demonstration program commenced in 2005. Six hydrogen fuel cell buses were operated by Alameda-Contra Costa Transit (AC Transit), the Santa Clara Valley Transportation Authority (VTA), and the San Mateo County Transit District (SamTrans) [123, 124]. The first demonstration program was a collaboration between VTA and SamTrans and involved three non-hybrid fuel cell buses. The demonstration program was evaluated in detail by the National Renewable Energy Laboratory (NREL), and the results are summarized in reports from May 2006 [125] and November 2006 [126]. Overall, the fuel cell buses used in the VTA/SamTrans project proved to be a challenge in terms of performance and reliability. Fuel economy results of the fuel cell buses were roughly on par with the baseline diesel buses and emphasized the need for hybridization. Dependability was also an issue—on a per-mile basis, the fuel cell buses were roughly ten times as likely as a diesel bus to need unscheduled maintenance based on the Miles Between Road Calls (MBRC) data collected [ibid]. AC Transit spearheaded the second Phase 1 demonstration project and put three hybrid-electric fuel cell buses in service starting in March 2006. As compared to the VTA/SamTrans project, the AC Transit demonstration yielded much more positive results [127]. The fuel cell bus uptime was vastly superior to the VTA/SamTrans buses, and, on a diesel equivalent basis, the fuel economy of the fuel cell buses was nearly 60% higher than the conventional diesels [ibid]. The three buses were operated from 2006 to mid-2010 and logged over 270,000 total miles and carried more than 700,000 passengers [128].

In addition to the six zero emission buses demoed by VTA/SamTrans and AC Transit, SunLine Transit also introduced a first generation hydrogen fuel cell bus during the same timeframe. Sunline's hybrid-electric fuel cell bus that was put into service in January 2006 was a sister to the three buses used in the AC Transit Phase 1 demonstration [124]. Another advanced technology that SunLine evaluated in the mid-2000s was a hydrogen internal combustion bus, which went into service in December 2004. As with the previous two programs, NREL collected data throughout the demonstration and released a series of evaluation reports between 2007 and 2009 [129].

As part of the 2006 ZEB rule modifications, the five northern California transit agencies on the diesel pathway were required to participate in an "advanced" demonstration project [72]. As with the Phase 1 demonstration, AC Transit is leading the project, and it operates the 12 third generation hybrid fuel buses as well as the hydrogen refueling stations. This project was phased-in between the summer of 2010 and early 2011 and are featuring the fuel cell buses on high-visibility, heavy ridership routes [128]. According to the NREL evaluation report from July 2012, the buses have logged over 270,000 miles and 29,000 hours of operation in carrying over 1 million passengers in full revenue service [130]. These latest results show that fuel economy (in diesel equivalent gallons) of the fuel cell buses is nearly double that of the conventional diesels. However, per-mile maintenance costs of the fuel cell buses are roughly 60% higher, and overall availability was well below the target of value of 85%, though the average availability of the three diesel control buses also fell short in terms of availability[13] at 77% [ibid].

In a review of the ZEB regulation in 2009, ARB program staff recommended that the MY 2011 (diesel pathway) and MY 2012 (alternative fuel pathway) purchase requirement be delayed [124]. The Board agreed with the assessment that the durability and reliability of ZEBs required improvement and that the advanced demonstration project was needed to collect more data on technology readiness. As described in the staff report [ibid] part of the readiness determination involved developing quantitative metrics in the following areas to aid the ARB in the future decision about the timeline for reinstating the purchase requirement of the ZEB regulation:

- Incremental cost ratios as compared to a conventional diesel bus

[13] "Availability" is a measure of reliability and is calculated by dividing the number of days that a vehicle is actually available for service by the number of days that the vehicle is planned for service.

- Durability and warranty
- Reliability (i.e. MBRC)
- Percent availability

As of this writing, fuel cell buses have not met these criteria, and the purchase requirement timeline has not yet been reinstated.

Currently, there are approximately 360 ZEBs operating in California [121]. The large majority of these buses are the San Francisco Municipal Transportation Authority's (SF MTA) fleet of roughly 340 electric trolley buses [131], which receive electricity via the grid through a catenary wiring system. The SF MTA's electric trolley bus fleet is the largest in North America, and service with this type of buses dates back to the 1930s [132].

In addition to the 12 hydrogen fuel cell buses operating in the northern California demonstration project, there are a handful of fuel cell and electric buses that are in service or soon-to-be in service, which are shown in Table 3-7 [133, 134]. In September 2010, Foothill Transit, which operates in the eastern portion of Los Angeles County, introduced three Proterra EcoRide BE35 (known as the "Ecoliner") transit buses as well as an in-route charging station, which is designed to recharge the bus in 10 minutes (see Figure 3-6) [135]. According to Foothill Transit, by April 2011 the buses had over 10,000 miles accumulated and hundreds of on-route fast charges [134]. In addition, the agency has secured funding for an additional nine buses, which they plan to use to fully electrify an individual bus route [ibid].

In addition to the SunLine Transit fuel cell bus that went into service in January 2006 (described above), the agency introduced two new hybrid fuel cell buses into service—one in April 2010 and the next in January 2012. According to SunLine, these three buses have logged over 140,000 miles, 57,000 miles, and 33,000 miles respectively [136]. NREL's latest evaluation for the bus introduced in 2010 reports that the fuel economy of the fuel cell bus is close to twice that of the CNG control bus, while per-mile maintenance costs of the fuel cell bus are almost four times as high [137].

In the summer of 2011, the City of Burbank (BurbankBus) introduced a battery-dominant plug-in hybrid fuel cell bus. According to NREL, the bus is fully charged at night by plugging into a standard 220-volt outlet. NREL began data collection on the bus in October 2012 and will be publishing an evaluation report in 2013 [133].

Finally, the San Joaquin Valley Transportation Authority is planning to introduce two battery electric buses into its fleet in 2013. As with the electric buses currently operating in the Foothill Transit fleet, this demonstration project will also include an on-route fast-charging station that will provide a full recharge in 10 minutes [138].

Table 3-7: Non-electric trolley zero emission buses currently operating in California

Transit Agency	**Type of Buses**	**Number of Buses**	**Introduction Into Revenue Service**
AC Transit	H_2 fuel cell hybrid-electric	12	September 2010 through November 2011
Foothill Transit	Electric (fast charge)	3	September 2010
SunLine Transit	H_2 fuel cell hybrid-electric	3	Bus #1: January 2006 Bus #2: April 2010 Bus #3: January 2012
City of Burbank	H_2 fuel cell hybrid-electric (battery dominant)	1	August 2011
San Joaquin Valley Transportation Authority	Electric (fast charge)	2	Planned in 2013

Figure 3-6: Foothill Transit's Ecoliner electric bus and its in-route fast-charging station [139]

3.2.2.2 Solid Waste Collection Vehicles

Following the rule for transit buses and fleet vehicles, the next regulation that the ARB enacted was the Solid Waste Collection Vehicle (SWCV) Rule, which was passed in September 2003 [140]. Vehicles affected by this rule include any refuse trucks over 14,000 lbs. GVWR that is used to collect residential or commercial waste. According to the ARB, when the SWCV program was introduced, approximately 11,800 trucks were subject to the rule [141].

The implementation schedule of the rule is summarized in Table 3-8 [142]. In the regulation, all owners and operators of affected vehicles are responsible for ensuring that their fleets meet the Best Available Control Technology (BACT) percentages outlined in the table. To meet California and federal model year 2007 engine standards, all manufacturers installed diesel particulate filters (DPFs), which typically reduce PM mass emissions by 85% to 95% (see

Section 2.1.3.1) and are considered a BACT. For pre-MY 2007 engines, diesel oxidation catalysts (DOCs), partial flow filters (PFFs), and DPFs are retrofit options. Per this rule, each pre-MY 2007 engine must be equipped with the device that provides the highest possible level of PM reductions. In addition, an alternative fuel engine such as one that runs on NG is considered a BACT. To summarize, a BACT can be a vehicle with one of the following:

- Model year 2007 or newer engine with an OEM-supplied aftertreatment system
- ARB-certified retrofit device that is provides the maximum PM reduction for that given engine make/model and the vehicle's duty cycle
- Alternative (i.e. non-diesel) fuel engine

Table 3-8: Compliance schedule for the SWCV Rule (adapted from Table 1 in [142])

Regulatory Group	Percent of Fleet with Best Available Control Technology	Deadline
Group 1: Vehicles with MYs 1988-2002 engines*	10%	December 31, 2004
	25%	December 31, 2005
	50%	December 31, 2006
	100%	December 31, 2007
Group 2a: Vehicles with MYs 1960-1987 engines with 15 or more vehicles in the fleet	15%	December 31, 2005
	40%	December 31, 2006
	60%	December 31, 2007
	80%	December 31, 2008
	100%	December 31, 2009
Group 2b: Vehicles with MYs 1960-1987 engines with 14 or fewer vehicles in the fleet*	25%	December 31, 2007
	50%	December 31, 2008
	75%	December 31, 2009
	100%	December 31, 2010
Group 3: Vehicles with MYs 2003-2006 engines*	50%	December 31, 2009
	100%	December 31, 2010

* Fleet owners with a total of 1 to 3 vehicles may delay compliance until the final deadline for each group.

As with transit buses, the SCAQMD also implemented a specific rule (Rule 1193) for refuse trucks, which required both government agencies and private companies with 15 or more solid waste collection vehicles in their fleet to purchase alternative fuel vehicles starting in June 2000

[143]. As a result of an aggressive mix of mandates and financial incentives, California has the largest number of NG vehicles in the country by far, and the nation's five largest NG refuse truck fleets are operating in California [144].

3.2.2.3 Bus and Truck Idling

In December 2002, the ARB passed the School Bus Idling Airborne Toxic Control Measure, which required operators of school buses, transit buses, and other commercial vehicles to manually shut off their engines upon arriving at a school [145]. Restarting the engines is limited to no more than 30 seconds before departing. "School" is defined as any public or private institution used for the purposes of education and instruction of more than 12 students at or below the 12th grade level. This rule applies to the approximately 26,000 buses and other HD vehicles that operate at or near schools and has been in effect since July 2003 [146].

At a hearing in July 2004, the Board subsequently adopted an additional idling regulation, which set a maximum primary engine (or diesel-fueled auxiliary power system) idling time of 5 consecutive minutes (or periods of time aggregating to more than 5 minutes in one hour) for any HD commercial truck or bus over 10,000 lbs. GVWR operating in California [147]. However, this new idling regulation that went into effect on February 1, 2005 did not apply to idling tractor trucks with sleeper cabs unless the vehicle was located within 100 feet from residential homes or schools.

To further reduce emissions of toxics and criteria pollutants, the ARB introduced a new anti-idling regulation in October 2005 as a follow-up to the 2004 idling measure [148] that became effective on January 1, 2008. This additional regulation is aimed at tractor-trailers with sleeper cabs, which are typically used by drivers for extended periods of rest or sleeping while the vehicle is stationary. Power is generally required for space heating or cooling as well as for operation of other amenities in the cabin, and to provide this power, the vehicle's primary engine or an auxiliary power system (APS) must be run at idle. An APS is a power source such as a small engine, fuel cell, battery pack, fuel-fired heater, or thermal energy storage system that meets the hoteling loads of the stationary vehicle in lieu of the primary engine. As with the previous idling regulation for trucks and buses, this rule prohibits truck drivers from idling the primary engine or a diesel-fueled APS without a DPF for more than 5 minutes at a time on California roads. The ARB estimated that in 2010 this rule would affect roughly 30,000 California registered sleeper trucks and 45,000 out-of-state sleeper trucks [149]. For vehicles with model year 2008 or newer diesel engines, these engines must be equipped with a non-programmable engine shutdown system that automatically turns the engine off after 5 minutes of idling or the engine must meet an optional 30 grams/hour NOx standard. In order to provide cabin comfort, drivers have the choice of operating one of the following auxiliary power systems:

- Battery-powered units
- Fuel-fired heaters from the ARB's "approved and verified equipment list" [150] (for vehicles with MY 2007 or newer engines only)
- Thermal energy storage systems (provides cooling only)
- Diesel-fueled APSs that are fitted with a DPF or have their exhaust routed to the main engine's exhaust upstream of the DPF
- Truck stop electrification (TSE) systems allow the vehicle to plug into the electrical grid or receive heating, ventilation, and air conditioning from an off-board gantry system. Of the roughly 500 truck stops in California [151], the Alternative Fuels Data Center

reports that 8 of these have electrification sites. These TSE truck stops are located along the principal north-south highways, Interstate 5 (I-5) and California 99 (CA-99) [40].

3.2.2.4 Truck Refrigeration Units

In November 2004, the ARB approved a measure to control criteria pollutants and toxic emissions from transport refrigeration units (TRUs) [152]. As described in the background information in the supporting regulatory documents [153], a TRU is a refrigeration system powered by a small engine (typically between 9 and 36 horsepower) that provides cooling or heating to perishable or sensitive goods that are being transported by a truck, trailer, or another type of enclosed shipping container.[14] The TRU regulation has been updated twice, and the two respective sets of amendments became effective in March 2011 [154] and October 2012 [155]. When the rule was initially introduced in 2003, the ARB estimated that approximately 31,150 California-based truck and trailer TRUs as well as 9,400 out-of-state trailer TRUs would be subject to the regulation [156].

The emissions performance requirements and compliance deadlines are summarized in Table 3-9 and Table 3-10 [155]. The in-use performance standards have two levels of stringency that are phased in over time: Low-Emission TRU (LETRU) and Ultra-Low Emission TRU (ULETRU). In general, partial flow filters (PFFs) are the aftertreatment devices that provide at least 50% particulate matter reductions (Level 2), and diesel particulate filters (DPFs) are verified to yield 85% or more in PM reductions. The standards can be met in one of three ways:

- Using an engine that is certified to the PM levels in Table 3-9

[14] Often, an entire refrigerated trailer is referred to as a TRU or “reefer” trailer.

- Retrofitting the engine with the required aftertreatment device per Table 3-9
- Using an alternative fuel engine or technology

In addition, the reporting provisions require that all California-based TRUs and TRU generator sets be registered by July 31, 2009. For new units that are based in California, owners must complete the registration process within 30 days of acquiring the TRU. While the regulation applies to any TRU operating in California, owners/operators of out-of-state TRUs may voluntarily register with the ARB.

Table 3-9: PM performance standards for the TRU regulation

Low-Emission TRU (LETRU) Performance Standards		
Horsepower	**Engine Certification**	**Diesel Exhaust Aftertreatment**
Less than 25	0.30 g/hp-hr	PFF: at least 50% PM reduction (Level 2)
25 or more	0.22 g/hp-hr	
Ultra-Low Emission TRU (ULETRU) Performance Standards		
Less than 25	-	DPF: at least 85% PM reduction (Level 3)
25 or more	0.02 g/hp-hr	

Table 3-10: Compliance schedule for the TRU regulation

Engine Model Year	**Compliance Deadline for LETRU**	**Compliance Deadline for ULETRU**
2001 or older	December 31, 2009	December 31, 2015
2002	December 31, 2009	December 31, 2016
2003	December 31, 2010	December 31, 2017
2004 (< 25 hp.)	December 31, 2011	December 31, 2018
2004 (> 25 hp.)	Must skip LETRU and go to ULETRU	December 31, 2011
2005 and newer	Must skip LETRU and go to ULETRU	December 31st of the MY + 7 years

3.2.2.5 Public Fleets and Utilities

The next group of vehicles targeted by the ARB for reduced particulate matter and toxic air contaminants was any on-road HD vehicle fleet owned or operated by public agencies or utilities. This public fleet regulation impacts any vehicle over 14,000 lbs. GVWR and was approved by the ARB in December 2005 [157], went into effect in 2007, and was subsequently amended in 2009 [158]. As defined by the regulation, a public agency (or municipality) is a city, county, or public entity of the state of California, and a utility is a private company that provides water, electricity, or NG, as a public utility operated by a municipality. At the time of the rule's adoption, the ARB estimated that there were roughly 27,000 HD vehicles operated by municipalities and utilities that fall subject to the program.

As with previous fleet rules, this regulation mandates that affected owners and operators reduce diesel PM emissions from their trucks through the application of Best Available Control Technology (BACT) devices on these vehicles by specified implementation dates, which are phased-in by engine model year groups as is shown in Table 3-11 [159]. As with the SWCV rule, a BACT is defined as an engine and aftertreatment package that can achieve the 0.01 g/hp-hr PM limit, an engine that has been retrofitted with the highest level PM reduction device (i.e. Level 1, 2, or 3) for that given engine make and model, or a non-diesel alternative fuel engine.

Table 3-11: Compliance schedule for the Public Agencies and Utilities Fleet Rule (adapted from Table 1 in [159])

Regulatory Group	% of Fleet with BACT	Dec. 31st Deadline	% of Fleet with BACT	Dec. 31st Deadline
	Applies to All Fleets		Option for "Low Population County" Fleets[b]	
Group 1: Vehicles with MYs 1960-1987 engines[a]			20%	2009
	20%	2007	40%	2011
	60%	2009	60%	2013
	100%	2011	80%	2015
			100%	2017
Group 2: Vehicles with MYs 1988-2002 engines			20%	2008
	20%	2007	40%	2010
	60%	2009	60%	2012
	100%	2011	80%	2014
			100%	2016
Group 3: Vehicles with MYs 2003-2006 engines			20%	2011
			40%	2012
	50%	2009	60%	2013
	100%	2010	80%	2014
			100%	2015
Group 4: Vehicles with MY 2007 and newer engines			20%	2012
			40%	2013
	100%	2012	60%	2014
			80%	2015
			100%	2016

(a) Level 1 aftertreatment devices (i.e. those certified to provide 25% PM reductions) may not be used for Group 1 vehicles

(b) A "low population county" is defined as a county with a population of less than 125,000 people as of July 1, 2005

3.2.2.6 Drayage Trucks

Cargo hubs such as ports and intermodal rail yards tend to be places where a large number of tractor trucks operate as they pick up and drop off containers, trailers, and goods that have been or will be transported by ships and/or trains. These dense locations of truck activity such as the Ports of Los Angeles, Long Beach, and Oakland have historically been areas where concentrations of air pollutants and toxic emissions are elevated due to the large number of trucks operating in a small area and the fact that drayage (or "port") tractors are typically older vintage vehicles whose engines emit pollutants at a higher rate than newer engines. To improve air quality in port and rail yard areas, the ARB introduced the Drayage Truck Regulation in December 2007, which was finally approved and became effective in December 2009 [160]. The regulation applies to all on-road Class 7 and 8 (greater than 26,000 lbs. GVWR) diesel trucks that transport cargo to and from California's ports and intermodal rail yards regardless of the state or country of origin or the frequency of visitation. The ARB estimated that the rule affects roughly 21,600 "frequent and semi-frequent" drayage trucks and an additional 55,000 to 81,000 "non-frequent" trucks [161].

The regulation requires action from five groups of stakeholders: truck drivers, truck owners, motor carriers that dispatch drayage trucks, port and marine terminal operators, and port and rail authorities. From the 2011 amended regulation [162], each group's responsibilities are as follows:

- Truck drivers: provide motor carrier contact details and load origin and destination information to enforcement officers, if requested
- Truck owners: register their trucks in the Drayage Truck Registry and ensure that all vehicles comply with the emission level and technology guidelines per Table 3-12 [163]
- Motor carriers: ensure that dispatched trucks in their fleet are compliant with the rule, provide a copy of the regulation to truck owners, and keep dispatch records for five years
- Port and marine terminal operators: collection information about every non-compliant truck entering the facility and report it to their respective port or rail authority
- Port and rail authorities: report non-compliant truck information to the ARB

Table 3-12: Compliance schedule for the Drayage Truck Regulation (adapted from Table 1 and 2 in [163])

Truck Engine Model Year	Emission Requirements	Deadline: By January 1st
Class 8 Truck Compliance Schedule		
Pre-1994	Trucks with pre-1994 engines are not allowed	2010
1994-2006	ARB verified Level 3 PM reduction device	2010
	Meet MY 2007 California and federal engine emission standard	2014
2007-2009	Compliant through 2022 and then are subject to the Truck and Bus Rule requirements (see Section 0 below)	-
2010 and newer	Fully compliant	-
Class 7 Truck Compliance Schedule		
2006 and older (for South Coast Air Basin)	ARB verified Level 3 PM reduction device	2012
	Meet MY 2007 California and federal engine emission standard	2014
2006 and older (outside of South Coast Air Basin)	Meet MY 2007 California and federal engine emission standard	2014
2007-2009	Compliant through 2022 and then are subject to the Truck and Bus Rule requirements (see Section 0 below)	-
2010 and newer	Fully compliant	-

3.2.2.7 On-road Truck and Bus Rule

The On-Road Truck and Bus Rule is a culmination of all of the previous measures to reduce criteria pollutant emissions and toxics from HD diesel vehicles in California. In December 2008, the ARB passed this landmark rulemaking, which was the first time that such a large proportion of private fleets were subject to an ARB regulation. Any person, business, school district, or federal government agency that owns, operates, leases or rents a vehicle in California with a GVWR greater than 14,000 lbs. is subject to this regulation. As with previous regulations, there are certain exceptions, but, in general, this rule applies to virtually every publicly, privately, and federally owned HD diesel truck or bus operating in California. This is particularly significant when considering the considerable number of LH trucks that travel into California from other states as well as from Canada and Mexico. Altogether, the ARB estimates that nearly one million California-based and out-of-state vehicles are subject to the Truck and Bus Rule [164].

Amendments to the rule were adopted in December 2011 [165], and the current compliance schedule for PM reductions and engine MY requirements is summarized in Table 3-13 and

Table 3-14. For vehicles greater than 26,000 lbs. (Class 7 and 8), there are two options: compliance by 1) engine MY or 2) a more flexible phased-in schedule. If electing to utilize the phased-in option (see

Table 3-14), individual fleets need to report information about their Class 7 and 8 trucks starting January 31, 2012. Starting January 1st, 2015, vehicles between 14,001 and 26,000 lbs. (Class 4, 5, and 6) that are 20 years old or older must be replaced with a vehicle with a MY 2010 or newer engine. Owner of these lighter vehicles also have the option of installing a PM filter retrofit and would be exempt from replacing the vehicle until January 1st, 2020.

Table 3-13: Engine MY requirements for Class 7 and 8 (> 26,000 lbs.) vehicles under the Truck and Bus Rule (adapted from Table 1 in [166])

Engine Model Year	Requirements	Deadline: By January 1st
Pre-1994	MY 2010 engine	2015
1994-1995	MY 2010 engine	2016
1996-1999	BACT PM control device	2012
	MY 2010 engine	2020
2000-2004	BACT PM control device	2013

	MY 2010 engine	2021
2005-2006	BACT PM control device	2014
	MY 2010 engine	2022
2007-2009	MY 2010 engine	2023
2010 and newer	Meets final requirements	-

Table 3-14: Phase-in compliance option for Class 7 and 8 (> 26,000 lbs.) vehicles under the Truck and Bus Rule (adapted from Table 2 in [166])

Percent of Fleet with BACT PM Filters	**Deadline: By January 1st**
30%	2012
60%	2013
90%	2014
100%	2016
All vehicles must adhere to compliance schedule in Table 3-13	2020

Fleets may take advantage of a number of credits and exemptions, which are summarized in the ARB compliance guidance fact sheet [166]. In addition to these stipulations, there are unique phase-in options as well as compliance deadlines available to the following types of vehicles:

- Small fleets (own between 1 and 3 vehicles) [167]
- Agricultural vehicles [168]
- Logging trucks [169]
- Low-mileage construction trucks [170]
- Low-use vehicles [171]

- School buses [172]

3.3 Fuel Consumption and Greenhouse Gas Focused Policies

As a result of the regulatory power granted by the Global Warming Solutions Act (AB 32), the ARB has taken an aggressive stance in curbing GHG emissions from all sectors of the economy, and the significant contribution of climate forcing emissions from the HD fleet has been the driving force behind the policies looking to cut fuel use from HD vehicles.

The first two sections are devoted to the US EPA's voluntary SmartWay Program and California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program. The final two sections discuss California's Heavy-Duty GHG Regulation, which builds off of the SmartWay Program, as well as the federal fuel efficiency and GHG regulation, which goes into effect in MY 2014 and impacts all on-road HD vehicles nationwide.

3.3.1 SmartWay Transport Partnership

The SmartWay Transport Partnership is a collaborative voluntary program between the US Environmental Protection Agency and the goods movement industry designed to improve energy efficiency and lower greenhouse gas (GHG) emissions and air pollution. Started in February 2004, the partnership aims to create strong market-based incentives that challenge companies shipping products and the truck and rail companies delivering these products, to improve the environmental performance of their freight operations [173]. The SmartWay program has served as a model for similar programs in many regions around the world, including Europe, Mexico and Guangdong, China.

From its inception, one of the earliest and most influential elements of the SmartWay program was the focus on technologies for reducing fuel use and emissions from tractor-trailers. The work done to test and verify the fuel consumption profiles of equipment and vehicle configurations lead to the *SmartWay* designation, which has become the de facto trademark that is somewhat analogous with the US Department of Energy's Energy Star label for household goods and appliances.

The significant amounts of tractor-trailer testing data amassed in the SmartWay program were an essential building block for the US fuel efficiency and GHG regulation for medium- and HD vehicles (Section 3.3.4)—particularly the portion of the rule focused on tractor efficiency. Moreover, the SmartWay program has helped the EPA to forge partnerships across a diverse set of stakeholders such as trucking fleets, shippers, truck and trailer manufacturers, academia, as well as other agencies in government [174]. As is discussed in Section 3.3.3, the SmartWay program is an essential building block of the ARB's regulation targeting improved efficiency from LH tractor-trailers.

An important function of the SmartWay Transport Partnership is the work done to determine the environmental benefits of commercial truck technologies through testing and analysis and to provide this information to SmartWay partners and the general public. As part of this effort, SmartWay is developing a fuel efficiency test protocol for HD trucks to better quantify the benefits of various designs and technologies. The EPA currently offers a SmartWay designation for tractor-trailer combination trucks. It is a design-based specification developed on the basis of test results for individual components (tires, wheels, aerodynamic equipment, auxiliary power units, and engines) that have been shown to improve fuel efficiency and reduce emissions. The EPA, its SmartWay partners, and others are working to transform the SmartWay designation for HD vehicles by moving towards a performance-based specification [175]. A performance-based specification would be technology-neutral and able to quantify a broad range of HD vehicle configurations and applications, and to measure technical innovations as they emerge.

An example of a SmartWay certified tractor is shown in Figure 2-24. The EPA currently recognizes 18 models as being SmartWay tractors [176]. Elements of the SmartWay specification include smoothed, aerodynamic shapes for the mirrors, bumper, and hood, an integrated roof fairing, cab side extenders (or “gap fairings”), and LRR steer and drive tires. To contrast, a “classic” or “conventional” style tractor is shown in Figure 2-25 [177]. On the classic tractor, there are elements that contribute to increased aerodynamic drag during vehicle operation—particularly at highway speeds. Drag-inducing features include the side exhaust stacks, the air cleaners, an angular front grille and bumper, and the fuel tanks and battery box.

Trailers can achieve SmartWay designation in a number of different ways. First, SmartWay certified LRR tires must be used, and there is an optional measure to use aluminum wheels (and/or integrate other lightweight materials into the design) to achieve weight reduction. For aerodynamic improvements, there are five options, each of which is certified to provide 5% or greater fuel savings [176]. These options are depicted in Figure 3-7. There are currently dozens of companies that offer SmartWay certified aerodynamic equipment that are available on new trailers as well as retrofit devices [178]. Also, there are roughly 40 different brand offerings of LRR tires (duals or single-wide tires) for tractor trucks and trailers [179].

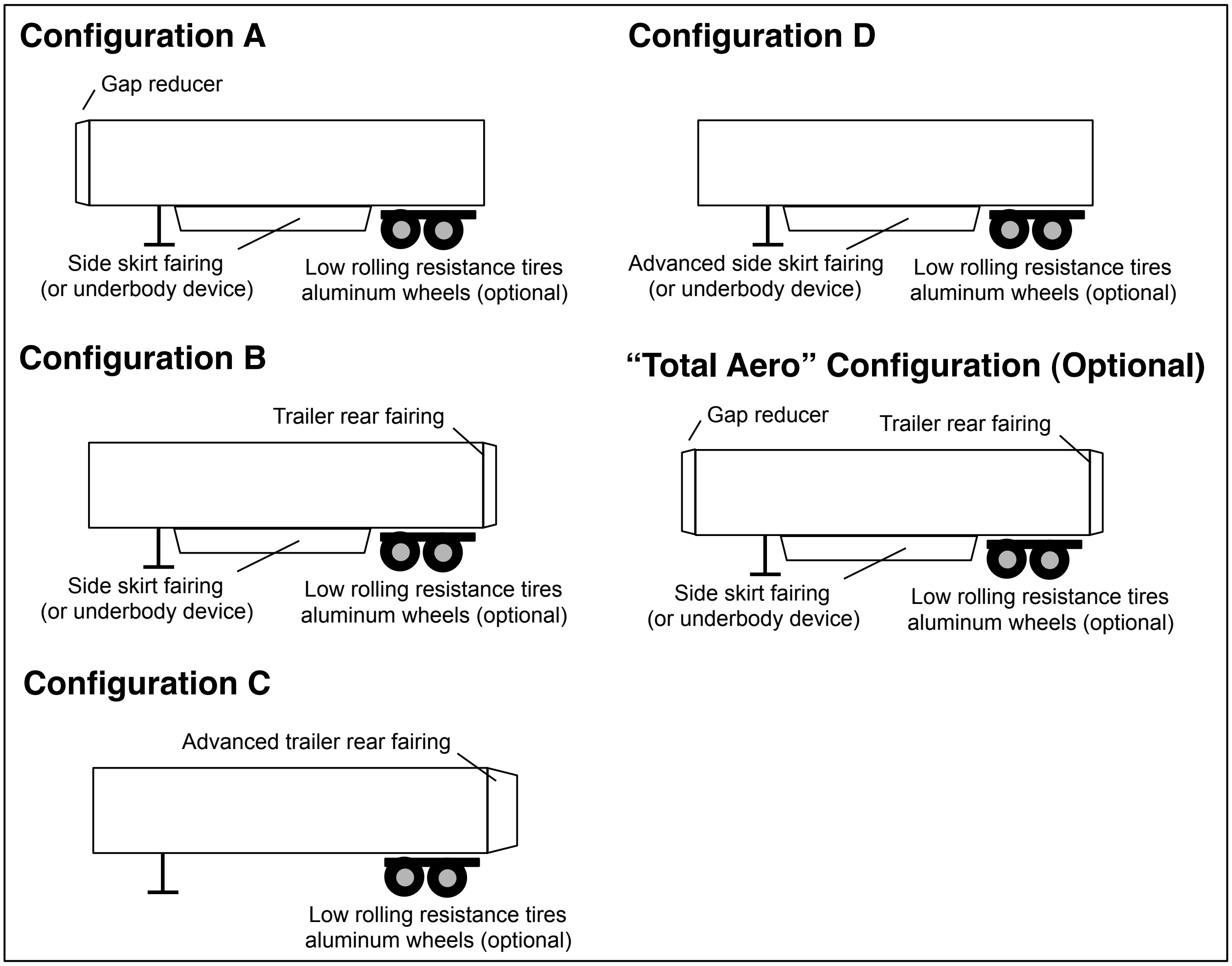

Figure 3-7: SmartWay certified trailer configurations (figures created using examples shown in [176])

3.3.2 Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program

The Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program (HVIP) was originally established in 2009 as a cornerstone of the Air Quality Improvement Program (AB 118) [180]. The purpose of HVIP is to encourage the purchase of hybrid and advanced technology trucks and buses by offsetting about half of the incremental cost of these vehicles. The program is structured such that end-user fleets apply for vouchers on a first-come, first-served basis, and fleets are able to redeem the incentive amount for an eligible vehicle at the dealership at the time of purchase. The HVIP is administered through a partnership between the ARB and CalStart.

The vouchers currently range from about $10,000 to $60,000 and are based on vehicle size as well as the level of electrification (i.e. hybrid, plug-in hybrid, or all-electric), as summarized in Table 3-15 [111]. Vouchers amounts increase as GVWR classes get heavier, and zero emission vehicles are eligible for roughly up to $15,000 more than hybrid vehicles.

Fiscal year 2012-2013 is the third year of the program, and there are twelve vehicle manufacturers offering a wide range of hybrid and electric vehicles, which are listed in the HVIP database [181]. Beginning in 2012, not only are traditional hybrids qualified for funding, but work site trucks with the ability to operate power take-off (PTO) systems in all-electric mode are eligible as well. As of November 2012, 1,130 vehicles have been funded through HVIP, and a breakdown of how the vouchers have been distributed by vehicle type is shown in Figure 3-8 [111]. Together, beverage and parcel delivery vehicles represent roughly two-thirds of the issued vouchers, with the remaining third made up of trucks and buses primarily operating in city or suburban applications.

Table 3-15: Voucher amounts available in the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program

Hybrid Vehicle Voucher Amounts		
Gross Vehicle Weight Rating	Incentive Amount*	
	First 3 Vouchers	4th through 100th Vouchers
6,001 – 8,500 pounds (plug-in hybrids only)	$10,000	$8,000
8,501 – 10,000 pounds (plug-in hybrids only)	$15,000	$10,000
10,001 – 19,500 pounds	$25,000	$15,000
19,501 – 33,000 pounds	$30,000	$20,000
33,001 – 38,000 pounds	$35,000	$25,000
Greater than 38,000 pounds	$40,000	$30,000
Zero Emission Vehicle Voucher Amounts		
5,001 – 8,500 pounds	$15,000	$12,000
8,501 – 10,000 pounds	$23,000	$18,000
10,001 – 14,000 pounds	$40,000	$30,000

14,001 – 19,500 pounds	$45,000	$35,000
19,501 – 26,000 pounds	$50,000	$40,000
Greater than 26,000 pounds	$55,000	$45,000

* Each fleet is able to receive a maximum of 200 vouchers. The 101st though the 200th voucher per fleet are discounted by roughly 25%.

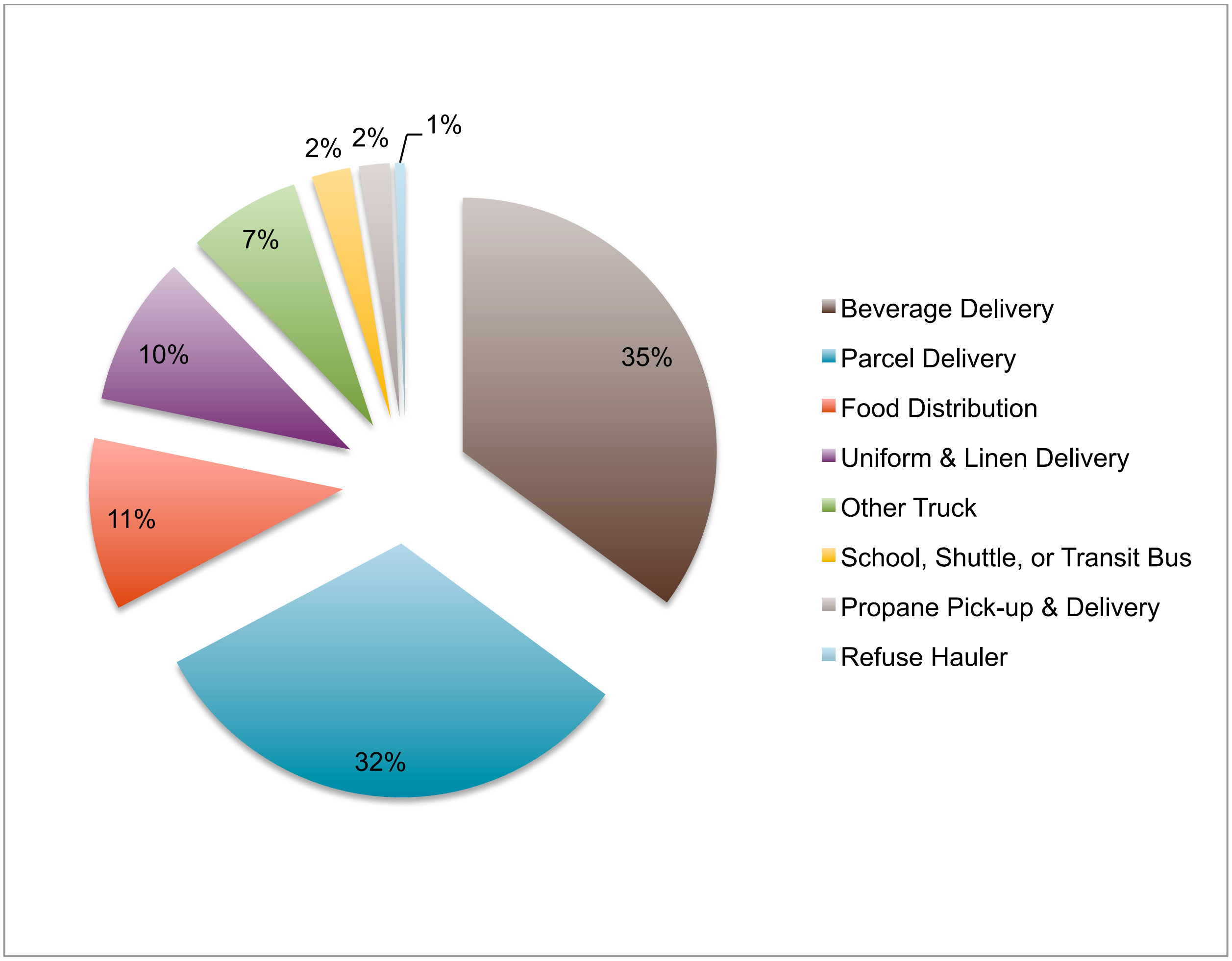

Figure 3-8: Breakdown of vouchers issued in the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program as of November 2012 (created using data from [111])

3.3.3 California Heavy-Duty GHG Regulation

As part of the AB 32 mandate to reduce GHG emissions from all sectors of the California economy, the ARB developed a regulation that aims to increase the efficiency of LH tractor-trailers operating in California. This regulation, which was first proposed in late 2008 and formally finalized in early 2012 [182], has mandatory equipment specification provisions for end-users that affect both tractors and trailers. The reduction in fuel use and GHG emissions will be achieved by requiring the use of aerodynamic tractors and trailers that are also equipped with low rolling resistance tires. The tractors and trailers subject to this regulation must either use US EPA SmartWay certified tractors and trailers or be retrofitted with SmartWay verified technologies. California's program is the first in-use GHG regulation in the world and is estimated to reduce GHG emissions by 6 to 10 percent for any LH tractor-trailer that operates in California, which is roughly 30 percent of all such tractor-trailers in the US [183].

The regulation affects owners of 53-foot or longer box-type trailers, including both dry-van and refrigerated-van trailers as well as the owners of the HD tractors that pull them on California highways. The owners of these types of equipment are responsible for replacing or retrofitting their affected vehicles and trailers with compliant aerodynamic technologies and low rolling resistance (LRR) tires. All owners, regardless of where their vehicles are registered, must comply with the regulation when operating in California. Equipment dealers who sell affected vehicles and trailers in California must provide disclosure about the regulation to the buyer.

Table 3-16 and Table 3-17 summarize the requirements of the program and compliance dates for fleets [182]. There are specific requirements for large fleets, which are defined as any fleet operating 21 or more trailers. Fleets operating 20 or less trailers are regulated under the small fleet provisions. The compliance schedule options for large and small fleets are shown in Table 3-18 and Table 3-19 [ibid].

The stipulations of the tractor component of the rule are fairly straightforward. Starting January 1st, 2010, MY 2011 and newer sleeper tractors must be SmartWay certified, and MY 2011 and newer day cabs must have SmartWay verified LRR tires. All MY 2010 and older tractors are required to have LRR tires by January 1st, 2013.

As with tractors, the requirements of the trailer program are based on the MY and the type of equipment. As shown in Table 3-17, there are unique provisions and compliance deadlines based on whether the trailer is refrigerated or a dry van as well as the trailer's MY. The aerodynamic requirements for trailers are given in terms of a percentage: 4% or 5%. The percentage refers to the SmartWay designation for the certified fuel-savings level of a given piece of equipment. In the SmartWay verification scheme, aerodynamic devices are certified as providing 1%, 4%, or 5% fuel-savings. For dry van trailers requiring 5% fuel savings, users can combine a 1% certified device with a 4% certified device or opt for a 5% certified device. Operators of refrigerated trailers are only required to install an aerodynamic device that is certified to the 4% level.

Table 3-16: Tractor requirements for the California HD GHG Regulation

Affected Tractors	Requirements	Compliance Date
MY 2011 and newer sleeper cab tractors	SmartWay Certified (no retrofit available)	January 1, 2010
MY 2011 and newer day cab tractors	SmartWay verified LRR tires	January 1, 2010
MY 2010 or older tractors (day and sleeper cabs)	SmartWay verified LRR tires	January 1, 2013

Table 3-17: Trailer requirements for the California HD GHG Regulation

Affected Trailers	Requirements	Compliance Date
MY 2011 and newer dry vans	LRR tires + 5% fuel-saving aerodynamic technologies	January 1, 2010
MY 2011 and newer refrigerated vans	LRR tires + 4% fuel-saving aerodynamic technologies	January 1, 2010

Affected Trailers	Requirements	Compliance Date
MY 2010 or older box-type trailers	5% or 4% fuel-saving aerodynamic technologies	January 1, 2013
	LRR tires	January 1, 2017
MY 2003-2004 refrigerated van trailers	LRR tires + 4% fuel-saving aerodynamic technologies	January 1, 2018
MY 2005-2006 refrigerated van trailers	LRR tires + 4% fuel-saving aerodynamic technologies	January 1, 2019
MY 2007-2009 refrigerated. van trailers	LRR tires + 4% fuel-saving aerodynamic technologies	January 1, 2020

Table 3-18: Large fleet (operating > 20 trailers) compliance options for MY 2010 and older box-type trailers

	Percent of Trailer Fleet that Must Comply					
By Jan 1st:	2011	2012	2013	2014	2015	2016
Option 1	5%	15%	30%	50%	75%	100%
Option 2	-	20%	40%	60%	80%	100%

Table 3-19: Small fleet (operating < 21 trailers) compliance options for MY 2010 and older box-type trailers

	Percent of Trailer Fleet that Must Comply			
By Jan 1st:	2014	2015	2016	2017
Option 1	25%	50%	75%	100%

Large fleets were required to submit a compliance plan to the ARB by July 1, 2010 if taking advantage of Option 1 and by June 1, 2012 for Option 2. Required compliance plan elements include a statement of intent, full trailer fleet inventory, number and listing of all affected trailers that operate in California, the annual conformance number for trailers, and the early compliance option report, if applicable. The early compliance option report lists the trailers that were in compliance by January 1, 2010 and which will be brought into compliance before January 1, 2017. If opting to take advantage of the schedule set forth in Table 3-19, small fleets were required to submit a compliance plan to the ARB by September 1, 2012.

Table 3-20 summarizes the exemptions and special provisions that are provided for certain types of equipment. Fleets must register with the ARB to take advantage of short haul, local haul or storage trailer exemptions, and passes [184].

Table 3-20: Exemptions and special provisions for the California HD GHG Regulation

Not Affected by the Regulation	Special Provisions Available
• Non-van type trailers such as flatbeds, tankers, grain, and dump trailers • Military tactical vehicles • Authorized emergency vehicles • Drayage tractors that operate within a 100-mile radius of a port of intermodal rail yard • Curtain side trailers • Solid waste vehicles • Drop-frame trailers • Container chassis	• SH tractors • Local-haul tractors • Storage trailers • Non-compliant tractors • Relocation of local-haul or storage trailers • Transfer of ownership of trailers • Open-shoulder drive tires

A short-haul (SH) tractor is defined as a tractor that travels less than 50,000 miles per year (both in and outside of California). SH tractors are not required to comply with the aerodynamic or tire requirements of the rule. There are no such provisions for "short-haul" trailers. However, trailers are not subject to any requirements when being pulled by SH tractors, but this exemption does not apply when the trailer is pulled by a regulated tractor.

A local-haul tractor is an affected tractor that operates exclusively within a 100-mile radius of its dispatch location or base. A local-haul distinction offers the tractor exemption from needing to be SmartWay certified, but LRR tire requirements are still in place. As with tractors, local-haul trailers operate within 100 miles of their home base and only have to comply with the LRR tire portion of the rule.

Trailers that are primarily used for stationary storage can register for an exemption. These trailers do not need to utilize aerodynamic devices or LRR tires but must be empty when traveling on California highways. In order to travel with freight, a storage trailer must be granted a relocation pass. In addition to storage trailers, relocation passes are issued by the ARB for the situations described in Table 3-21.

Table 3-21: Relocation passes available for tractors and trailers

Pass Type	Description	Situation
Relocation pass for local-haul and storage trailers	• 4 passes/year limit • Pass good for 3 days	Allows movement of loaded exempt local-haul or storage trailers
Transfer of ownership pass for trailers	Pass good for 3 days	Allows delivery of loaded trailers from transferor's location to transferee's location
Non-compliant tractor pass	• 1 tractor per fleet per year • Pass good for 3 days • Sunsets in 2015	Allows a non-compliant tractor to pull a trailer in CA

Due to the fairly extensive reach of this regulation, the ARB has developed and maintains a widespread outreach and education campaign. During the multi-year regulatory development process, the ARB held numerous public workshops to engage with a host of different stakeholders on a wide range of technical and economic issues. In addition, the ARB continually holds free courses across the state that present information about the program and detailed compliance training for affected parties [185]. Also, the ARB has developed a website called the *Truck Stop*, where users can navigate to information about all of the state's regulations affecting in-use HD diesel vehicles and equipment. All of the reporting for the Tractor-Trailer GHG Rule (as well as the Truck and Bus Rule) can be conducted through the Truck Regulation Upload, Compliance, and Reporting System [186].

To help with purchasing equipment that is required under the regulation, both large and small fleets are eligible for incentive funding through the ARB Heavy-Duty Vehicle Air Quality Loan Program, the SmartWay Finance Program, and the SmartWay Clean Diesel Finance Center [184]. In addition, Cascade Sierra Solutions (CSS) is a non-profit organization that promotes SmartWay verified technologies primarily by helping fleets obtain grants, tax incentives, and low-interest loans to aid in the purchase of emission-reducing and fuel-saving equipment. CSS operates Green Truck Centers nationwide and has already helped hundreds of fleets procure equipment that is needed to comply with California's HD GHG rule [187].

3.3.4 US Heavy-Duty Vehicle Fuel Efficiency and GHG Regulation

In addition to the California regulation, policy action at the federal level is also impacting how HD vehicles in California will improve over time in terms of fuel efficiency and GHG performance. The national HD vehicle fuel consumption and GHG program, which was finalized in August 2011, regulates not only tractors but all on-road vehicles greater than 8,500 pounds. However, unlike the California regulation, the national regulation does not include trailers.

The standards are the first fuel efficiency regulatory program for HD vehicles that target improvements beyond the engine. Japan bears the important distinction of establishing the first fuel economy standards for HD vehicles in 2006, but those standards are primarily focused on the engine rather than the full vehicle [188]. Compared to Japan's regulation, the US rule adds two important elements: 1) separate standards to drive engine and vehicle improvements and 2) standards for four major GHGs (CO_2, CH_4, N_2O, and hydrofluorocarbons) in addition to fuel consumption provisions.

The EPA and NHTSA worked collaboratively to develop regulations under their respective authorities: the EPA developed GHG emission standards under the Clean Air Act, and NHTSA developed fuel efficiency standards under the Energy Independence and Security Act (EISA). The standards in the EPA and NHTSA programs are identical, based on conversion factor for fuel consumption to CO_2 emissions. In addition, the EPA standard also includes limits on engine N_2O and CH_4, as well as limits on emissions of refrigerant from air conditioning systems. The EPA program begins in MY 2014, while the NHTSA program will be voluntary in MYs 2014 and 2015 and will become mandatory starting in MY 2016. The reason for the difference in timelines is the EISA requires NHTSA to have four full years of lead-time following the finalization of the rule. The EPA has no such lead-time provision under the Clean Air Act.

Across the various vehicle categories in the regulation, the stringency of the program ranges from 6 to 23% reduction in fuel consumption and CO_2 emissions in the MY 2017 timeframe as compared to a MY 2010 baseline. From Table 6-11 in the Regulatory Impact Analysis [105], the EPA and NHTSA estimate that fleet-wide per-vehicle fuel consumption (gallons/100 miles) will decrease between 5% and 16% by MY 2018, which is shown in Figure 3-9. This represents annual fuel consumption reductions between 1.1% and 3.4%.

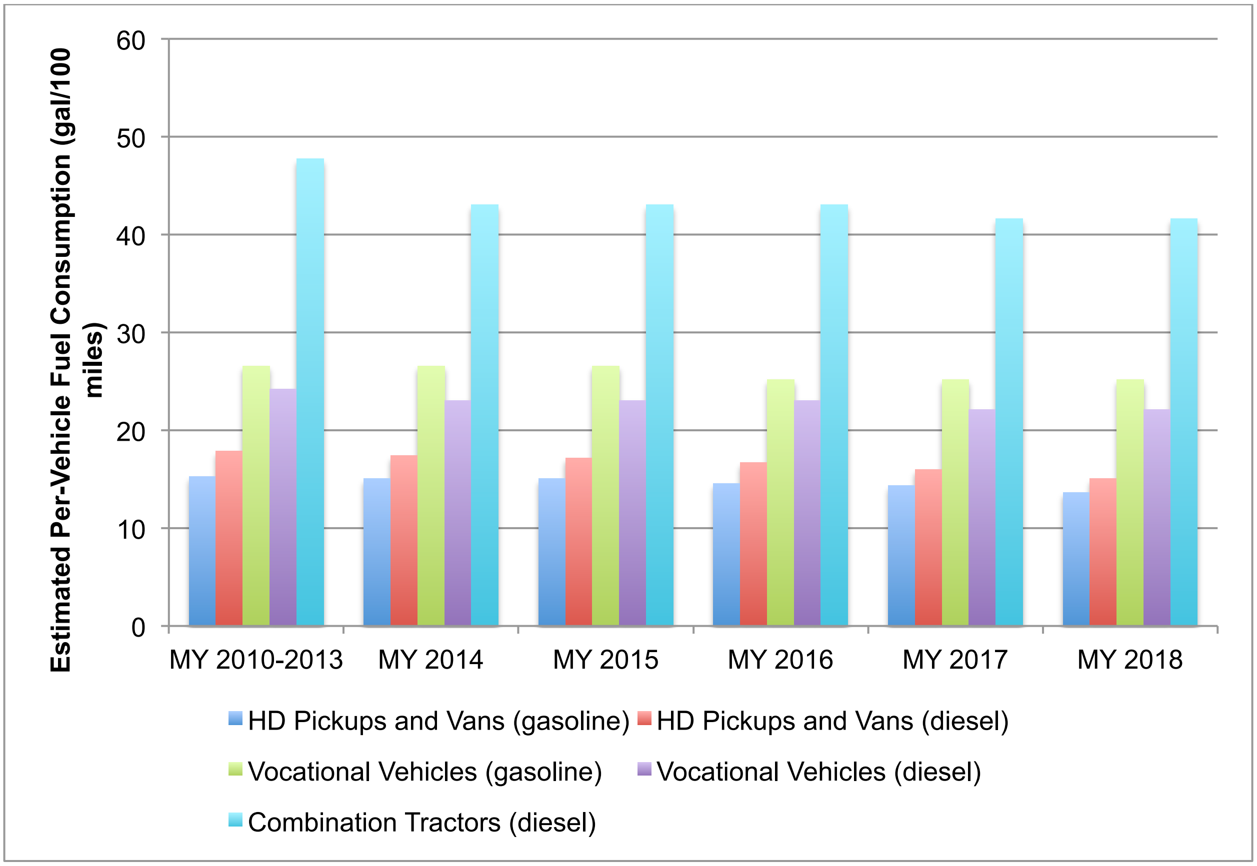

Figure 3-9: Estimated per-vehicle fuel consumption by MY due to the EPA and NHTSA HD vehicle standards (created using data from Table 6-11 in [105])

The stringency levels of the regulation vary based on vehicle subcategories that are defined by weight classes and vehicle attributes. The rule is best understood as three separate regulatory programs linked to specific provisions for Class 7 and 8 tractor trucks, “vocational” vehicles, and Class 2B and 3 pickup trucks and vans. For tractors and vocational vehicles, the engine and the overall vehicle are subject to separate regulations, whereas Class 2B and 3 pickup trucks and vans are regulated as whole vehicles, and there are no specific engine provisions. Each of the programs for these three vehicle regulatory subcategories is summarized below.

3.3.4.1 Class 7 and 8 Tractor Trucks

For the vehicle-based part of the tractor program, the regulation outlines nine subcategories based on three dimensions: GVWR, cab configuration (day or sleeper cab), and roof height (low, medium, or high). The respective metrics for the EPA and NHTSA vehicle programs are grams of CO_2 per ton-mile and gallons of fuel per 1,000 ton-miles, where a ton-mile is defined as a ton of payload transported one mile. The EPA standards for all of the vehicle subcategories are shown below in Figure 3-10. As compared to the baseline values, which are meant to represent average MY 2010 tractors, the values for MY 2014 are a 7 to 20% improvement, depending on the specific tractor subcategory. The tightening of the standard in MY 2017 represents a 9 to 23% improvement over the MY 2010 values. The increased stringency in the MY 2017 standard is predicated solely on a tightening of the engine regulation in MY 2017.

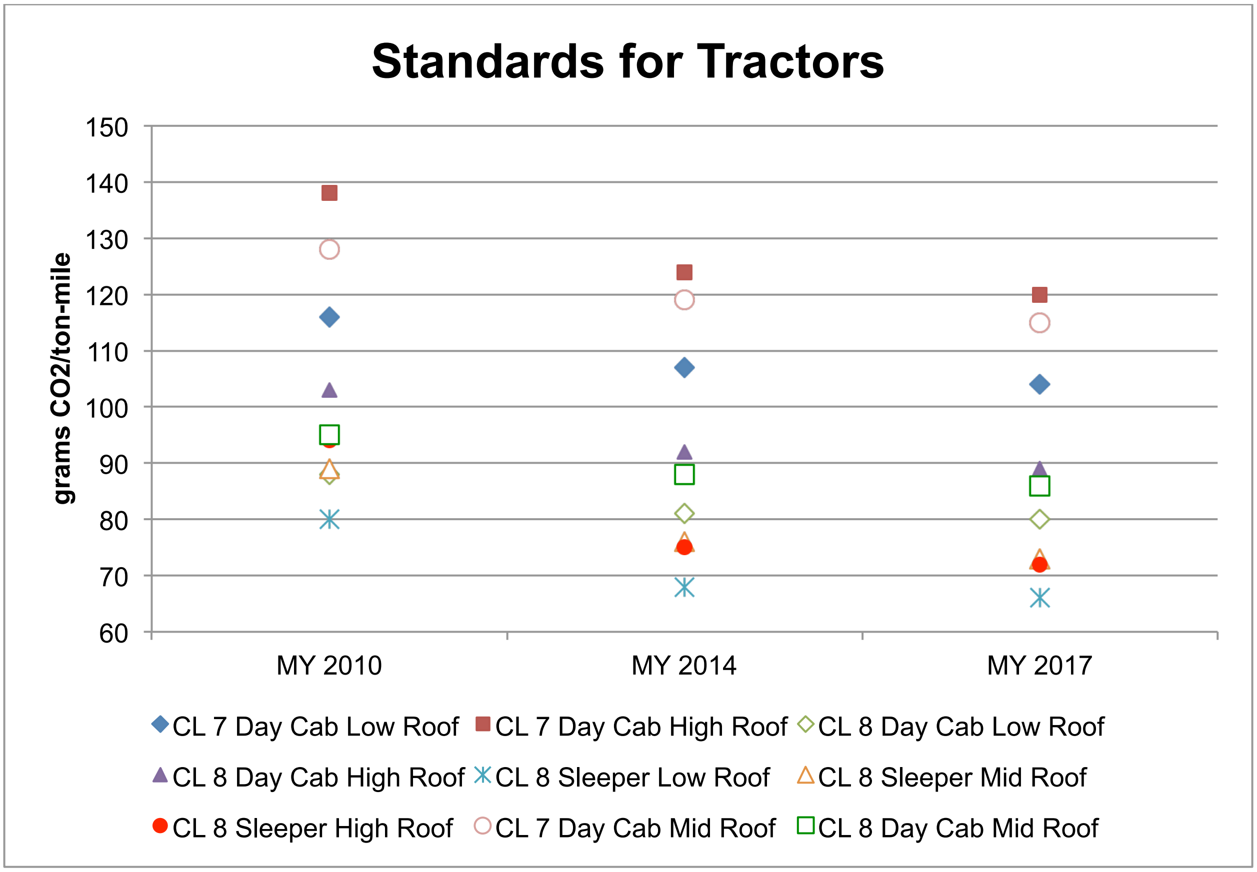

Figure 3-10: EPA CO_2 standards for tractors (created using data from Table II-1 in [189])

The stringency levels of the tractor standards are based on the adoption of currently available technologies and include improvements in aerodynamic design, use of lower rolling resistance tires, vehicle weight reduction, and extended idling reduction technologies.

The EPA and NHTSA developed a MATLAB/Simulink-based software program called the Greenhouse gas Emissions Model (GEM) to evaluate fuel use and CO_2 emissions through the simulation of whole-vehicle operation. This model is used to certify vehicle compliance with GHG and fuel efficiency standards, based on model inputs specific to each vehicle. Conceptually, GEM is similar to many models that have been developed by other research institutions and commercial entities in that it uses various inputs to characterize a vehicle's properties (weight, aerodynamics, and rolling resistance) and predicts how the vehicle would behave on a second-by-second basis when following a specific drive cycle [190].

The inputs in the GEM are associated with many features of the vehicle that have a strongest impact on fuel consumption and CO_2 emissions. In GEM the pre-defined parameters include the tractor-trailer combination curb weight, payload, engine characteristics, and drivetrain for each vehicle type. For tractors, manufacturers have five modeling inputs available: 1) coefficient of drag (C_d), 2) rolling resistance (kg/metric ton) for both steer and drive tires, 3) weight reduction credits (for any use of lightweight materials), 4) extended idle reduction technology, and 5) vehicle speed limiting.

To determine the aerodynamic coefficient of drag, tractor manufacturers may use coastdown testing, wind tunnel testing, or computational fluid dynamics (CFD) simulation. However, to address consistency and level playing field concerns, the enhanced coastdown method has been set as the reference test method, and, as such, all C_d results developed using wind tunnel testing or CFD must be aligned against the reference method. Any alternative aerodynamic testing method must be correlated to the enhanced coastdown procedure using a reference vehicle. After determining a C_dA result from testing, the tractor will be assigned a bin number based on the values in Table 3-22 (or Table 3-23 in the case of low and mid roof tractors), and the corresponding C_d value in the lower portion on the table will be the actual input into the GEM.

Table 3-22: Aerodynamic test results and GEM inputs for high roof tractors (created using data from Table II-7 in [189])

	Class 7	Class 8	
	Day Cab	Day Cab	Sleeper Cab
	High Roof	High Roof	High Roof
Aerodynamic Test Results (C_dA in m^2)			
Bin I	≥ 8.0	≥ 8.0	≥ 7.6
Bin II	7.1 – 7.9	7.1 – 7.9	6.7 – 7.5
Bin III	6.2 – 7.0	6.2 – 7.0	5.8 – 6.6
Bin IV	5.6 – 6.1	5.6 – 6.1	5.2 – 5.7
Bin V	≤ 5.5	≤ 5.5	≤ 5.1
Aerodynamic Input to GEM (C_d)			
Bin I	0.79	0.79	0.75
Bin II	0.72	0.72	0.68
Bin III	0.63	0.63	0.60
Bin IV	0.56	0.56	0.52
Bin V	0.51	0.51	0.47

Table 3-23: Aerodynamic test results and GEM inputs for low and mid roof tractors (created using data from Table II-8 in [105])

	Class 7		Class 8			
	Day Cab		Day Cab		Sleeper Cab	
	Low Roof	Mid Roof	Low Roof	Mid Roof	Low Roof	Mid Roof
Aerodynamic Test Results (C_dA in m^2)						
Bin I	≥ 5.1	≥ 5.6	≥ 5.1	≥ 5.6	≥ 5.1	≥ 5.6
Bin II	≤ 5.0	≤ 5.5	≤ 5.0	≤ 5.5	≤ 5.0	≤ 5.5
Aerodynamic Input to GEM (C_d)						
Bin I	0.77	0.87	0.77	0.87	0.77	0.87
Bin II	0.71	0.82	0.71	0.82	0.71	0.82

For tire rolling resistance, manufacturers must determine GEM input values experimentally by using the International Organization for Standardization (ISO) 28580 test method. This test will be used to determine the rolling resistance coefficient (C_{RR}, measured in kilogram per metric ton) for both the steer and drive axle tires. In addition, tractor manufacturers can use up to three other parameters in the vehicle certification process:

- *Speed limiter* – if top speed is limited to below 65 mph an alternate test cycle is used to reflect this lower top speed.
- *Weight reduction* – if manufacturers use single-wide tires, aluminum wheels, or substitute aluminum or high-strength steel for other vehicle components, they can increase the payload weight used for fuel use and CO_2 calculations by the amount that the actual truck weight is reduced as compared to the standard value. The complete list of weight reduction default values, which are based on material substitution, can be found in Table II-9 of the regulation [189].
- *Extended idling reduction (Class 8 sleeper cab tractor only)* – If equipped with this technology, the GEM model credits the tractor 5 g/ton-mile CO_2 emissions. For low-, mid-, and high-roof sleeper cabs, this 5 g/ton-mile credit is 6.3%, 5.6%, and 5.3% of total baseline emissions, which are 80, 89, and 94 g/ton-mile for the respective subcategories.

The engine component of the tractor (and vocational vehicle) regulation is designed as an extension of the EPA's criteria pollutant regulatory program. Engine testing for compliance with GHG and fuel efficiency standards will occur simultaneously with testing for criteria pollutants including oxides of NOx, PM, CO, and HC using the same procedures and test cycles. In effect, three more pollutants must be measured and reported: CO_2, CH_4, and N_2O.

As with the vehicle regulation, the EPA engine standard (grams per bhp-hr) begins in MY 2014, For the MY 2014 standard, the engine technology package includes engine friction reduction, improved aftertreatment devices, improved combustion processes, and low temperature exhaust gas recirculation (EGR) optimization. The engine standard ratchets down in MY 2017 and adds turbocompounding to the MY 2014 technology package. As described above, the more stringent tractor standards for MY 2017 (see Figure 3-10) reflect the CO_2 emissions reductions required through the MY 2017 engine standards. Figure 3-11 shows the standards for medium- and heavy-heavy engines in MYs 2014 and 2017, as well as the MY 2010 baseline values. An engine is categorized as medium-heavy if its intended use is in Classes 6 and 7 vehicles and heavy-heavy for use in Class 8 vehicles. Along with these CO_2 standards, the limits for both N_2O and CH_4 are 0.10 grams/bhp-hr.

In addition to the engine and vehicle standards for CO_2 and the engine limits on N_2O and CH_4, there is a separate standard to reduce leakage of hydrofluorocarbons (HFCs). These standards are structured in 'percentage of refrigerant leakage per year' to reflect the variety of air conditioning designs in the HD sector. The EPA has finalized a standard of 1.5% leakage per year for Class 7 and 8 tractors that have a refrigerant capacity of greater than 733 grams. It is estimated the average percent leakage for a MY 2010 vehicle is roughly 2.7%. For vehicles with air conditioning systems with a refrigerant capacity of 733 grams or lower, the EPA has defined the standard in terms of leakage rate, at 11.0 grams per year.

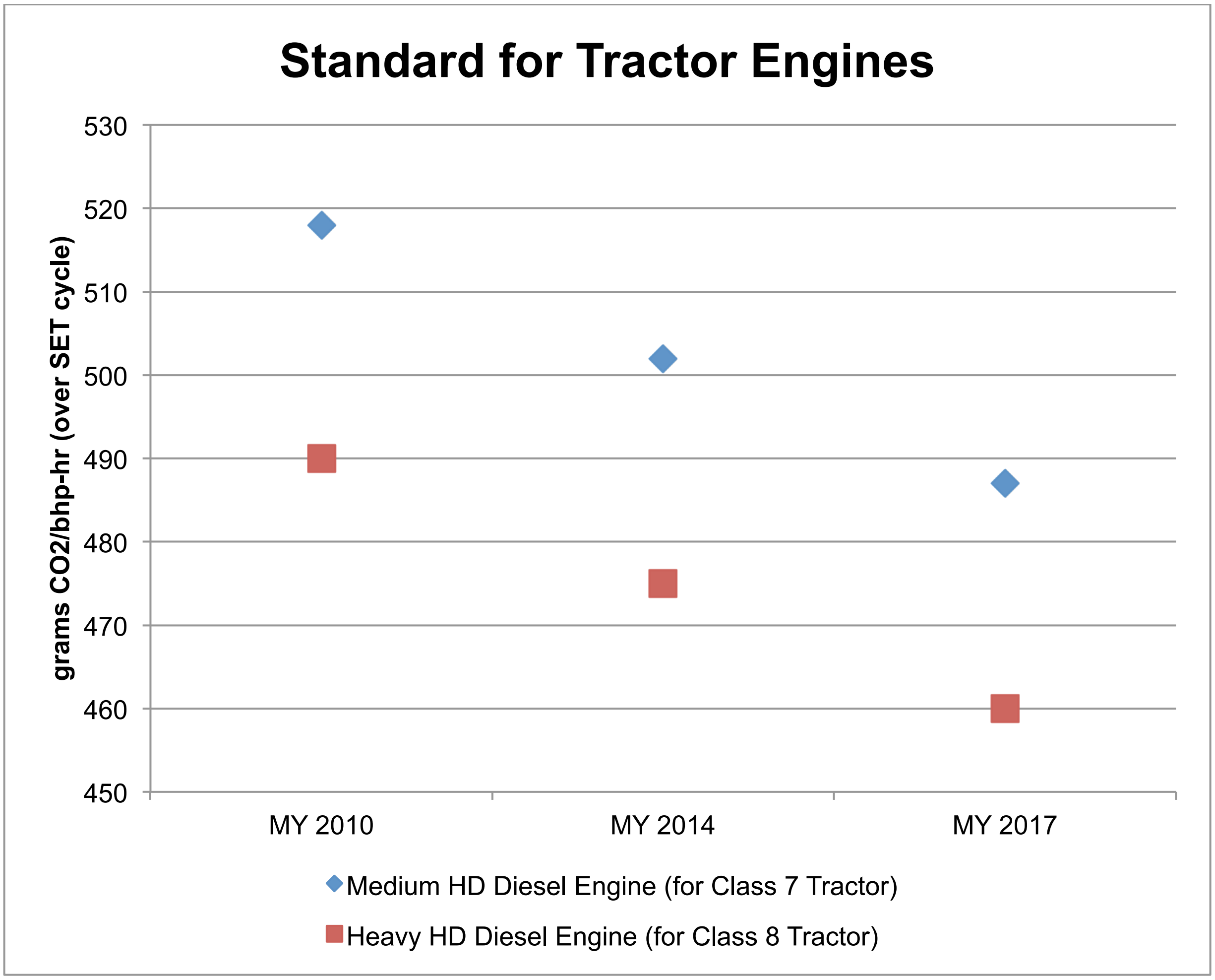

Figure 3-11: EPA CO_2 standards for tractor engines (created using data from Table II-3 in [189])

For tractors, Class 2B and 3 pickup trucks and vans, vocational vehicles, and engines, compliance with the standards is based on sales-weighted averaging. In this flexibility scheme, each individual vehicle (or engine) model is not required to meet the standard. Rather, the vehicle model generates a credit for certifying at a lower CO_2 value than the standard or a debit for certifying above the standard value. For example, credits or debits for tractors are calculated in terms tons CO_2 (or gallons for the NHTSA regulation) based on the following equation:

Credit (or debit) = (Standard – Actual) x (Payload Tons) x (Volume) x (UL) x (10-6) *where*

Standard = the standard of the specific tractor regulatory class (grams/ton-mile)
Actual = certification results from the GEM simulation (grams/ton-mile)
Payload tons = 12.5 tons for Class 7 tractors and 19 tons for Class 8 tractors
Volume = (projected or actual) production volume of the tractor model
UL = useful life of the tractor (435,000 miles for Class 8 and 185,000 miles for Class 7)

Final production volumes are needed to determine each manufacturer's compliance status. Manufacturers must make a "good faith" demonstration of their production estimates for a given MY, and then after production ends, the manufacturers' compliance credits (or debits) are calculated. Manufacturers are allowed to carry forward deficits from the regulatory subcategories for three years before reconciling the shortfall. For vehicles, there are three categories for averaging, banking, and trading (ABT) credits: light HD (Classes 2B through 5), medium HD (Classes 6 and 7), and heavy HD (Class 8). For engines, the ABT categories are based on the same three weight designations (light, medium, and heavy HD) based on the class of vehicle in which the engine is used. Credits or debits generated within an ABT subcategory are useable in that specific subcategory only. Also, credits are not transferrable between engine and vehicle regulatory categories. An exception is that advanced technologies (i.e. hybrid, all-electric, fuel cell vehicles, or engines with Rankine cycle waste heat recovery systems) can generate credits applicable to any category, including engines.

3.3.4.2 Class 2B and 3 Heavy-Duty Pickup Trucks and Vans

The standards for HD pickups and vans are based on a "work factor" attribute that combines vehicle payload capacity and vehicle towing capacity, in pounds, with an additional fixed adjustment for four-wheeled drive vehicles. The definition for work factor (WF) is as follows:

WF = [0.75 x (Payload Capacity + xwd)] + [0.25 x Towing Capacity] *where*

Payload Capacity = GVWR (lbs.) – Curb Weight (lbs.)
xwd = 500 if the vehicle is equipped with 4 wheel drive and 0 otherwise

In the rule, the grams CO2/mile (EPA) and gallons/100 miles (NHTSA) standards are a function of the work factor. As shown in Figure 3-12 below, as the work factor value increases, the limit values for fuel use and CO2 increase linearly. The regulation will be implemented in phases from MY 2014 to 2018 and include separate standards for diesel and gasoline vehicles based on differing technology potential. In MY 2014 the performance standard for diesel and gasoline vehicles in terms of CO2 (and fuel use) per mile are almost identical; however, by MY 2018 the limit line for diesels is roughly 6% lower. The EPA and NHTSA estimate that in MY 2018 the average CO2 emissions as compared to a MY 2010 baseline will be 12% lower for gasoline vehicles and 17% lower for diesel vehicles.

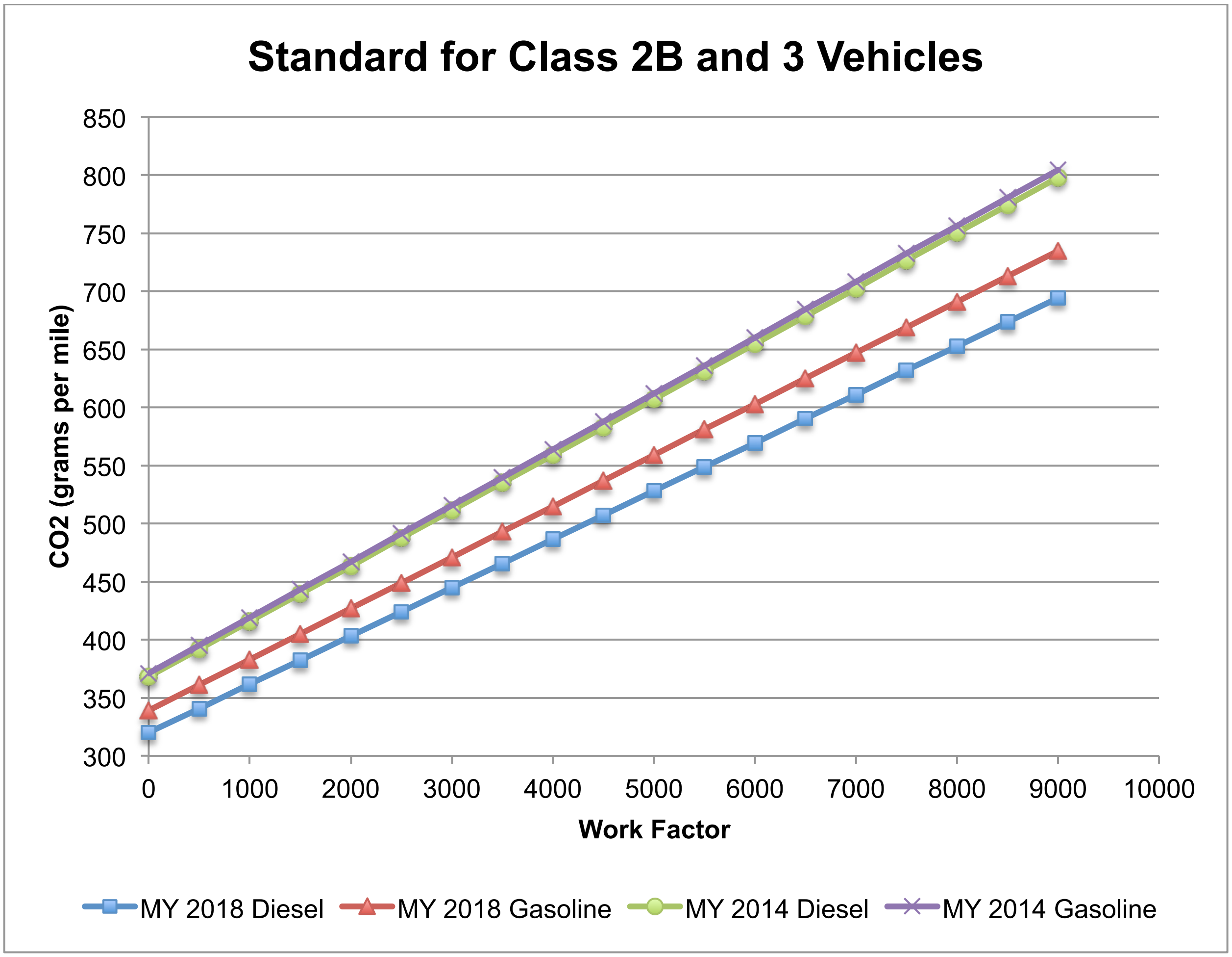

Figure 3-12: EPA CO_2 standards for HD pickup trucks and vans (created using data from Table II-7 in [189])

For HD pickups and vans, vehicle fuel efficiency and CO_2 emission performance is determined on a chassis dynamometer, which closely mirrors the light-duty vehicle program. The primary motivation behind this regulatory approach is the fact the physical characteristics and production of these vehicles are often very similar to their light-duty counterparts in the Class 2A category.

3.3.4.3 Vocational Vehicles

The vocational category encompasses any HD vehicles that are not classified as a tractor or HD pickup or van. This diverse grouping includes vehicles such as bucket trucks, urban delivery vehicles, refuse trucks, and buses. As with the tractors, the EPA and NHTSA have finalized separate vehicle and engine standards for vocational vehicles. Engine manufacturers are subject to the engine regulation, and chassis manufacturers are required to install certified engines in their chassis. Similar to the tractor program, vocational vehicles are certified using the GEM program.

Vocational trucks are divided into three sub-categories by weight: light HD (Class 2B through 5), medium HD (Class 6 and 7) and heavy HD (Class 8). Also, the respective metrics for the EPA and NHTSA programs are grams of CO_2 per ton-mile and gallons of fuel per 1,000 ton-miles. The EPA standards for all of vehicle subcategories are shown below in Figure 3-13. As compared to the baseline MY 2010 values, the standards for MY 2014 are a 4 to 5% improvement, depending on the specific subcategory. The tightening of the standard in MY 2017 represents a 6 to 9% improvement over the MY 2010 values. As with tractors, the increased stringency in the MY 2017 standard is based solely on the MY 2017 engine improvements.

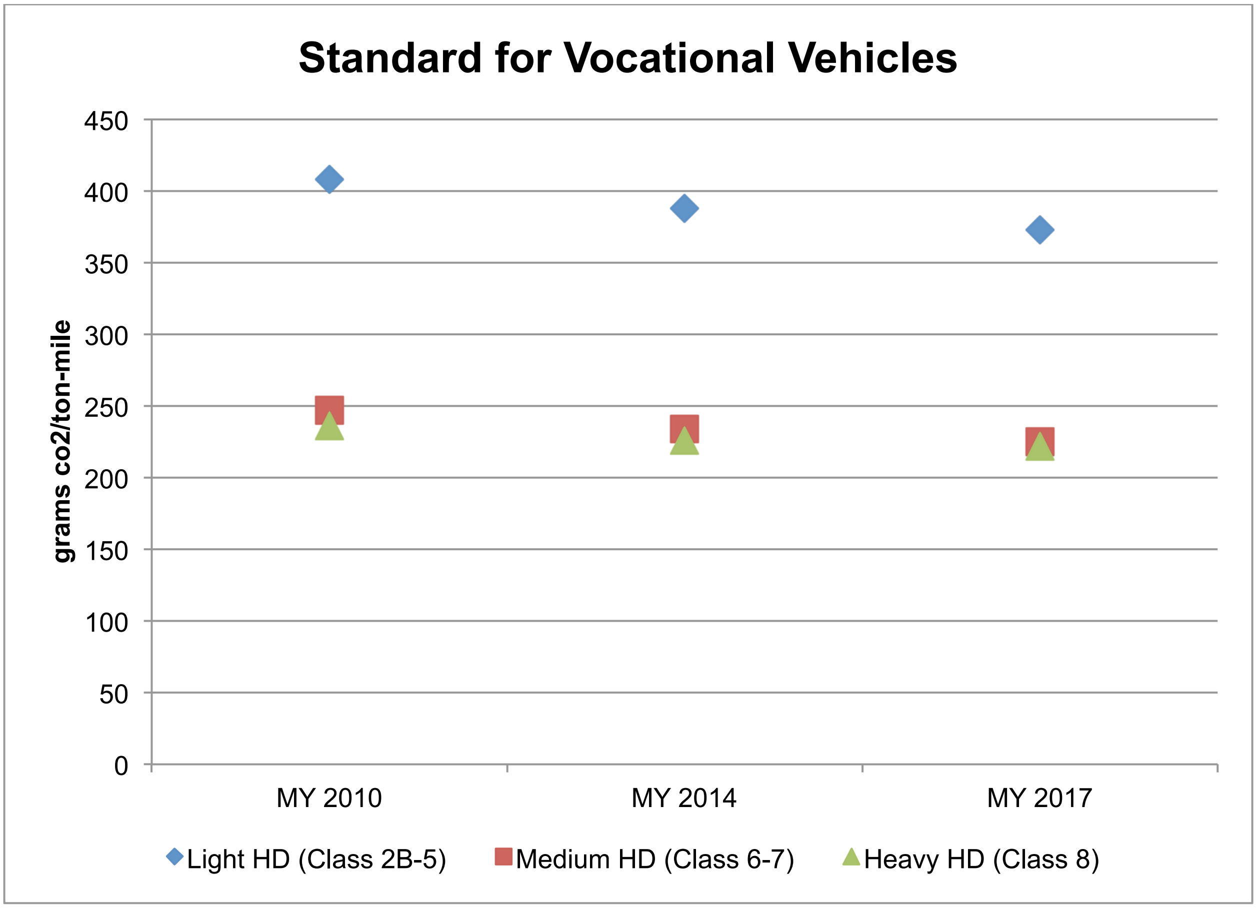

Figure 3-13: EPA CO_2 standards for vocational vehicles (created using data from Table II-15 in [189])

In determining the standard for vocational vehicles, the EPA and NHTSA choose to limit the stringency to what could be achieved with engine improvements and by using low rolling resistance tires. For non-engine systems, they acknowledge the potential in technology areas such as aerodynamics, weight reduction, and transmissions but have decided to only focus on tires to avoid the challenges that are inherent when trying to regulate such a diverse group of vehicles. Including aerodynamics, weight reduction, and transmissions in the program would require that the agencies regulate a wide range of small entities that are final bodybuilders, which is something that was not feasible at the time of the rulemaking.

In addition to the standards for tractors, pickup trucks and vans, and vocational vehicles, there are a number of special provisions and crediting options available to vehicle and engine manufacturers. Some of these include:

- Special certification and compliance provisions for gasoline and alternative fuel engines
- Alternative compliance pathway option for engine manufacturers
- Early credits for compliance prior to MY 2014
- Advanced technology credits for hybrid, all-electric, fuel cell vehicles, or engines with Rankine cycle waste heat recovery systems
- Innovative technology credits for technologies whose fuel use and emissions benefits are not readily captured over the engine test cycles or in GEM simulations (i.e. “off-cycle” benefits)

4 THE TECHNOLOGY OPTIONS AND PATHWAYS FOR HEAVY DUTY VEHICLES (TOP-HDV) MODEL

4.1 Introduction

The Technology Options and Pathways for Heavy Duty Vehicles (TOP-HDV) model examines the emissions, energy use, and costs from the HD vehicle fleet in California over a time horizon between 2010 and 2050. There are a host of various user inputs and data set choices that are all related to the California HD vehicle (HDV) fleet. Included are parameters such as vehicle population and activity, fuel efficiency, private and societal costs, and the discount rate.

The primary objective of this chapter is to provide a detailed description of the external data, user inputs, and calculations used in TOP-HDV. The methodology for calculating vehicle activity, emissions, fuel use, end-user costs, and externality costs are explained as well as the interactions of these individual modules. The chapter begins by describing the model software platform and general flow of data and processes. Following a brief discussion of the six core scenarios in TOP-HDV (Chapter 5 provides much more thorough description of each scenario), the remainder of the chapter details the data and calculation methods utilized in the model.

4.1.1 Software platform, general operating instructions

TOP-HDV is a macro-enabled Microsoft Excel workbook comprised of 54 sheets that is approximately 130 megabites in size. Due to the large data storage and computational requirements, Visual Basic (VB) macros are used as the principal calculation method in the model, and many of the intermediate and final results are stored as values rather than having formulas in each of the applicable cells. While many spreadsheet-based models rely on in-cell calculations, macro-based computation is used in TOP-HDV to improve model stability and ease-of-use. This approach greatly improves the model performance, stability, and size. However, a significant downside of replacing in-cell calculations with VB macros is the reduced transparency of the calculations. Defined names, standardized sheet layouts, and *master macros* (i.e., macros that run a number of sub-macros) have been utilized whenever possible to improve VB code transparency and to reduce the burden during the review and auditing process.

As described in more detail below, the TOP-HDV sheets can generally be grouped into four categories: 1) user interface sheets, 2) data storage sheets, 3) calculation sheets, and 4) output sheets. The user interface sheets are the primary sheets for entering/choosing inputs, building the scenarios, and reviewing the outputs. The user goes through all of the input modules to develop a scenario (or scenarios) on the *Scenario Builder* sheet and then must push a button that will run the requisite macros to create the results that populate tables and graphs on the two output sheets.

4.1.2 Model flow diagram

Figure 4-1 below is a diagram of the model data flows and processes. The four primary types of worksheets in the model are designated by the colors in figure.

> *User interface and inputs (blue)*. The primary place for entering data and making selections that control model parameters is the *Scenario Builder* sheet. Here, users input two types of data. First, *Global Controls* are data that affect calculations for the entire model and include variables such as year-one vehicle miles traveled (VMT), vehicle survival rates, and CO_2 equivalency factors. Second, *Scenario Controls* are inputs for each of the six scenarios that govern technology penetration rates for each of the eight vehicle types.

Data storage and calculation (green). These worksheets serve two functions: storing data that is used as inputs for macros and then storing these macro calculation results in tables. For example, the External Damage Costs worksheet has the unit damage cost values for emissions, energy security, and noise. These factors are used in a macro, and the total emissions, energy security, and noise damage costs for each scenario are then stored in a table on this worksheet.

Calculation-only (grey). These worksheets are similar to the green sheets, except they are only used to store macro results. All of the requisite data used by the macros that output to the grey sheets are stored on green sheets as well as the Scenario Builder worksheet.

Outputs (red). There are two worksheets that summarize the final results of the model. The first contains all of the results for the six scenarios, and the second presents the per-vehicle results for each technology type for the eight vehicle categories.

Macros are the primary calculation engines of TOP-HDV. The macros take inputs from the *Scenario Builder* sheet as well as values from the tables in the data storage sheets in their calculations, and the macro results are written into results tables as *values* on the destination sheets, which can be calculation-only (grey) sheets or data storage and calculation sheets (green). The results that are stored in the green and grey worksheets are then used by *summary* macros, which calculate final results that are displayed in tables and figures on the two outputs worksheets.

The master macros that develop the final results for each of the six scenarios are made up of a sequence of many smaller macros. This progression of calculations and the flow of data are described briefly below and in more detail throughout the chapter.

1. Emission factors: vehicle per-mile and per-hour emission factors (EFs) are adjusted based on user selections and inputs on the Scenario Builder worksheet.
2. Vehicle stock and VMT: this series of macros calculates vehicle populations and VMT for each technology type over time based on 2010 population data and user inputs for survival rates, per-vehicle VMT, and advanced vehicle adoption.
3. Vehicle operating emissions and fuel use: this sequence of macros combines per-mile and per-hour EFs with activity data to calculate total emissions in each year.
4. Fuel and electricity upstream emissions: this group of macros uses unit EFs for fuel and electricity (grams per Btu, grams per kWh) along with the fuel and electricity consumption totals to compute the emissions associated with fuel and electricity production and distribution.
5. Manufacturing and scrappage emissions: these two macros use match EFs (grams per vehicle pound) to annual vehicle production and scrappage totals to calculate the emissions associated with vehicle manufacturing and decommissioning.
6. Private costs (vehicle retail, fuel, operating, and refueling station construction): each of these cost items has a series of macros that links results from previous steps to unit cost data and then outputs totals.
7. Societal damage costs (emissions, energy security, and noise): as with private costs, this final set of macros links results from previous modules with unit cost factors to compute total societal damage costs.

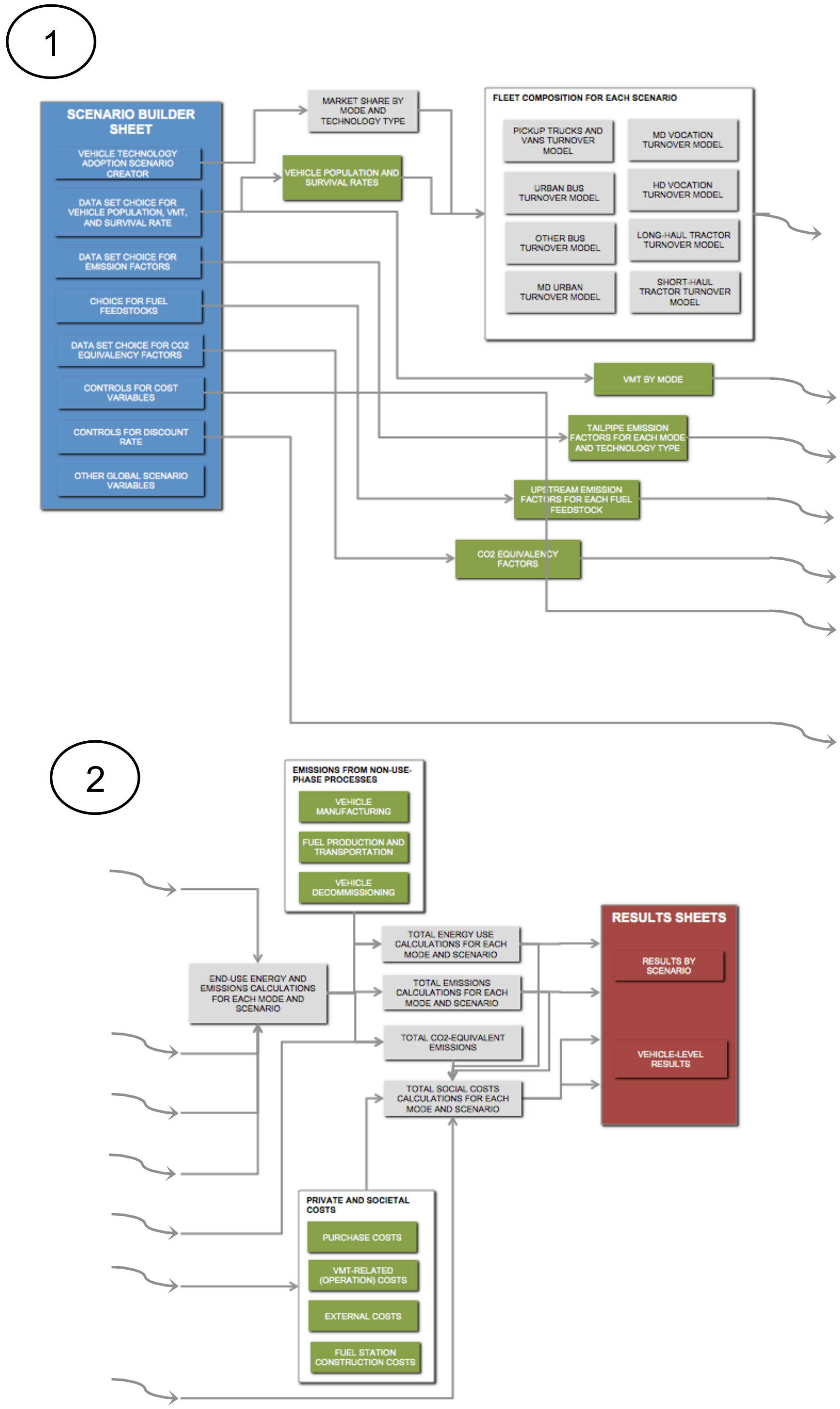

Figure 4-1: Diagram of TOP-HDV data flows and processes (the right side of part 1 connects to the left side of part 2)

4.2 Scenario descriptions

TOP-HDV is designed to have six discrete scenarios. However, as the parameters for each scenario can be modified quickly and each of the scenarios can be run individually, it is perhaps more useful to think of the model as having *scenario groups*. For the sake of simplicity, the term *scenario* will be used to refer to each of the scenario groups.

Forecasting over a 40-year time period is at best a dubious prospect, so none of the six scenarios represent definitive forecasts for the California HD vehicle fleet. Rather, each of the scenarios is intended to illustrate the total costs and benefits of a future that is premised on a particular set of assumptions about vehicle technologies and fuels. The six scenarios are as follows:

- Baseline
- High Efficiency
- Plug-in Hybrids and Electric Vehicles ("PHEVs+EVs")
- Fuel Cell Vehicles ("FCVs")
- Alternative Fuels
- 80% Reduction in CO_2-equivalent Emissions by 2050 ("80in50")

The Baseline scenario represents a trajectory for future developments in the HD vehicle market that resembles status quo vehicle technology improvements and the continued dominance of petroleum-based fuels, namely diesel and gasoline. The commercial introduction of advanced technologies is limited to hybridization, and the demand for alternative fuels such as NG is assumed to remain approximately at 2010 levels and be restricted to captive fleets (i.e. fleets such as transit buses that typically return to a central base(s) on a frequent basis for refueling and maintenance). This scenario assumes no new additional policies aimed at the HD sector are enacted. In other words, if a regulation or program was not implemented by December 31, 2009, the Baseline ignores this policy. An example of a program that is not included in the Baseline scenario is the ARB's Heavy-Duty Greenhouse Gas Regulation, which went into effect in model year (MY) 2011.

The High Efficiency scenario is identical to the Baseline scenario in its technology mix and includes conventional, NG, and hybrid vehicles. The High Efficiency scenario diverges from the Baseline in assuming both larger annual efficiency improvements in new vehicles as well as accelerated penetration of hybrids into the fleet. Unlike the Baseline, the High Efficiency scenario accounts for all policies—both state and federal—that effect HD vehicles in California. Examples of applicable regulations include California's Heavy-duty GHG Regulation and the US EPA and NHTSA's fuel efficiency/GHG program for HD vehicles. In addition to accounting for these policies, this scenario anticipates that GHG-related regulations will be extended beyond their current policy timelines at increasingly stringent levels and continue to drive annual efficiency improvements in new vehicles at a higher rate than is assumed in the Baseline.

The first scenario that assumes significant penetration of advanced driveline electrification (beyond charge-sustaining hybridization) in the HD fleet is the Plug-in Hybrid Electric Vehicles and Electric Vehicles (PHEVs+EVs) scenario. PHEVs+EVs assumes the same annual efficiency improvements in new vehicles as the High Efficiency scenario, but the primary difference is in the large-scale introduction of plug-in hybrid electric and full battery-electric vehicles. For applications such as LH trucking where full electrification does not seem practical given the current and projected limits in battery energy density, there is increased uptake of hybrids at faster rates than were assumed in the High Efficiency scenario.

The second scenario based on widespread adoption of zero tailpipe emission technology is the Fuel Cell Vehicles (FCVs) scenario. However, in this scenario the source of vehicle power is hydrogen fuel cells rather than batteries. At present, fuel cell technology for HD vehicles has only been commercially introduced in the transit bus market and, to smaller extent, in certain urban and regional applications. Nonetheless, this scenario assumes that fuel cell vehicles begin entering the market in the 2025-2030 timeframe, with increasing penetration rates out to 2050. Prior to the introduction of fuel cell vehicles, this scenario assumes increased new vehicle efficiency and hybrid uptake levels similar to the High Efficiency scenario.

The Alternative Fuels scenario focuses on the proliferation of non-petroleum fuels such as NG and renewable diesel derived from waste streams such as forestry residue and municipal solid waste. The assumptions regarding vehicle efficiency and technology uptake are similar to the High Efficiency scenario. Fuel feedstocks are a critical factor in the well-to-tank energy use and emissions of bio-based alternative fuels, and the choice of feedstock (or the combination of feedstocks) is a parameter that can be easily modified in TOP-HDV.

The final scenario, 80% Reduction in CO_2-equivalent Emissions by 2050 (80in50), has aggressive adoption rates of advanced technology and low-carbon fuel options that leads to an 80% reduction in lifecycle CO_2-equivalent emissions from the HD vehicle fleet in California as compared to estimated 1990 levels. This scenario is motivated by the California ARB's Global Warming Solutions Act (AB32) and Executive Order S-3-05. The AB32 rule mandates that California bring total GHG emissions to 1990 levels by 2020, and the Executive Order of former Governor Schwarzenegger calls for statewide GHG reductions of 80% lower than 1990 levels by 2050. Though both of these mandates apply to the entire state and not specific sectors per se, the 80in50 scenario is designed to achieve these targets in the HD vehicle fleet on a lifecycle basis, accounting for emissions related to vehicle operation, fuel production and distribution, vehicle manufacturing, and vehicle scrappage. A key difference between the ARB's analysis of the state climate regulations and this research is the set of emitted species that are included in each study. In AB32 and the Executive Order, the following GHGs are included in the calculation of CO_2-equivalency: CO_2, CH_4, N_2O, sulfur hexafluoride (SF_6), HFCs, and perfluorocarbons (PFCs). In this study, CO_2-equivalency is based on a different set of gases (CO_2, CH_4, N_2O, NOx, CO, SOx, and NMHCs) as well as particle emissions (black carbon, BC and organic carbon, OC). As such, the results from this study are not entirely comparable to the ARB inventories that form the basis for the AB32 programs. Nevertheless, the aim of this scenario is to reduce total lifecycle CO_2-equivalanet emissions 80% below 1990 levels—not simply the gases for which there are overlap between the ARB methodology and this study (i.e. CO_2, CH_4, and N_2O).

4.3 Data and calculation modules

4.3.1 Vehicle categories

The TOP-HDV model is designed to include all on-road vehicles in California with a gross vehicle weight rating (GVWR) greater than 8,500 pounds, except motorhomes. This entire fleet of trucks and buses is collectively referred to as "heavy-duty" in this study, although, as is described below, a subset of vehicles are labeled as "medium-duty" (MD). The truck and bus categories modeled in TOP-HDV encompass the large variety of vehicles that are not passenger (or "light-duty") vehicles. The HD vehicle fleet is incredibly heterogeneous, spanning a wide range of sizes, configurations, and work functions. For the purposes of modeling this diverse assortment of vehicles, it was necessary to categorize vehicles into groups according to size and typical mission profiles. In the model, within each of the categories, all vehicles are assumed to be identical in terms of size, configuration, and activity. Simplifying the HD fleet by modeling in terms of distinct groups is fairly common in vehicle emission inventory analysis and is typified by such models as the ARB's EMission FACtor (EMFAC) model and the US EPA's MOtor Vehicle Emission Simulator (MOVES) [191, 192]. In TOP-HDV, there are eight vehicle categories, which are described below.

HD Pickup Trucks and Vans: this category represents pickup trucks and vans between 8,501 and 14,000 lbs. GVWR. In the US truck classification system, these are Class 2B and 3 vehicles. Figure 4-2 [193] shows the US truck classification system along with examples of typical vehicles within each weight category. Unlike the vehicles in the other categories in the model that are used almost exclusively for commercial purposes, many of the vehicles in this category are used for personal transportation. This is especially true of pickup trucks. Examples of vehicle models in this category include the Ford Super Duty, the Ram 2500, and the GMC Savana Cargo Van. These vehicles are used in a wide variety of different functions and are operated in virtually every sector of the economy that involves physical work—construction, telecommunications, service and repair, etc. For the fuel use and emissions calculations in the model, the assumed vehicle in this category is a Class 2B pickup truck.

Urban Buses: this category represents buses that generally operate in urban areas. Though buses in this category span a large range of weights and functions (transit buses, school buses, shuttles, etc.), for modeling purposes, the representative vehicle for this category is a Class 8 40-foot transit bus.

Other Buses: as opposed to urban buses, which spend the majority of their time in cities in stop-and-go driving, this group of vehicles is analogous to coach buses, which normally spend a much higher percentage of time at highway speeds for intercity and regional passenger movement. The modeled vehicle in TOP-HDV is a Class 8 coach bus.

MD Urban Vehicles: this group captures a large diversity of trucks in Classes 4 through 6 (14,001 to 26,000 lbs. GVWR). As the name suggests, these vehicles spend the majority of their time operating in urban areas, performing a number a different work tasks. While a great range of sizes, configurations, and mission profiles are encompassed by vehicles in this category, a Class 6 pickup and delivery straight (i.e. non-combination) truck is used in the model as the representative vehicle for fuel use and emissions modeling [36]. Some examples of pickup and delivery vehicles include parcel delivery trucks (e.g. UPS, FedEx) and box trucks.

MD Vocational Vehicles: the main distinction of these vehicles from the MD urban category is that vocational vehicles are assumed to spend a sizeable percentage of their operating time powering attachments or separate machines that are not directly related to driving (i.e. the vehicle is often parked at job sites during these work operations). These trucks utilize power-take-off (PTO) devices that transform the rotational energy from the main engine (or power plant) into power for a piece of equipment such as a hoist bucket, trash compactor, or cement mixer. The operator of the vehicle can engage the PTO shaft when a particular device is needed and then disengage the PTO when that work is no longer required. In TOP-HDV, the activity of MD vocational vehicles is modeled in terms of both mileage as well as hours of PTO operation. As with MD urban vehicles, there is significant diversity within this category; however, for modeling purposes, the representative vehicle is a Class 6 bucket truck [36].

HD Vocational Vehicles: as with the MD vocational category, these vehicles operate PTO devices as part of their primary job function. However, these vehicles are in the heaviest range of the spectrum, representing Class 7 and 8 vocational trucks (great than 26,000 lbs.). Based on the

National Academy of Sciences study [36] and the MOVES model [192], the representative vehicle for this category is a Class 8 refuse truck.

LH Tractors: trucks in this category are typically part of tractor-trailer combinations that are responsible for the large majority of long-distance on-road freight movement. Generally, the duty cycles of these tractors are dominated by high-speed driving at steady-state conditions. Most LH tractors performing these over-the-road operations are equipped with habitation quarters for sleeping and comfort during overnight stays in the vehicle, which is fairly typical so that drivers can maximize their productivity and avoid hotel room costs. Tractors with these extended cabins are commonly referred to as *sleeper cabs*. Tractors are often customized according to their expected towing loads and drive cycles. For example, a tractor designed to haul potato chips over mainly flat terrain would be configured much differently than a tractor that needed to haul bricks over the Rockies. A Class 8 sleeper cab tractor with a payload of approximately 40,000 pounds is the assumed configuration in TOP-HDV based on estimates of average payloads for LH tractors in the US [105].

SH Tractors: these tractors are distinguished from LH tractors based on their propensity to operate in a distinct region—usually within a radius of 100-150 miles. Another distinct feature of SH tractors is that these vehicles are not usually sleeper cabs, but rather, they are *day cabs* that are not designed with the additional compartment for overnight stays. A key caveat is the fact that as LH tractors age and acquire high cumulative mileage, these vehicles typically migrate to secondary and tertiary owners that use them for shorter, regional hauls. An example of this phenomenon is drayage or port tractors, which have historically had higher average ages than tractors involved in long-distance operations [194]. As with LH tractors, SH tractors haul a large variety of loads and also traverse all types of terrain. In TOP-HDV, the modeled vehicle is a

Class 7 day cab tractor with a payload of approximately 25,000 pounds, which, as with LH tractors, is an approximation of the average payload in the US for this type of vehicle [105].

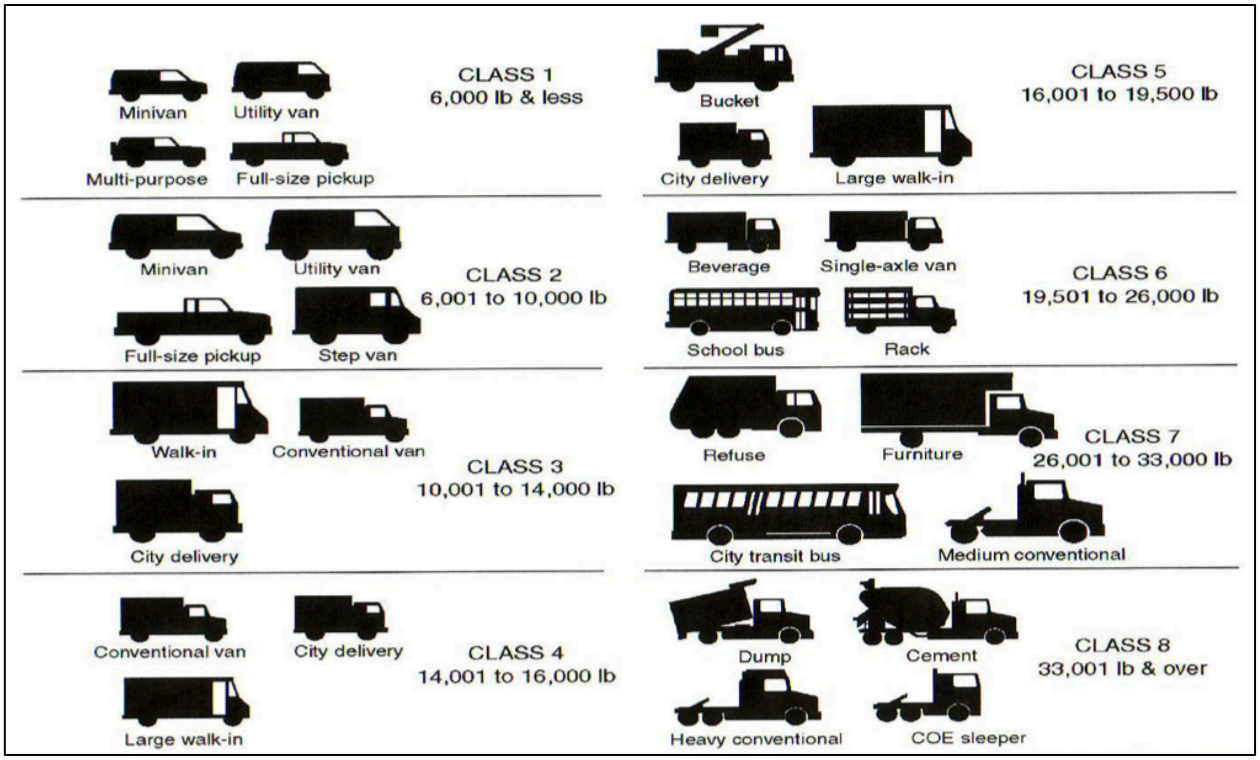

Figure 4-2: US commercial truck classification system (Eberhardt [195], page 9)

4.3.2 Fuel and Technology Options

One of the principle features of TOP-HDV is the ability to model the adoption of non-conventional fuels and advanced technologies. The options that are available in TOP-HDV are not meant to be an exhaustive set of all of the existing and future fuels and technologies for the HD fleet. Rather, the fuels/technologies in Table 4-1 are representative groups of the prominent power pack and driveline options for current and future HD fleets. In terms of fuel pathways that are included in TOP-HDV, a notable exclusion is coal-to-liquids (CTL) fuel. Coal is a relatively carbon-intense feedstock, and given the lifecycle GHG emission constraints imposed by the Low Carbon Fuel Standard in California [196], a key assumption in developing the fuel pathway options in TOP-HDV is that high-carbon fuels such as CTL will not have any significant penetration in California.

A simplifying assumption in the model is that each technology provides an identical level-of-service in terms of vehicle activity and drive cycle performance (acceleration, towing capacity, gradeability, cabin comfort, etc.). In other words, for each of the eight vehicle categories, the model treats the various technology options as being completely interchangeable.

Table 4-1: Fuel and technology options in TOP-HDV

Technology	Power Pack Description
Conventional diesel or gasoline	Internal combustion engine (ICE) powered by diesel or gasoline. Vehicles in this category are also assumed to be able to utilize fuels that are compatible with ICEs such as biodiesel, ethanol, and Fischer-Tropsch diesel.
Natural gas	NG ICE. For each vehicle category, users may input what percentage of vehicles carry the NG onboard as a gas versus a liquid (combustion in a NG engine is identical, regardless of how the NG is stored onboard). As a simplification, NG vehicles are *not* assumed to be hybridized.
Hybrid-electric	Driveline employs batteries and power electronics in combination with a diesel or gasoline ICE.
Hydraulic hybrid	Driveline employs accumulator tanks and hydraulic motor(s)/generator(s) in combination with a diesel or gasoline ICE.
Plug-in hybrid-electric	Hybrid vehicle with the ability to re-charge its batteries using an external electricity source. Batteries in charge-depleting plug-in hybrids are typically larger than in charge-sustaining hybrids, which often can allow for limited amounts of all-electric operation.
Battery electric	Batteries are the sole energy storage device. Electric vehicles must recharge via the grid.

Technology	Power Pack Description
Hydrogen fuel cell	As with NG vehicles, users may specify the percentage of vehicles carrying the hydrogen onboard as a gas versus a liquid. For each vehicle category, the user can specify the percent of FCVs that are hybridized.

4.3.3 Vehicle populations

The TOP-HDV model includes calendar years 2010 through 2050, and each vehicle is assumed to have a lifetime of 30 years, thus giving each calendar year 30 model years of vehicles. For example, the year 2010 has model years 1981 through 2010. A simplifying assumption in the model is that model years are directly correlated to calendar years. In other words, model years and calendar years are perfected matched such that, for example, only MY 2010 vehicles are sold in 2010. Another key assumption in the model is that all vehicle turnover (i.e. sales and scrappage) occurs instantaneously on January 1st of each year. For example, all MY 2015 vehicles enter the fleet on January 1st, 2015 and accrue their activity over the course of the year. Such assumptions are conventional in mobile emissions inventory modeling.

The first step in developing the vehicle stock turnover models was to estimate the populations on January 1st, 2010. The data that was used as the basis for the 2010 vehicle populations for each of the eight vehicle categories was provided by the California Energy Commission [197]. This CEC data set organizes vehicle populations by vehicle model year, fuel type (diesel, gasoline, NG, propane, electricity), GVWR (Classes 3 through 8), and 39 unique vehicle types. The CEC spreadsheet for the year 2007 has full vehicle data information through MY 2007 and partial data for MY 2008. There are population totals by model year for each of the 39 vehicle categories. Excluding MY 2008, there are population totals for each MY between 1992 and 2007. The MY 1991 value is the sum of all vehicles MYs 1991 and older.

The first step in transforming the CEC data, which is organized by vehicle class (Classes 3 through 8) and 39 configurations/vocations, was to map these 39 categories into the eight TOP-HDV vehicle categories. One exception was the tractors, which were grouped into Class 7 and 8 tractors. In TOP-HDV, there are controls on the *Scenario Builder* sheet that allow the user to specify what percentage of Class 7 and 8 tractors are long- and SH tractors. As described above, LH tractors are modeled as Class 8 tractors with sleeper cabs, and SH tractors as Class 7 tractors with day cabs. However, the model is built with the flexibility for the user to determine what percentage of Class 7 and 8 tractors (as estimated using the CEC data) are modeled as LH and SH tractors. Another exception was the HD Pickup Trucks and Vans category, whose diesel and gasoline populations were estimated using 2010 populations in the EMFAC2007 model. The EMFAC data was used to estimate the populations of these Class 2B and 3 pickup trucks and vans since the CEC data did not include Class 2B vehicles. EMFAC data was also used directly for the Urban Bus and Other Bus populations because the CEC data set did not have any distinctions within its “Bus” category. From the EMFAC data, the populations of Urban Buses and School Buses were summed and exported to TOP-HDV, where the sum of these two vehicle groups are designated “Urban Buses.”

To create a 30 model year fleet for 2010 using the CEC data, it was necessary to 1) estimate MYs 2008, 2009, and 2010 and 2) disaggregate the MY 1991 and older totals into unique model years for MYs 1981 to 1991. This projection out to MY 2010 and disaggregation of MYs 1991 and older was done using model year population totals for 2010 and 2007 from EMFAC as well as adjustment for recession effects based on ARB analysis that was done to support regulatory development for the Truck and Bus Rule [183]. The HD vehicle categories in EMFAC are not identical to those used in TOP-HDV, so assumptions had to be made about comparable vehicle groupings between the two models so that population estimates are made based on the CEC data using ratios from the EMFAC model. The calculations for developing population estimates for the year 2010 in TOP-HDV are given in Equation 4-1 though Equation 4-4. In the equations, the year at the beginning of the terms (e.g. the 2010 in "2010 TOP-HDV population_MY_i") represents the calendar year, and MY20xx (or MY_i) designates a particular model year in that calendar year. The recession adjustment values are based on ARB analysis [183] and reflect the fact that HD vehicle sales decreased substantially in the wake of the recession, and this drop in sales is not captured in EMFAC2007. The vehicle categories from EMFAC that are used for the ratios from which the 2010 population estimates for TOP-HDV are developed are shown in Table 4-2.

For MYs 2007 through 2010:

2010 TOP-HDV population_MY_i =

[(Recession adjustment_MY_i) * (2010 EMFAC population_MY2006) /

(Recession adjustment_MY2007) * (2010 EMFAC population_MY2006)] *

(2007 CEC population_MY2007)

Equation 4-1

For MY 2007:

2010 TOP-HDV population_MY2007 =

[(Recession adjustment_MY2007) * (2010 EMFAC population_MY2006) /

(Recession adjustment_MY2007) * (2007 EMFAC population_MY2006)] *

(2007 CEC population_MY2007)

Equation 4-2

For MYs 1992 through 2006:

$$2010\ \text{TOP-HDV population\_MY}_i =$$

$$[(2010\ \text{EMFAC population\_MY}_i) / (2007\ \text{EMFAC population\_MY}_i)] *$$

$$(2007\ \text{CEC population\_MY}_i)$$

Equation 4-3

For MYs 1981 through 1991:

$$2010\ \text{TOP-HDV population\_MY}_i =$$

$$[(2010\ \text{EMFAC population\_MY}_{i+1}) / (2010\ \text{EMFAC population\_MY}_i)] *$$

$$(2010\ \text{TOP-HDV population\_MY}_{i+1})$$

Equation 4-4

Table 4-2: Vehicle categories in EMFAC used for developing population estimates in TOP-HDV

TOP-HDV category	EMFAC category used for developing population estimates for the year 2010
HD Pickup Trucks and Vans	Light-Heavy-Duty (LHDT1)
Urban Buses	Urban Buses
Other Buses	Other Buses
MD Urban Vehicles	Medium-Heavy-Duty
MD Vocational Vehicles	Medium-Heavy-Duty
HD Vocational Vehicles	Heavy-Heavy-Duty
LH Tractors	Heavy-Heavy-Duty
SH Tractors	Heavy-Heavy-Duty

In developing the 2010 population estimates for the model, another key assumption was that the only categories with non-conventional (i.e. not diesel or gasoline) vehicles on the road were the Urban Bus and HD Vocational categories. In the CEC data, the Bus and Garbage categories had a relatively large percentage of NG vehicles. Because the markets for other advanced technology vehicles (e.g. battery electric, hybrid, fuel cell, etc.) were so nascent prior to 2010, a simplifying assumption in TOP-HDV is that the populations of all non-NG advanced technology vehicles are zero in 2010.

The vehicle population breakdowns by model year developed using the CEC spreadsheets were validated using EMFAC2007 data. While the populations for Heavy-Duty Pickup Trucks and Vans (i.e. Class 2B and 3 vehicles), Urban Buses, and Other Buses were generated using EMFAC due to limitations of the CEC data, the other five vehicle categories in TOP-HDV were created using CEC data. As the EMFAC vehicle categories have a higher level of aggregation than those of TOP-HDV, the comparison for the two sets of fleet populations was performed as follows:

TOP-HDV MD Urban + MD Vocational → EMFAC Medium HD Vehicles

TOP-HDV HD Vocational + LH Tractors + SH Tractors → EMFAC Heavy HD Vehicles

These comparisons are depicted graphically in Figure 4-3. In general, for MYs 2007 and older (recall, MYs 2008-2010 in TOP-HDV are recession-adjusted), the two sets of population distributions seem to follow similar patterns, which is reasonable, given that the source data for both databases are California Department of Motor Vehicles (DMV) registration records [198, 199]. For the MD vehicle populations, TOP-HDV is consistently larger than EMFAC, but the opposite is true for HD vehicles, suggesting that the ARB and CEC utilized differing methodologies for processing the DMV registration data.

Overall, the total 2010 populations for the two models across all HD vehicle categories (including Class 2B and 3 vehicles and buses) are within two percent (EMFAC = 1,106,012; TOP-HDV = 1,088,617).

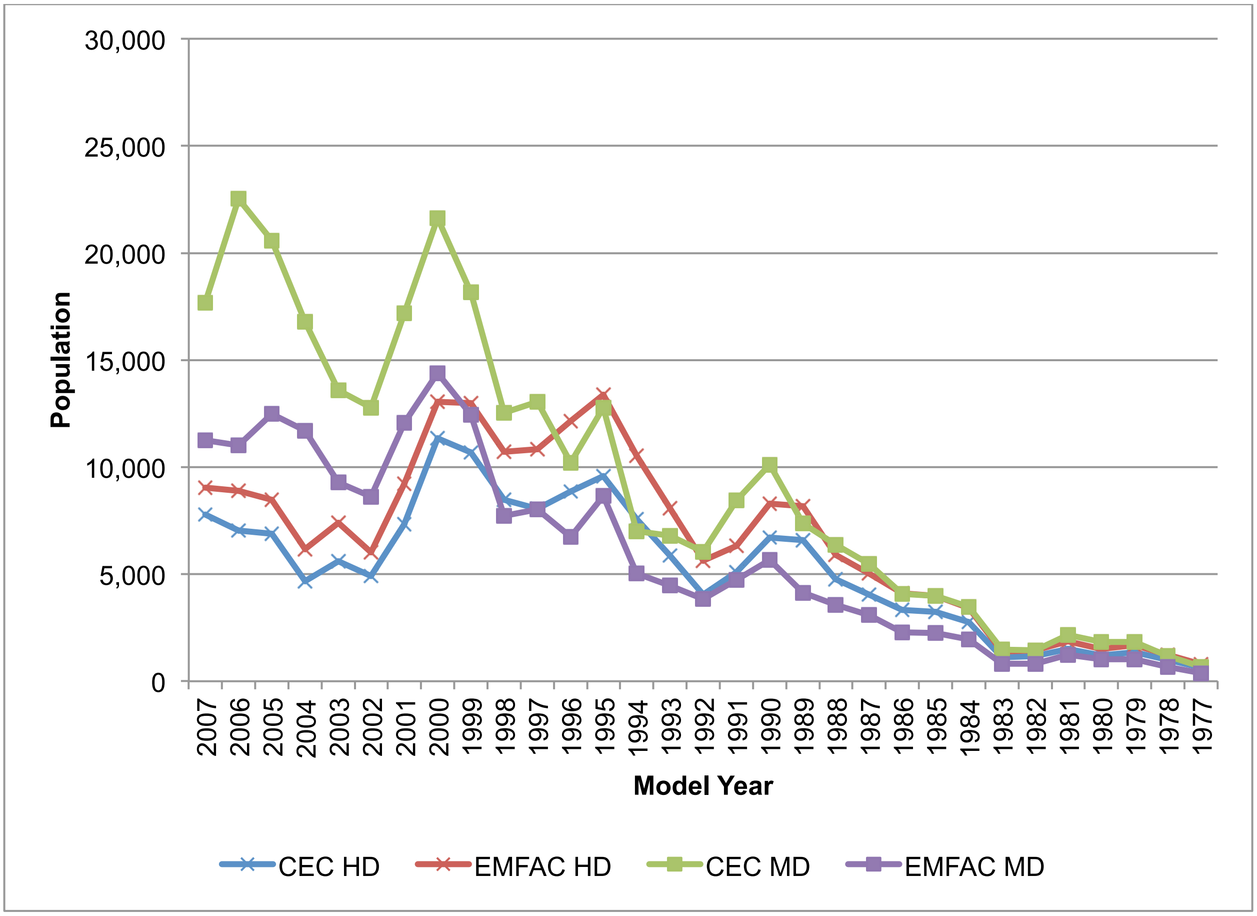

Figure 4-3: Populations by model year in 2010 for TOP-HDV vs. EMFAC

Other HD vehicle populations (e.g. other states, regions, etc.) can be modeled in TOP-HDV by modifying the model year populations for 1981 through 2010 on the *CEC Vehicle Populations* sheet.

4.3.4 Advanced Technology Vehicle Adoption

The uptake of advanced (i.e. non-conventional) technology vehicles is modeled using a methodology that is based on the market share of new vehicle purchases. In this approach, all advanced vehicles enter the fleet as replacements for vehicles that have been retired following their 30-year lifetime.

Starting in 2011, all of the vehicles that are scrapped are instantaneously replaced with new vehicles.[15] The number of new vehicles that are introduced in a given year can be controlled in the *Vehicle Population and Activity* module on the *Scenario Builder* sheet. For each 5-year interval (i.e. 2011-2015, 2016-2020,…, 2046-2050), the user may enter a value that controls the ratio of vehicles sold to vehicles scrapped. A value greater than 1 represents fleet growth.

Market shares of each advanced vehicle (AV) option as well as that of conventional diesel and gasoline vehicles can be controlled between 2011 and 2050. An AV is defined as any technology option that is not a conventional diesel or gasoline vehicle. For each of the six scenarios, there is an *Adoption Controls* module, where there are three input years for each vehicle type, as shown in Table 4-3. These three input values define four time periods. Period 0 is the set of years from 2010 to the year entered in the *Initial year of advanced vehicle (AV) adoption* cell. Period 1 is the set of years between the *Initial year of AV adoption* and *Pivot year 1* cell. Period 2 is the set of years between *Pivot Year 1* and *Pivot year 2*. Period 3 is the set of years between *Pivot year 2* and 2050.

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[15] Beginning in 2011, the instantaneous scrappage and replacement of vehicles occurs on January 1st of each year.

Table 4-3: Example user inputs for adoption control pivot years

	HD Pickups	**Urban Bus**	**Other Bus**	**MD Urban**	**MD Vocation**	**HD Vocation**	**LH Tractor**	**SH Tractor**
Initial year of AV adoption	2020	2011	2020	2015	2015	2015	2020	2020
Pivot year 1	2030	2020	2030	2025	2025	2025	2030	2030
Pivot year 2	2040	2030	2040	2035	2035	2035	2040	2040

Table 4-4: Example user inputs for controlling conventional vehicle market share

	HD Pickups	**Urban Bus**	**Other Bus**	**MD Urban**	**MD Vocation**	**HD Vocation**	**LH Tractor**	**SH Tractor**
Period 1 annual percent change in market share	-2%	-2%	-2%	-2%	-2%	-2%	-2%	-2%
Period 2 annual percent change in market share	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%
Period 3 annual percent change in market share	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%

Table 4-5: Example user input table for controlling advanced vehicle market share

	HD Pickups	**Urban Bus**	**Other Bus**	**MD Urban**	**MD Vocation**	**HD Vocation**	**LH Tractor**	**SH Tractor**
Initial percent of new AVs	10%	75%	10%	50%	50%	75%	10%	10%
Period 1 annual change (percentage points)	-2%	-2%	-2%	-2%	-2%	-2%	-2%	-2%
Period 2 annual change (percentage points)	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%
Period 3 annual change (percentage points)	-10%	-10%	-10%	-10%	-10%	-10%	-10%	-10%

Two additional sets of user input tables are used to control the new vehicle market shares of conventional and advanced vehicles. First, for conventional diesel and gasoline vehicles, there are inputs that control the annual percent change in new vehicle market share for Periods 1, 2, and 3. Negative values imply a decrease in market share. See

Table 4-4 and take the following example for HD Pickups. Say that in the Adoption Controls table (Table 4-3), 2020 is entered in the *Initial year of AV adoption* cell. In the conventional diesel or gasoline market share table (

Table 4-4), -2% is entered in the *Period 1 annual percent change in Market Sharpe (MS)* cell. In this case, the market share of conventional vehicles will be 100% of sales for 2010 to 2019. Starting in 2020, the market share of conventional vehicles will decrease 2% annually until the year specified in the *Pivot year 1* cell (Table 4-3). So, the market share in 2020, 2021, 2022,… etc. would be 98%, 96.04%, 94.12%,…etc. Starting in the year specified in the *Pivot year 1* cell, the annual percent change in conventional vehicle market share will change according to the value in the *Period 2 annual percent change in MS* cell. Starting in the year specified in the *Pivot year 2* cell, the annual percent change in conventional vehicle market share will change according to the value in the *Period 3 annual percent change in MS* cell.

The final user input table (

Table 4-5) controls the market shares of each of the five advanced technology options: NG, hybrids, plug-in hybrids, full electric, and hydrogen fuel cell.[16] For each of the technology types that are activated via a checkbox, there are four input values per vehicle type. The topmost cell,

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[16] For NG and hydrogen fuel cell vehicles users can specify the percentage of vehicles carrying fuel onboard as a gas versus a liquid for each of the eight vehicle categories. However, these percentages are assumed to apply over the entire study period. For hybrids, users can specify the percentage of hybrid-electrics versus hybrid-hydraulics in each vehicle category, but, as with the LNG-CNG and LH_2-CH_2 breakdown, these percentages are assumed to be constant between 2011 and 2050.

Initial percent of new AVs, represents what percentage of the advanced market[17] will go to that specific technology option. To continue the example from above, say that the user would like to model the introduction of hybrid and NG vehicles, and each of these AV types will have 50% of the advanced vehicle market. In the *Initial percent of new AVs* cell in the NG and hybrid tables, a value of 50% would be entered. In the above example for HD Pickups, the initial year of advanced vehicle adoption is specified as 2020, and the conventional vehicle market share in 2020 is 98%. So, the market share for both NG and hybrid electric vehicles would be (100% - 98%) * 50% = 1%. To change the market share for each active technology type over time, you may enter positive or negative percentages in the *Period [1, 2, 3] annual change (percentage points)* cells. These percentages represent changes in percentage points of market share. To continue the example, say that the user would like the market share of NG vehicles to decrease by 1 percentage point per year in period 1 and the market share of hybrids to increase during period 1. Because NG and hybrids are the only advanced vehicle types, the hybrid market share must increase by 1 percentage point during period 1. So, for Periods 1, 2, and 3, the total of annual change (percentage points) values for all active AV types must equal zero. If not, the model will return an error message. In the example, for 2021, the AV market share for NG and hybrid vehicles would be 49% and 51% respectively. The total new vehicle market share for NG vehicles would be (100% - 98%) * 49% = 0.98%, and the market share for hybrids would be (100% - 98%) * 51% = 1.02%.

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[17] For each year between 2011 and 2050, the total advanced vehicle market share = 1 – (conventional vehicle market share).

4.3.5 Vehicle activity

In TOP-HDV, activity is modeled at the individual vehicle level in three distinct ways: 1) annual vehicle miles traveled (VMT), 2) extended idling (i.e. idling for longer than five minutes), and 3) PTO operations, which are only assumed to occur for MD and HD Vocational Vehicles such as refuse, cement, and bucket trucks.

The VMT in the first year of a vehicle's life is entered for each of the eight vehicle types in the *Vehicle Population and Activity* module on the *Scenario Builder* sheet. To reflect what typically happens as a vehicle ages, VMT is assumed to decrease year-by-year over the vehicle's lifetime. Over time, the percent that VMT decreases as compared to year one VMT is based on calculated values from EMFAC or MOVES, and the user must choose between the data from either of these two models. The mileage accrual rates in both EMFAC and MOVES were developed using data from the US Census Bureau's Vehicle Inventory and Use Survey (VIUS) [200], which was a comprehensive nationwide analysis of HD vehicle populations, physical characteristics, and activity. The VIUS program began in the early 1960s and released reports roughly every 5 years until the program was discontinued shortly after the release of the 2002 data report in 2004. Though EMFAC and MOVES use VIUS as the source data for estimating mileage profiles over time, the individual methodologies and HD vehicle categories employed by the EPA and ARB were different, thus resulting in unique mileage accrual rates [201, 202]. The VMT accrual rates and the resulting VMT values for each vehicle category over its 30-year life can be found on the *Survival* and *VMT* sheets respectively.

Extended idling (i.e. idling for longer than a few minutes) is modeled in total hours per year. Drivers typically idle for long periods of time to provide cabin temperature and humidity comfort and/or to power other appliances such as lights or entertainment devices that are used while the vehicle is stationary. TOP-HDV users may input total annual extended idling hours for any of the eight vehicle categories; however, extended idling is mainly found in the long distance trucking sector, in which the sleeper cabs of tractors are typically used for overnight stays. During extended idling, the main engine or an auxiliary power unit must provide power for cabin comfort and other hotel loads. According to ARB estimates, a typical LH tractor idles for approximately 2,000 hours per year [203]. As described in Section 3.2.2.3, the ARB implemented an anti-idling regulation beginning in 2008 that requires all LH tractors equipped with sleeper cabs to shut off their main engines after five minutes of idling. To power hotel loads after this five minute period, LH tractors have auxiliary power units (APUs), which are typically small diesel engines, fuel fired heaters, or battery-powered systems. Or, tractors can be designed to be fully electric during idling by taking advantage of electricity at truck stops.

In the model, users can specify the percentage of LH Tractors using APUs for extended idling (i.e. those LH drivers and tractors that are in compliance with the ARB regulation). Also, there are input cells that allow the user to control the fuel consumption (and the associated CO_2 emissions) and criteria pollutant emission rates of the APU as compared to the idling rates of the main engine.

In addition to extended idling, TOP-HDV also models PTO operations in which a truck uses power from the main engine for a work function other than driving. Typically, the PTO system is engaged when the vehicle is stationary at a job site. The main engine must idle while the PTO is engaged, and, as such, the energy and emissions of PTO operations are modeled as if the main engine were extended idling [105]. Only MD and HD Vocational vehicles are assumed to operate PTOs, and users can specify the total annual hours of PTO operation in the *Vehicle Population and Activity* module on the *Scenario Builder* sheet.

4.3.6 Lifetime fuel use and lifecycle emissions

TOP-HDV models the energy use and emissions associated various aspects of the vehicle and fuel *lifecycles*. The term lifecycle implies an analytical perspective that takes into account the energy use and emissions beyond the use (or operational) phase of the vehicle. The four lifecycle phases included in TOP-HDV are illustrated in Figure 4-4 and include 1) vehicle operation, 2) fuel production, refining, and distribution, 3) vehicle manufacturing, and 4) vehicle scrappage. Sections 4.3.6.1 through 0 describe each of these processes in more detail.

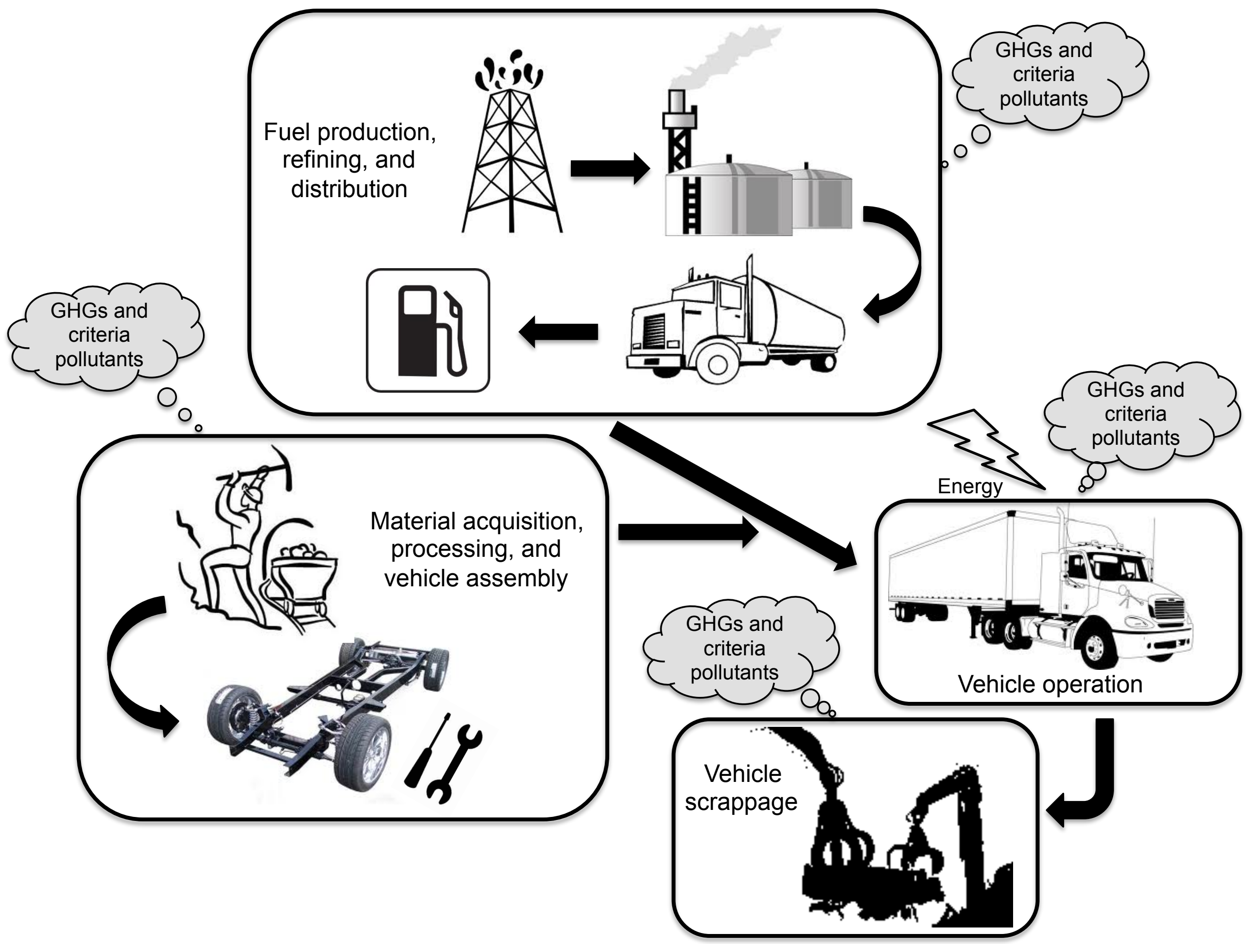

Figure 4-4: Lifecycle energy use and emissions modeled in TOP-HDV

The processes shown in Figure 4-4 are modeled in TOP-HDV as four lifecycle modules. The fuel production and vehicle manufacturing phases are referred to as *upstream* processes, implying that these activities are not directly associated with the use of the vehicle. The emissions attributed to upstream processes are modeled as aggregate EFs. For example, all of the upstream emissions associated with fuel production and transportation are modeled in terms of grams of pollutant emitted per million BTUs of fuel delivered to the end-user. Emissions associated with vehicle decommissioning are estimated at the per-vehicle level. Upstream EFs and vehicle scrappage emissions are discussed in more detail in Sections 4.3.6.3 through 0. While the criteria pollutant and GHG emissions from upstream processes and vehicle scrappage are included in the model, the specific energy feedstocks (e.g. coal, NG, electricity, etc.) associated with these activities are not inventoried. For the vehicle operation phase, both the energy use and emissions are accounted for in the model outputs.

4.3.6.1 Vehicle fuel/energy use

Vehicle fuel consumption is highly dependent on a variety of factors such as physical attributes of the vehicle, operating patterns, grade, ambient conditions, and driver behavior. The vehicles within each of the eight categories are assumed to be identical, and this extends to fuel consumption rates as well. The fuel consumption (FC) rates are modifiable inputs on the *Scenario Builde*r sheet. For this project the FC rates for each technology type are based on a review of the literature. The sources and methods for determining the per-mile and per-hour consumption rates for each technology across the eight vehicle types are summarized in Table 4-6.

Table 4-6: References and methods for the fuel consumption rates in TOP-HDV

Fuel / Tech.	HD Pickups	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
Diesel, Gasoline	[204]	[205]	[206]	(a)	[105]	[205]	[105, 192, 203]	[105]
NG	(b)	[205]	(b)	(b)	(b)	[205]	(b)	(b)
HEV	[36]	[36]	[36]	[36]	[36]	[36]	[36]	[36]
PHEV(c)	[207]	[207]	[207]	[207]	[207]	[207]	[207]	[207]
BEV	(d)	[208]	(d)	(d)	(d)	(d)	(e)	[209]
H_2 FCV	(f)	[210, 211]	(f)	(f)	(f)	(f)	(g)	[209]

(a) MD Urban and MD Vocational vehicles are assumed to have identical FC rates.

(b) These FC rates are calculated by multiplying the FC rate for the NG Urban Bus by that vehicle type's diesel-equivalent FC divided by the FC of a diesel Urban Bus.

(c) Across all eight vehicle types, PHEVs are assumed to be able to operate in both an all-electric mode as well as a *blended* mode, where both the ICE and the battery provide power. For each vehicle type, the FC during all-electric and blended modes are calculated by multiplying the ratio of the FC rates of a plug-in hybrid sedan to an equivalent conventional sedan to the diesel vehicle FC rates of each of the eight vehicle types. For each of the eight vehicle types, there are user controls for the percentage of time that PHEVs spend in all-electric mode for driving as well as idling/PTO operations.

(d) These FC rates are calculated by multiplying the FC rate for the battery electric Urban Bus by that vehicle type's diesel equivalent FC divided by the FC of a diesel Urban Bus.

(e) The energy consumption of a battery electric LH Tractor is assumed to be identical to that of a SH Tractor. However, it is useful to note that absent a breakthrough in battery energy density, it's unlikely that battery electric vehicles will penetrate the LH trucking sector.

(f) These FC rates are calculated by multiplying the FC rate for the fuel cell Urban Bus by that vehicle type's diesel equivalent FC divided by the FC of a diesel Urban Bus.

(g) The FC of a fuel cell LH Tractor is assumed to be identical to that of a SH Tractor.

The model generates estimates for fuel/energy use by matching the inputs for per-vehicle activity (i.e. VMT as well as extended idling or PTO hours if applicable) with the inputs for fuel consumption rates. For each model year and technology type within each vehicle category, the total fuel use is calculated per Equation 4-5. As described in Section 4.3.5, only MD and HD Vocational vehicles are assumed to operate PTOs, but extended idling hours can be modeled for any of the eight vehicle categories.

Total fuel use for each model year in each calendar year = (vehicle population) * [VMT * (unit of fuel/mile) + ((extended idling hours) + (PTO hours)) * (unit of fuel/hour)]

Equation 4-5: Fuel use calculation

TOP-HDV also models the increased fuel efficiency of new vehicles over time. There are inputs for the annual percent change in fuel consumption for each technology and vehicle type. However, a key assumption is that fuel efficiency improvements over time only apply to driving—not idling or PTO operations. This is based on the fact that technologies that boost fuel efficiency are typically not applicable when the engine is idling [36].

Fuel efficiency in new HD vehicles has generally increased over time for a number of reasons, including evolutionary technology improvements, new technologies, highly volatile fuel prices, and consumer demand. Over the past four decades, fuel consumption of HD vehicles has decreased by approximately one percent per year (See slide 3 in [212]. An assumption is that historical rates of HD vehicle fuel efficiency progress in the US have been similar to trends in Europe). For the Baseline scenario model runs, vehicle fuel efficiency improvements from MY 2011 to 2050 are assumed to continue at historical rates. Thus, across all eight vehicle categories and for each of the technology types, the annual reduction in fuel/energy consumption for new vehicles is assumed to be one percent. For MYs 1981 to 2010, annual reductions in fuel consumption rates are also assumed to be one percent.

4.3.6.2 Tailpipe emissions

As with fuel consumption rates, the exhaust emissions resulting from vehicle operation are highly dependent on a number of different variables related to vehicle systems and operating patterns as well as exogenous factors such as temperature and humidity. However, as a simplification, within each vehicle category all vehicles of a particular technology type are assumed to emit each individual criteria pollutant and GHG at identical gram per mile (g/mile) and gram per hour (g/hour) rates. The exception is carbon dioxide (CO_2), which is calculated using the vehicle's fuel/energy consumption coupled with fuel carbon content factors or upstream CO_2 EFs.

TOP-HDV includes not only the gaseous and particle-phase emissions that are a consequence of imperfect combustion, but there are also estimates of the particulate matter that is released into the atmosphere as a result of tire and brake wear as well as vehicle-induced road dust. For the sake of simplicity in terminology, all emissions resulting from vehicle operation are referred to as *tailpipe* emissions. The emitted species that are inventoried in TOP-HDV are described in Table 4-7.

Table 4-7: Descriptions of the gases and particle emissions inventoried in TOP-HDV

Emission Type	Abbreviation	Description
Particulate matter	$PM_{2.5}$	Diesel exhaust particles are comprised mostly of inorganic solid carbonaceous material, soluble organics, and sulfate aerosols. A large majority are fine particles, which have diameter less than 2.5 microns ($PM_{2.5}$).
Black Carbon	BC	BC refers to the all of the carbonaceous aerosols (including elemental carbon) in PM that are light absorbing.
Organic Carbon	OC	Like BC, these aerosols are also a component of PM. OC is a complex mixture of compounds containing carbon-carbon bonds.
Nitrogen Oxides	NOx	NOx is created as a by-product of combustion. Air contains primarily nitrogen (N_2) and oxygen (O_2). The heat generated during combustion causes these to merge to form NO and NO_2. The term *NOx* represents the sum of NO and NO_2 emissions.
Non-Methane Hydrocarbons	NMHC	NMHCs represents all of the hydrocarbons resulting from unburned (or partially burned) fuel and lube oil, expect for methane.
Carbon Monoxide	CO	The carbon in vehicle fuel often does not fully oxidize into CO_2, leaving CO as one of the products of incomplete combustion.
Sulfur Oxides	SOx	Sulfur is a naturally occurring component of fossil fuels, and during combustion this sulfur is oxidized into many variants (SO, SO_2, SO_3, etc.). SOx is the sum of these sulfur oxides.
Methane	CH_4	CH_4 is a GHG byproduct of incomplete combustion. In vehicle engines, the amount of CH_4 emitted is often much less than other hydrocarbons. The exception is NG vehicles, where CH_4 is the main component of the fuel.
Nitrous Oxide	N_2O	As with NOx, N_2O forms as a result of N_2 and O_2 being present during combustion, though in much smaller quantities.

Carbon Dioxide	CO_2	CO_2 is the primary byproduct of combustion, other than water vapor. By weight, CO_2 is by far the most prominent GHG of combustion-elated emissions.

Vehicle emissions are modeled based on units of activity—driving mileage or hours operating in extended idle or with the PTO engaged. As vehicles age, the performance of emission control equipment typically degrades, and emissions per unit of activity tend to increase over time. To model this reality, TOP-HDV has *year-one* EFs (EFs) for new vehicles in their first year of operation as well as average deterioration rates to model how the emissions performance will degrade over its 30-year lifetime.

The year-one EFs are largely based on outputs from the MOVES model. MOVES is the US EPA's official vehicle emission simulation and inventory tool. In MOVES, vehicle emissions are function of a complex range of factors including operating conditions, vehicle type, vehicle age, meteorology, and other variables. MOVES is structured to draw from hundreds of distinct databases, and one of these databases, EmissionRate, estimates mass (or energy) EFs per unit of activity based on the following parameters:

- Operating mode
- Fuel type
- Engine technology, size, and model year
- Vehicle weight

The primary reason that MOVES was chosen as the basis for the TOP-HDV EFs is that this EmissionRate database in MOVES was derived from a number of extensive HD vehicle testing programs—both chassis dynamometer testing and on-road measurement during vehicle operation using portable emissions measurement system (PEMS) devices [213]. The MOVES EmissionRate database is an amalgamation of all many testing projects that span over a decade and, as of this writing, is arguably one of the most comprehensive sources of HD emissions data for new and in-use vehicles.

MOVES version 2010a was run at the state level for California in *Inventory* mode in order to generate aggregate fleet totals by HD vehicle type for the mass of emissions and VMT for all of the HD vehicle types as well as the total idling hours for LH tractors[18]. Using data post-processing and SQL database queries, the emission and activity results were cataloged by model year, vehicle type, and fuel type. In terms of modeled fuel types for the HD fleet, MOVES provides emissions estimates for diesel, gasoline, and NG vehicles for the instances in which that particular fuel has had significant penetration in a vehicle category by the year 2010. For example, for NG, there are only emissions estimates for transit buses. This isn't to say that NG vehicles do not exist in other HD vehicle categories; it is simply reflecting the fact that beyond transit buses, the penetration levels of NG vehicles in the rest of the HD sector during the time of MOVES development (i.e. the early to late 2000s) was relatively small. Another example is gasoline, which is virtually nonexistent as a power pack option for the heavier (i.e. Class 6 and larger) truck applications.

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[18] MOVES can be run in *National*, *County*, or *Project* scale. National scale is most appropriate for this work, as County and Project scales are typically used to developed detailed inventories for county- or project-level analyses. In National scale, the user chooses a particular state, and the model uses national default data and allocation factors for each state for local fleet and activity inputs. MOVES can also be run in *Inventory* or *Emission Rates* mode. The only substantive difference is that Inventory mode generates output in unit mass of emissions (grams, kilograms, or tons), while Emission Rates produces grams/mile and grams/hour outputs. The outputs of Inventory mode were post-processed and paired with activity data for this project, as the MOVES run times using Emission Rates mode are significantly longer.

MOVES 2010a does not provide emissions estimates for any type of hybrid vehicle (i.e. hybrid-electric, hydraulic hybrid, or plug-in hybrid-electric). All forms of hybridization alter the ways that the engine (or primary power pack) operates compared to how that engine would function in a conventional drivetrain, and, as such, hybridization impacts the emissions performance. As with conventional vehicles, a variety of factors such as driving patterns, meteorology, grade, and payload all have an effect on the emissions characteristics of a hybrid vehicle. Given that the emissions benefits (or disbenefits) of hybridization are subject to such a wide range of parameters, a simplification in TOP-HDV is that the user can specify the percentage difference between a hybrid vehicle EF and a conventional vehicle EF for each pollutant. These hybrid vehicle EF ratios as compared to a conventional diesel or gasoline vehicle are assumed to be identical across all eight vehicle categories.

The year-one EFs for MYs 1990 and 1999-2010 for each fuel and vehicle type were derived by dividing the total mass of emissions by the total activity (miles or hours) in the corresponding calendar year. For example, the year-one EFs for MY 1990 vehicles were calculated using 1990 model outputs.[19] Due to the fact that the HD vehicle categories in MOVES are not identical to those in TOP-HDV, correlation assumptions were necessary in order to assign EFs derived from MOVES to each of the TOP-HDV vehicle categories. This vehicle type correlation is shown in Table 4-8.

[19] Due to its underlying database structure, the MOVES model can only be run for the years 1990 and 1999 through 2050.

Table 4-8: Correlation used to assign EFs for TOP-HDV based on outputs from MOVES

TOP-HDV Vehicle Category	MOVES Vehicle Category
Heavy-duty Pickup Trucks and Vans	Light Commercial Trucks
Urban Buses	Transit Buses
Other Buses	Intercity Buses
MD Urban Vehicles	Single Unit SH Trucks
MD Vocational Vehicles	Single Unit SH Trucks
Heavy-duty Vocational Vehicles	Refuse Trucks
LH Tractors	Combination LH Trucks
SH Tractors	Combination SH Trucks

MOVES cannot model calendar years 1981 through1989 or 1991 through 1998, so additional data and assumptions were needed to develop the year-one EFs for the associated model years. Year-one EFs based on EMFAC output data were developed for model years 1987, 1991, and 1994. These particular model years were selected because in each of these years, there was an engine emission standard that went into force for both California and the US.[20] In general, the emissions performance of engines remains relatively constant in the years between emission standards, and this is reflected in both MOVES[21] and EMFAC. Due to this stability in emission rates in the years between engine standards, year-one EFs for the *gap* MYs were developed based on the MOVES-based EFs for 1990 and 1999 in combination with ratios of the EMFAC EFs. The equations for deriving these year-one EFs are detailed in Table 4-9.

[20] In the real-world, typically the model year of an engine is one year older than the model year of the HD vehicle in which it is installed. For example, a MY 2010 vehicle will generally have a MY 2009 engine. As a simplification in TOP-HDV, the model years of vehicles are assumed to be identical to the model years of engines.

[21] As aforementioned, MOVES does not have the ability to model calendar years in the 1980s or 1991-1998. However, for the years in the 2000s, MOVES emission rate changes are evident as a result of the standards that were implemented in MYs 2004, 2007, and 2010. Note: the tightening of emissions in MY 2010 was not a unique standard per se, but rather, represented the full implementation of the NOx levels that are associated with the MY 2007 regulation.

Table 4-9: Methods for developing year-one EFs for MYs 1981-1989 and 1991-1998

MY in TOP-HDV	Method for Calculating Year-One EF
1981-1986	= [MOVES-based EF for 1990] * [EMFAC-based EF for 1987] / [EMFAC-based EF for 1980]
1987-1990	= [MOVES-based EF for 1990]
1991-1993	= [MOVES-based EF for 1990] * [EMFAC-based EF for 1991] / [EMFAC-based EF for 1987]
1994-1997	= [MOVES-based EF for 1990] * [EMFAC-based EF for 1994] / [EMFAC-based EF for 1987]
1998-1999	= [MOVES-based EF for 1999]

For calendar year 2010, in order to estimate the EFs for all of the legacy (i.e. MYs 1981 through 2009) model years in the fleet, it was necessary to model how emissions control systems perform over the life of a vehicle. The first step involved estimating how emission control systems deteriorate as mileage accumulates over time. In MOVES, emission rates typically remain stable for 3 to 5 years before increasing to the next rate bin, whereas in EMFAC, emission rates deteriorate linearly with cumulative mileage (i.e. grams per mile per 10,000 miles). TOP-HDV uses the EMFAC linear deterioration approach for estimating changes in emission rates over time.[22] However, the deterioration rates used in TOP-HDV are based on MOVES rather than EMFAC data. The TOP-HDV grams/mile/10,000 mile deterioration rates for each vehicle category were developed using Equation 4-6.

Deterioration rate (g/mile/10,000 mile) = [(MOVES year 30 EF) – (MOVES year 1 EF)] /

[22] As a simplifying assumption, emission factors (grams/hour) for idling/PTO operations are assumed to remain constant over the life of the vehicle.

[(MOVES total lifetime miles) / 10,000]

Equation 4-6

In the second step, mileage accumulation curves (see Section 4.3.5) were used in conjunction with the deterioration rates to determine the gram/mile EFs for each model year in the year 2010. The MY 1981-2009 (i.e. "in-use" or "legacy") vehicles are assumed to have traveled a certain number of cumulative miles by the beginning of 2010 based on their age. The EF for each model year in 2010 and each subsequent year is calculated according to Equation 4-7.

Emission factor for each model year in each calendar year, g/mile = (year-one EF, g/mile) + (deterioration rate, g/mile/10,000 mile) * (cumulative miles)

Equation 4-7

To model technological progress in emissions control, TOP-HDV allows users to input an annual percent change in year-one EFs for new vehicles. As aforementioned, in the absence of new engine emissions regulations, emissions performance tends to remain relatively constant. Rather than allowing users to input the specific years and the magnitude of the change in emission standards (e.g. the percent reduction from previous standard levels), the approach in TOP-HDV is simplified. For each pollutant, the user inserts the average annual percent change over the 40-year study period compared to the year-one MY 2010 base EF.

4.3.6.3 Upstream emissions from fuel and electricity production and distribution

In addition to vehicle operation, the second lifecycle system modeled in TOP-HDV (see Figure 4-4 for a depiction of the four lifecycle systems in TOP-HDV) are the emissions associated with extracting and transporting raw energy sources such as crude oil or NG, transforming these sources into refined products or energy carriers (e.g. diesel, gasoline, hydrogen, electricity, etc.), and transporting these products for distribution to the end-user. In TOP-HDV the total of all of these upstream processes for each fuel pathway are modeled as aggregate EFs—grams of pollutant emitted per million BTUs (MMBtu) of fuel delivered or grams per kilowatt-hour (kWh) of electricity available at user sites (e.g. wall outlets).

The fuel pathways available in TOP-HDV are shown in Table 4-10. This is not meant to be a comprehensive list of every fuel and feedstock combination that currently exists or that may become available for HD vehicles in the time period between 2010 and 2050. However, these fuel pathways represent a diverse cross-section of both conventional and lower-carbon fuel options for the HD vehicle fleet. In addition to these twenty fuel pathways, TOP-HDV has been structured to accommodate seven additional pathways should the user opt to model fuel and feedstock combinations that are not included in Table 4-10.

As a simplification, the percentage contribution from each feedstock option for each delivered fuel are modeled in 10-year spans—2010 to 2020, 2021 to 2030, 2031 to 2040, and 2041 to 2050. For example, users can choose feedstock percentages for CNG of fossil-based NG, landfill gas, and dairy biogas. Any combination of percentages (that add up to 100%) for the three feedstocks during the any given 10-year time period is constant over the decade.

Table 4-10: Fuel and feedstock combinations available in TOP-HDV

Delivered Fuel	**Feedstock**
Reformulated gasoline	Crude oil
Ultra-low sulfur diesel (ULSD)	Crude oil
Fischer-Tropsch diesel	Natural gas
Liquefied Petroleum Gas (LPG)	Crude oil
Liquefied Petroleum Gas (LPG)	Natural gas
Fuel oil	Crude oil
Compressed NG (CNG)	Fossil-based NG
Compressed NG (CNG)	Landfill gas
Compressed NG (CNG)	Dairy biogas

Delivered Fuel	Feedstock
Liquefied NG (LNG)	Fossil-based NG
Liquefied NG (LNG)	Landfill gas
Liquefied NG (LNG)	Dairy biogas
Biodiesel	Soy
Ethanol	Corn
Ethanol	Cellulosic material
Gaseous hydrogen	Fossil-based NG
Gaseous hydrogen	Water
Liquefied hydrogen	Fossil-based NG
Liquefied hydrogen	Water
Electricity	3 scenarios available for feedstock evolution over time

The grams/MMBtu and grams/kWh EFs come directly from outputs of the Lifecycle Emission Model (LEM) [214]. The LEM was developed by Mark Delucchi to estimate the energy use, criteria pollutant emissions, and climate-forcing emissions associated with a number of transportation modes and energy lifecycles. The characterization of upstream fuel and energy pathways in the LEM includes the following modules:

- Feedstock production
- Feedstock transportation
- Fuel production
- Fuel distribution
- Dispensing of fuels

The LEM totals the emissions for all five of these processes and has summary data tables that report the grams of pollutant per MMBtu of fuel (or kWh of electricity) delivered to the end-user. The LEM has the ability to model any year between 1970 and 2050, and the fuel upstream EFs for 2010 to 2050 were exported directly to TOP-HDV.

With regard to modeling fuel and energy pathways for California, one shortcoming of using the LEM outputs is that these EFs are based on US averages. Using the EFs derived from the

LEM for all of the fuel and feedstock options introduces additional inaccuracy in TOP-HDV since California has a unique profile of energy sources and systems. Furthermore, California's Low Carbon Fuel Standard could play a part in widening the differences between fuel upstream EFs in the state as compared to US averages.

The composition of feedstock sources for the electrical grid is different in California from US averages, as there is a heavier reliance on NG and lower-carbon sources and less dependency on coal generation. To account for these differences, the default values for electricity feedstock percentages were modified in the LEM. For 2010, CEC data [215] was used to develop the feedstock generation percentages. To model how the grid mix percentages change between 2010 and 2050, three scenarios were developed for TOP-HDV. These scenarios for changes in the electrical grid over the study period are based on a review of the literature [216-219] as well as the author's judgment. A description of each electrical grid scenario is given in Table 4-11, and pie charts of the feedstock percentage breakdowns in 2020, 2035, and 2050 are shown in Figure 4-5.

The three scenarios are largely defined in terms of the increased contribution of renewable energy resources in meeting California's electricity demands over time. For this project, the definition of "renewable" sources is taken directly from the ARB and includes solar photovoltaic, solar thermal, wind, geothermal, municipal solid waste, biomass and biogas, and hydroelectric facilities that are 30 megawatts or less in size [220].

In this project, changes in the electrical grid are modeled at a high level. While each of these scenarios would require substantial investment and development over a long period, it is beyond the scope of this study to do a detailed examination of the transitions in electricity generation, transmission, and system integration and management.

Table 4-11: TOP-HDV electrical grid scenario descriptions

Electrical Grid Mix Scenario	Description
20-30-40-50% Renewables (Number 1 in Figure 4-5)	A 20%, 30%, 40%, and 50% renewables contribution to the California grid in 2020, 2030, 2040, and 2050 respectively. The percent contribution from each non-renewable source changes such that the proportion of each individual non-renewable source compared to the total non-renewable contribution stays relatively constant over time. For example, NG makes up slightly more than half of the non-renewable total in all years in the study period (see Figure 4-5). In the intermediate years (i.e. 2010-2019, 2021-2029, …), the percentages of each feedstock changes linearly (this is true for all three scenarios).
20-30-40-50% Renewables (High Nuclear) (Number 2 in Figure 4-5)	Identical penetrations of renewables as in the 20-30-40-50% Renewables scenario combined with increasing contribution from nuclear power over time. This scenario assumes a major policy and societal shift with regards to nuclear power and a ramp-up of the contribution from nuclear plants beginning in 2021.
33-50-75-100% Renewables (Number 3 in Figure 4-5)	A 33%, 50%, 75%, and 100% renewables contribution to the California grid in 2020, 2030, 2040, and 2050 respectively. A key assumption of this scenario is that an electrical grid based solely on renewables will be sufficiently supported by an array of storage systems as well as sophisticated demand-response measures.

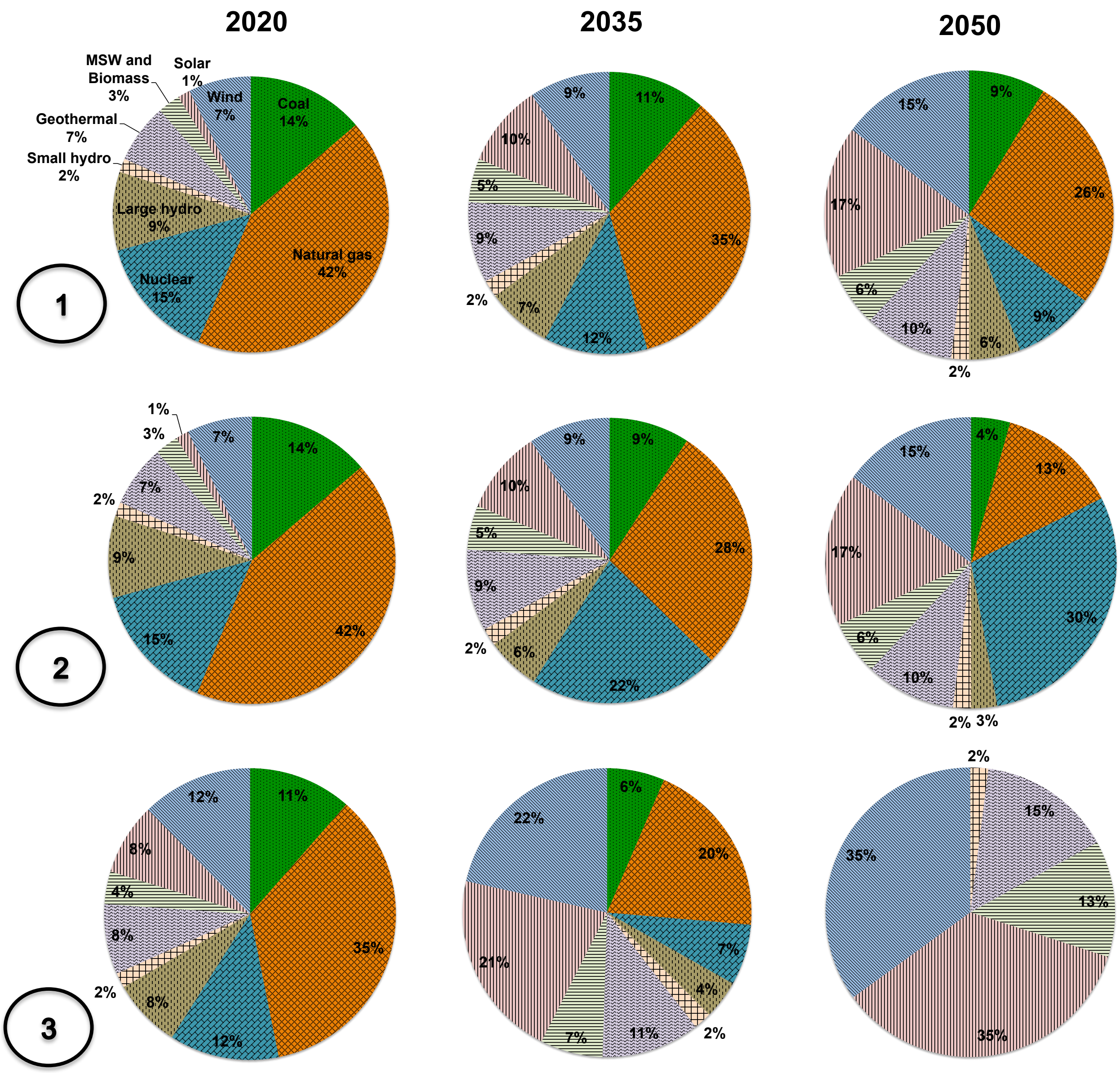

Figure 4-5: Electrical grid mix breakdowns for each scenario in 2020, 2035, and 2050

To summarize, the differences between the US and California electrical grids are accounted for in the following ways in TOP-HDV:

1. The default electricity feedstock percentages between 2010 and 2050 were changed in the LEM to match the 20-30-40-50% Renewables scenario. The fuel upstream EFs for all of the non-electricity fuels were generated using this scenario's assumed electricity

feedstock percentages. However, the choice of electrical grid mix scenario does not affect the grams/MMBtu EFs for fuels, which were developed using the 20-30-40-50% Renewables scenario values in LEM. Altering the grid mix scenario only affects the grams/kWh EFs for plug-in hybrid and battery-electric vehicles.

2. Three electrical grid scenarios are available in TOP-HDV. For each year between 2010 and 2050, the choice of scenario determines the active grid mix percentages, which are then multiplied by the grams/kWh EFs for each individual feedstock and then summed to give the aggregate grams/kWh EF for each pollutant. These grams/kWh EFs are then used by the model in calculating the emissions associated with vehicles that draw energy from the grid.

4.3.6.4 Upstream emissions from vehicle manufacturing

In addition to modeling the upstream emissions associated with fuels, the third lifecycle system included in TOP-HDV is a module for estimating the emissions resulting from vehicle manufacturing (see Figure 4-4). As with fuels, the emissions related to vehicle manufacturing are modeled as aggregate EFs that are meant to represent the sum total of all of the individual processes (i.e. raw materials acquisition and processing, materials transportation, and vehicle assembly) that are involved at various steps in the vehicle production process. These EFs are expressed in grams of pollutant per manufactured vehicle and, as a simplification, are assumed to occur instantaneously in the beginning of the year that a vehicle is sold. For example, if a vehicle enters the fleet in 2015, the emissions associated with its production are accounted for in 2015.

As with fuels upstream processes, the EFs for vehicle manufacturing also are based on outputs from the LEM. One of the intermediate data tables in the LEM summaries the emissions from materials manufacturing and vehicle assembly in grams of pollutant per pound of the finished vehicle. For the individual pollutants (i.e. CO_2, CO, PM, etc.), these grams/pound factors do not include the weight of batteries, fuel storage tanks, or fuel cell systems. However, the LEM does provide CO_2-equivalent grams/pound EFs to account for the weight of batteries, fuel storage tanks, and fuel cell systems. In TOP-HDV, the methods for estimating the emissions associated with manufacturing are structured to mirror the output data from the LEM and are calculated according to Equation 4-8 and Equation 4-9. For each of the eight vehicle types:

Emissions per manufactured vehicle, excluding fuel storage devices and/or fuel cell systems =

(EF, grams/lb.) x (vehicle curb weight, lbs.)

where vehicle curb weight = (maximum allowable weight of the vehicle) – (maximum payload)

Equation 4-8

CO_2-equivalent emissions for batteries, fuel storage tanks, and fuel cell systems =

(EF, grams/lb.) x (component weight, lbs.)

Equation 4-9

The estimates of vehicle curb weight along with the literature references are summarized in Table 4-12 for each of the eight vehicle categories. These vehicles are assumed to be conventional diesel vehicles. For six of the eight vehicle types, a specific vehicle model was chosen from which to establish the curb weight values. For MD Urban vehicles and SH Tractors, estimates for the curb weight come the EPA/NHTSA rulemaking to establish fuel efficiency and GHG standards for HD vehicles [105]. As part of the test procedure development process, the agencies developed estimates for average curb weight and payload for the vehicle types in each of the various regulatory subcategories. For MD Urban vehicles, the value of 13,950 lbs. comes from the EPA/NHTSA's estimate of the curb weight of a medium HD vocational vehicle (see

Chapter II section D. (2) (c) (iii) in [189]). The curb weight of a SH Tractor is based on that of a *Class 7 Day Cab High Roof* tractor (see Table II-11, ibid).

For all of the technology types—including conventional diesel vehicles—the weight of batteries and fuel storage tanks (and fuel cell systems if applicable) were estimated based on available industry literature and a number of assumptions. The estimated weights of each component as well as the sources and assumptions are given in Table 4-13 and

Table 4-14 respectively. A number of approximations were necessary because many of the technologies in each vehicle category do not currently exist or are in their infancy commercially. For hybrids, these estimates are for hybrid-electric vehicles. These weights—and the emissions associated with manufacturing—apply to hydraulic hybrids as well, though these vehicles are quite different in their energy storage devices (i.e. reliance on high-pressure accumulator tanks as opposed to batteries) and hybrid components (e.g. motors/generators). This was deemed a reasonable modeling simplification, given that hydraulic hybrids are only assumed to gain market share in heavy vocational applications such as refuse hauling.

Table 4-12: Representative vehicle models and assumed curb weights

Vehicle Type	Representative Vehicle Model	Estimated Curb Weight (lbs.)	Reference
HD Pickup Truck	GMC Sierra 2500 HD	5,862	(ANL, 2009) [204]
Urban Bus	40-foot Orion V	28,795	(ANL, 2009)
Other Bus	MCI E-Series Coach	38,000	(MCI, 2012) [221]
MD Urban	N/A	13,950	(EPA, 2011) [105]
MD Vocational	GMC C-series C5C042 2WD regular cab	9,859	(ANL, 2009)
HD Vocational	Side-loader refuse truck based on the Autocar chassis	56,000	(Drozdz, 2005) [222]
LH Tractor	Kenworth T660	19,701	(ANL, 2009)
SH Tractor	N/A	11,500	(EPA, 2011)

Table 4-13: Estimated weights (lbs.) for batteries, fuel tanks, and fuel cell systems

	Gasoline/ Diesel		**NG**		**HEV**		**PHEV**		**BEV**	**FCV**		
	Bat.	Fuel Tank	Bat.	Fuel Tank	Bat.	Fuel Tank	Bat.	Fuel Tank	Battery Pack	Bat.	Fuel Cell	Fuel Tank
HD Pickup	30	89	30	1,063	300	89	727	89	1,154	109	175	341
Urban Bus	135	158	135	1,440	800	126	2,050	95	3,300	800	2,000	1,024
Other Bus	260	229	260	1,440	970	40	2,486	30	4,001	970	2,425	1,241
MD Urban	50	79	50	1,860	110	79	1,055	79	2,000	110	273	1,134
MD Vocation	50	79	50	1,860	110	79	1,055	79	2,000	110	193	1,134
HD Vocation	164	88	164	656	220	88	2,110	66	5,550	220	386	2,268
LH Tractor	70	252	70	755	154	252	3,165	189	8,250	352	752	898
SH Tractor	70	252	70	755	154	252	3,165	189	8,250	352	752	898

Table 4-14: References and methods for determining energy storage system and fuel cell weights

	Gasoline/ Diesel		**NG**		**HEV**		**PHEV**		**BEV**	**FCV**		
	Bat.	Fuel Tank	Bat.	Fuel Tank	Bat.	Fuel Tank	Bat.	Fuel Tank	Battery Pack	Bat.	Fuel Cell	Fuel Tank
HD Pickup	a	[223][h]	a	[224][i]	[225][b]	j	c	j	[226][d]	e	f	g
Urban Bus	a	[227][h]	a	[228]	[229]	l	c	l	[208, 230]	[231]	[232]	k
Other Bus	[233]	[234][h]	a	m	[235]	[235][h]	c	m	m	m	m	m
MD Urban	[236]	[237][h]	a	[238][i]	[239]	j	c	j	[240]	o	e	p
MD Vocation	n											
HD Vocation	[241][a]	[241][h]	a	[48][r]	q	j	q	m	[230, 242]	q	q	q
LH Tractor	[243]	[244][h]	a	[245][i]	s	j	s	m	s	t	p	p
SH Tractor	u											

a) Developed using data in [246] and [247]. Also, the battery weights of NG vehicles are assumed to be identical to batteries in gasoline and diesel vehicles.

b) Assumes that the battery pack size of a large hybrid sport utility vehicle (SUV) would be comparable that of a hybrid HD pickup truck.
c) The battery pack size of a PHEV is assumed to be midway between the size of the battery pack in a hybrid and a full electric vehicle.
d) The battery pack size of a full electric HD pickup is estimated based on the size of the battery pack in a Nissan Leaf and a ratio of the curb weights of the two vehicles.
e) Estimate based on the reported value of energy storage or fuel cell weights in the LEM and a ratio of the curb weights of the two vehicles (i.e. curb weights of TOP-HDV vehicles versus the curb weight of the HD vehicle in the LEM).
f) Estimate based on the reported value of a fuel cell system in a light-duty vehicle in the LEM and a ratio of the curb weights of the two vehicles.
g) Given the desired range and fuel consumption of this vehicle type, this estimates that the hydrogen tank weight is 1/3rd that of an Urban Bus.
h) Estimate based on a ratio of the weight of the fuel (using the reported fuel tank volume from the reference and an assumed diesel fuel density of 7 lbs./gal) of this vehicle type as compared to the value of the weight of the fuel in a HD diesel vehicle in the LEM.
i) In the LEM, the desired driving for a diesel HD vehicle is 450 miles, and the fuel tank is sized accordingly. The fuel tank weights for each vehicle type are estimated based on ratios using these modified desired driving ranges: [HD Pickup: 300 mile; MD Urban and Vocational: 525 mile; LH and SH Tractors: 600 mile].
j) Fuel tank is assumed to be the same size as that of a conventional vehicle. In the case of PHEVs that spend a large amount of time in PTO operations or idling, the battery pack's energy may be used primarily during non-driving functions, and the fuel tank would need to be sized such that the vehicle would have adequate driving range capabilities.
k) Calculated based on the estimated weight of NG fuel tanks in an Urban Bus and the ratio of the LEM reported values for fuel tank weight of a fuel cell HD vehicle as compared to a NG vehicle.
l) Hybridization is assumed to allow for a reduction in fuel tank size (Urban Bus: 20% reduction for a HEV, 40% for a PHEV)
m) Estimated using the ratio of the battery pack, fuel tank, or fuel cell sizes in an Urban Bus.
n) See Table 4-13. The battery pack, fuel tank, and fuel cell size of MD Urban and MD Vocational vehicles are assumed to be identical.
o) The battery weight of a FCV is assumed to be comparable to that of a HEV.
p) In the LEM, the desired driving for a CH_2 fuel cell HD vehicle is 350 miles (450 miles for a LH_2 vehicle) and the fuel tank is sized accordingly. The weights for each vehicle type are estimated based on ratios using these modified desired driving ranges: [MD Urban and Vocational (CH_2): 350 mile; LH and SH Tractors (LH_2): 600 mile].
q) Battery packs and fuel cell systems in hybrid HD Vocational vehicles are assumed to be twice as heavy as those in hybrid MD Vocational based on additional loads and power demands.
r) The assumption is an LNG vehicle with total tank capacity of 150 gallons. The fuel tank weight estimate is based on a ratio of the weight of the fuel (using the reported tank volume from the reference and an assumed LNG fuel density of 3.8 lbs./gal) of this

vehicle type compared to the value of the weight of the fuel in a HD LNG vehicle in the LEM.

s) Battery weights of LH and SH Tractors are scaled up based on MD and HD Vocational estimated battery weights.
t) Taken directly from the value of the battery weight in a LH_2 HD vehicle in the LEM.
u) See Table 4-13. The battery pack, fuel tank, and fuel cell size of LH and SH Tractors are assumed to be identical.

4.3.6.5 Emissions from end-of-life vehicle decommissioning

The final lifecycle phase modeled in TOP-HDV aims to capture the emissions that are consequence of disposing of a vehicle at the end of its useful life. Activities in this phase include vehicle disassembly, parts recycling, and waste management. Mirroring the approach taken with fuels upstream activities and vehicle manufacturing, the emissions estimates related to the end-of-life phase are based on aggregate EFs, which represent the sum total of all of the individual vehicle decommissioning processes.

The LEM does not include a vehicle scrappage module, so another data source was necessary for developing these estimates. Based on a search of lifecycle analysis (LCA) literature, only one source was found that contained estimates of the emissions associated with the disposal of a HD truck. Data from an Environmental Product Declaration (EPD) from the Volvo Truck Corporation [248] about their Euro III FH12 and FM12 tractors is the basis for the TOP-HDV scrappage module. According to Li (2009) [249], who analyzed this Volvo EPD in detail, most of the truck's steel, aluminum, and plastics as well as the battery and fluids (i.e. fuel, oil, etc.) are recycled, while the remaining materials are disposed of in a landfill. Overall, the majority of the vehicle—by weight—can be recycled. Focusing on the end-of-life phase, the processes that are accounted for in the Volvo analysis are summarized in Figure 4-6, which is adapted from Figure 4.1 in [249]. Due to a lack of information, the only end-of-life activity that is included in the Volvo LCA is recycling.

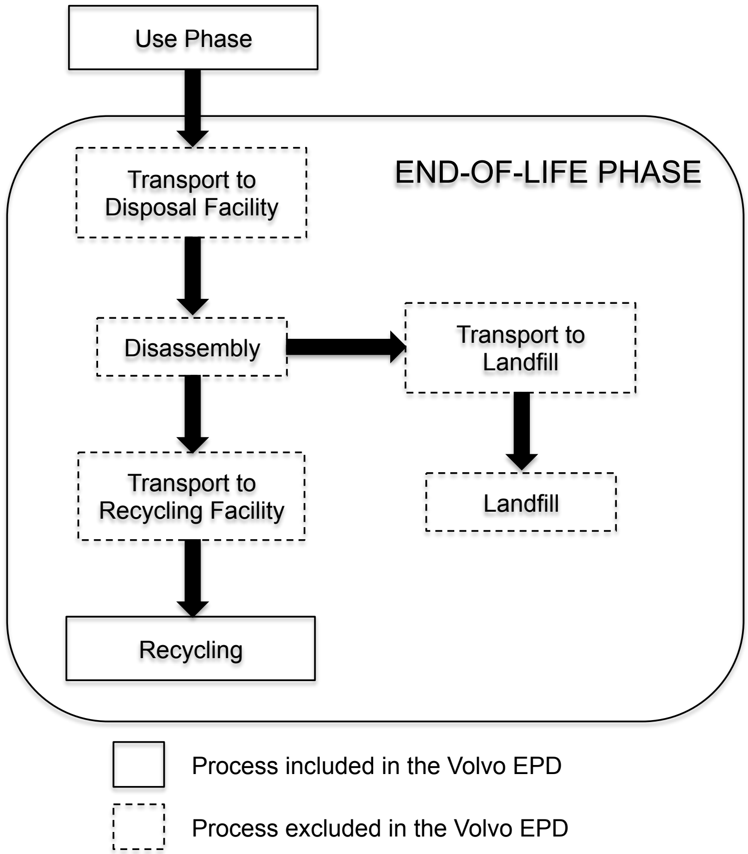

Figure 4-6: End-of-life processes accounted for in the Volvo EPD

The method for calculating per-vehicle scrappage emissions assumes that the emissions totals due to scrappage are a linear function of vehicle weight, based on proportions of the reported mass of the Volvo tractor in the EPD (7,000 kg) to the estimated curb weight values for each of the eight vehicle categories (see Table 4-12). This assumption of a linear relationship between vehicle weight and scrappage emissions is a simplification. However, it is likely the case that there is a close relationship between the energy and resources required for recycling and waste management activities and the size of the vehicle. As another simplification, there is no distinction for the various technology vehicle types. In reality, there are likely differing recycling rates and disposal demands of the different energy storage and driveline components of certain advanced vehicles such as hybrids, battery-electric, and fuel cell vehicles.

The method for determining the per-vehicle-scrapped emission totals in 2010 is given in Equation 4-10. To estimate how these per-vehicle emissions will change over time, it was assumed that scrappage emissions for each year between 2011 and 2050 are exactly proportional to changes in vehicle manufacturing emissions over the study period. For each of the eight vehicle types:

Emissions per decommissioned vehicle =

(vehicle curb weight in lbs. per Table 4-12) / (FM/FH12 curb weight = 7,000 kg = 15,432 lbs.) x

(Volvo EPD emissions estimate)

Equation 4-10

The emitted species in the Volvo EPD that are relevant to the TOP-HDV model include CO, CO_2, HC (VOC), NOx, SO_2, and PM. For particulate emissions, the reported value in the EPD is given as "PM" and does not specify between PM_{10} and $PM_{2.5}$, so this PM value is assumed to be total PM. To determine the $PM_{2.5}/PM_{10}$ ratio, the 2008 ARB statewide PM_{10} and $PM_{2.5}$ emissions totals for *Industrial Processes* were utilized [250]. Estimates for black and organic carbon are calculated using the $BC/PM_{2.5}$ and $EC/PM_{2.5}$ ratios for comparable years in the TOP-HDV tables for emissions per vehicle manufactured. For CH_4 and N_2O, scrappage emissions estimates are derived using $NMHC/CH_4$ and N_2O/NOx ratios from the vehicle manufacturing emissions tables.

4.3.7 Direct Costs

In addition to estimating lifecycle fuel use and emissions for various long-term technology adoption scenarios, the second primary function in TOP-HDV is estimating the direct expenses and externality costs associated with the California HD vehicle fleet. As with the other modules in TOP-HDV, the cost assessment methodology takes a lifecycle perspective. Within the cost estimation framework, there are two major areas: 1) the direct costs incurred by users of HD vehicles and 2) the externality costs related to pollution, global warming, energy security, and noise imposed by HD vehicle fuel use and emissions. For this project, the labor costs of HD vehicle operation are not included in the analysis, which is based on the assumption that labor costs are equivalent from technology to technology and, in turn, from scenario to scenario. The first item—the direct costs to HD vehicle owners and operators—is discussed in this section, while the valuation of externalities is examined in Section 4.3.8. Figure 4-7 summarizes the four user cost areas that are included in the model: 1) vehicle purchase costs, 2) refueling station costs, 3) fuel costs, and 4) maintenance and insurance costs. These costs are discussed in Sections 4.3.7.1, 4.3.7.2, 0, and 0 respectively.

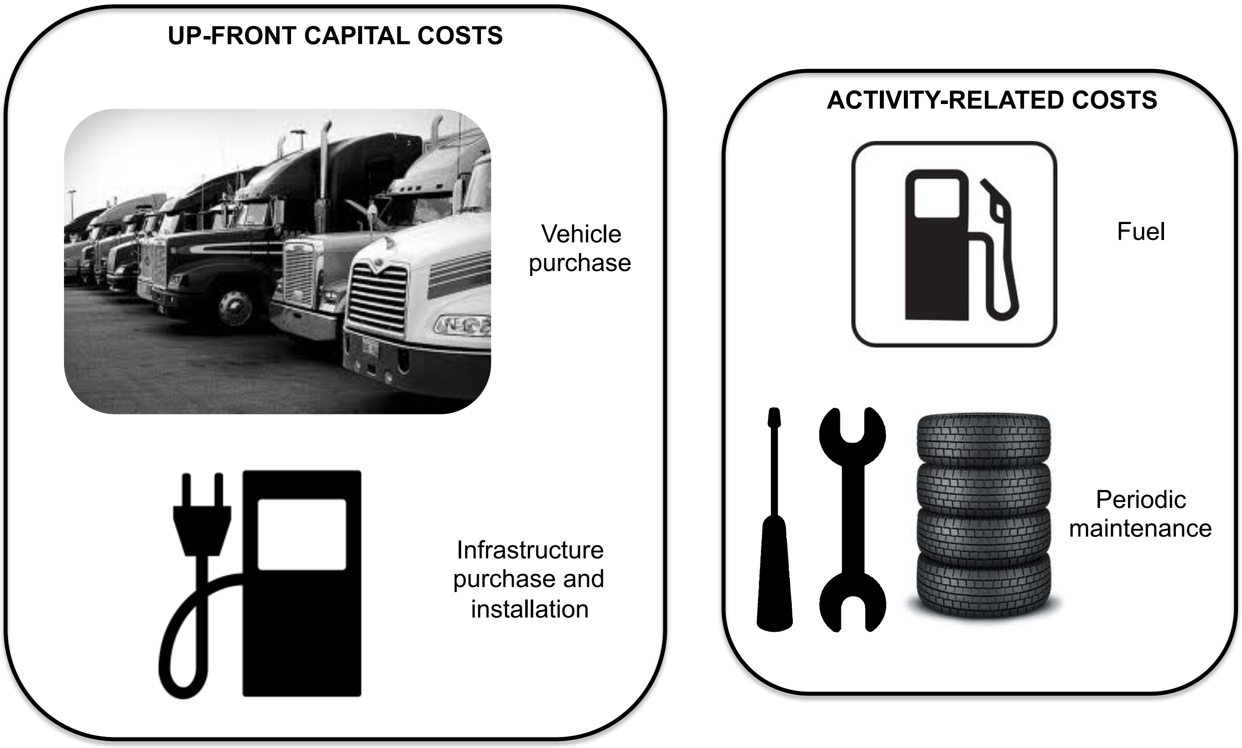

Figure 4-7: Cost elements included in TOP-HDV

4.3.7.1 Vehicle retail prices

Obtaining a new vehicle typically involves a large up-front expenditure or making financing provisions. In TOP-HDV, vehicle acquisition is modeled as a one-time expense of the entire retail price of the vehicle and does not take into account any subsidies that may exist at the federal, state, or local level to decrease the purchase price of the vehicle for the end-user. This expenditure is assumed to occur in the same year that the vehicle enters the fleet, which is also identical to the model year vintage. The used vehicle market (i.e. resale of vehicles to secondary, tertiary, etc. owners) is not included in the model.[23]

[23] At the end of their 30 years of useful life, vehicles are assumed to have zero scrappage value.

The HD vehicle industry has tremendous diversity, and there is a high level of vehicle customization in order to accommodate specific duty cycles, operating conditions, and customer preferences. As with the vehicle manufacturing module in TOP-HDV, the purchase prices for each of the eight vehicle categories are based on representative vehicle models (e.g. Freightliner Cascadia, Ford F-250, etc.). For five of the six truck categories, MY 2010 Manufacturer's Suggested Retail Price (MSRP) estimates for conventional diesel vehicles were developed by reviewing data in the online truck valuation tool, Truck Blue Book [251]. The retail price for HD Vocational vehicles is based on a refuse truck and comes from Burke (2008) [252]. The Truck Blue Book does not have MSRP data for buses, so Mancini (2010) [253] and Lowell (2011) [206] were used to estimate the purchase price for Urban and Other Buses respectively. Table 4-15 summarizes the MY 2010 purchase price estimates for conventional diesel truck and buses that are used for this project.

Table 4-15: Estimated retail prices for conventional diesel vehicles in 2010

HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
$40,000	$325,000	$500,000	$75,000	$75,000	$200,000	$160,000	$145,000

For gasoline and advanced technology vehicles, rather than estimating the absolute values for each MSRP, the model allows users to input multiplication factors that ratio each technology to the price of a MY 2010 diesel vehicle. For example, an input value of 1.5 implies a 50% price premium in 2010 compared to a conventional diesel vehicle, and 0.9 represents a 10% lower purchase price. The primary reason for this approach is that many of the technology options are either not commercially available, or reliable cost information is sparse in the literature. The retail price factors assumed for this project as well as the sources and methodologies used in developing these factors are shown in Table 4-16 and Table 4-17.

Table 4-16: Purchase price factors for MY 2010 vehicles

	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
Gasoline (gsl.)	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Diesel (dsl.)	1	1	1	1	1	1	1	1
NG	1.2	1.2	1.2	1.7	1.7	1.3	1.5	1.5
Gsl. HEV	1.3	1.6	1.1	1.3	1.4	1.2	1.2	1.2
Dsl. HEV	1.3	1.7	1.1	1.3	1.4	1.2	1.2	1.2
Gsl. HHV	2.4	1.5	1.2	1.7	1.7	1.5	1.6	1.6
Dsl. HHV	2.5	1.6	1.3	1.8	1.8	1.6	1.7	1.7
Gsl. PHEV	1.9	2.1	1.6	1.9	1.9	1.5	1.5	1.5
Dsl. PHEV	2	2.2	1.6	2	2	1.5	1.6	1.6
BEV	3.8	2.8	2.5	2.5	2.5	3.0	3.0	3.0
FCV	4.0	5.5	4.0	3.0	3.0	3.0	3.0	3.0

Table 4-17: References and methods for the vehicle purchase price ratios

<table>
<tr><th></th><th>HD Pickup</th><th>Urban Bus</th><th>Other Bus</th><th>MD Urban</th><th>MD Vocation</th><th>HD Vocation</th><th>LH Tractor</th><th>SH Tractor</th></tr>
<tr><td>Gasoline</td><td>[254]</td><td colspan="7">a</td></tr>
<tr><td>Diesel</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>NG</td><td>[255]</td><td>[253]</td><td>f</td><td colspan="2">[256]</td><td>[252]</td><td>[257]</td><td>[257]</td></tr>
<tr><td>Gsl. HEV</td><td rowspan="2">[36]</td><td colspan="7">a</td></tr>
<tr><td>Dsl. HEV</td><td>[253]</td><td colspan="6">[36]</td></tr>
<tr><td>Gsl. HHV</td><td colspan="8">a</td></tr>
<tr><td>Dsl. HHV</td><td colspan="5">b</td><td>[258]</td><td colspan="2">b</td></tr>
<tr><td>Gsl. PHEV</td><td colspan="8">a</td></tr>
<tr><td>Dsl. PHEV</td><td colspan="3">c</td><td colspan="2">[259][c]</td><td colspan="3">c</td></tr>
<tr><td>BEV</td><td>[260]</td><td>[253]</td><td>d</td><td colspan="2">[261]</td><td colspan="3">d</td></tr>
<tr><td>FCV</td><td>e</td><td>[253]</td><td colspan="6">e</td></tr>
</table>

a) Gasoline-powered vehicles are virtually nonexistent in the heavier truck and bus categories (i.e. Classes 6, 7, and 8). These factors for gasoline vehicles are simply placeholder estimates and do not imply that gasoline engines are expected to have increased market share in these vehicle categories. In the HD Pickup category, hydraulic hybridization is not very attractive from an engineering standpoint due to the additional weight imposed by the high-pressure accumulator tanks. For this technology, this retail price factor is the author's best judgment.
b) More so than electric hybrids, hydraulic hybrids present a weight penalty, which makes these systems less attractive in lighter HD vehicles (i.e. Class 2B through 5/6). To date, one of the applications where hydraulic hybrids are in early commercialization is in refuse hauling. Therefore, HD Vocation is the only category for which there is a concrete

estimate for the incremental cost of this technology. For all of the other categories, the factors are the author's best judgment.

c) Currently, plug-in hybrid technology is in the early commercialization phase in the HD sector in a limited number of MD truck applications. There is very limited incremental cost information available. The factor for MD Urban and Vocational plug-in hybrid vehicles assumes an additional cost of $75,000 in 2010, which is based on cited ranges in a Government Fleet (2009) [259] publication.

d) Full electrification is not commercially available in these HD vehicle categories, and these values for the retail price factors in 2010 are the author's best estimates.

e) To date, fuel cell technology in the HD sector has primarily been limited to transit buses. Though there are some proof-of-concept FCVs that have been recently developed for other HD applications (e.g. the Vision Tyrano drayage tractor [262]), there are no publically available cost estimates. These price factors are the author's best judgment based on the incremental cost of fuel cell Urban Buses.

f) The estimate of the incremental cost of a LNG coach bus is based on the cost of an LNG tractor compared to a conventional diesel.

The changes in purchase price for new diesel vehicles over time are modeled using inputs for the average annual percent change in prices in 2010 dollars. To model how the retail prices of advanced technology vehicles will change over time compared to conventional vehicles, TOP-HDV uses a *learning curve* methodology. Learning curves describe the reductions in unit costs for each advanced technology type as a function of cumulative production volume. In employing this learning curve methodology, the retail price estimates are linked directly to the TOP-HDV scenario data for technology adoption over time. The learning curve for each technology type is defined by three user input parameters: 1) the initial production volume (or threshold) after which cost reductions begin to take place; 2) the rate at which cost reductions occur with each subsequent doubling in cumulative production beyond the initial threshold; and 3) the "price floor," after which no cost reductions occur.

Initial Production Volume Threshold. As summarized by Schwoon (2008) [263], many studies of the effect of *learning-by-doing* on production costs assume that cost reductions begin only after some initial volume threshold has been reached. In TOP-HDV, for each technology and vehicle type this input value sets the cumulative production volume limit after which reductions in retail price begin. Say, for example, this value is set to 1,000 vehicles. The retail price for vehicles 1 through 1,000 remains constant, and stating with vehicle number 1,001, prices decrease according to the value input for the *progress ratio*.

Progress Ratio. The *learning rate*, L, is typically expressed as the percent by which the average unit cost declines with a doubling of cumulative production. The value (1 - L) is usually referred to as the progress ratio (PR). For example, as before, for a given technology type, say the threshold volume is set at 1,000 vehicles, and the PR is 80%. There is no reduction in cost for the first 1,000 units, but afterwards the production costs decline such that by the time the 2,000th vehicle is produced, the costs are 80% of the production costs of the first vehicle. The progress ratio methodology for estimating the cost reductions of new technology over time has been employed in various passenger vehicle studies [263-269], but published studies that use this approach to estimate the costs of advanced technology HD vehicles are limited. In the studies that estimate the learning effects for advanced passenger vehicles (e.g. hybrid-electric, battery-electric, hydrogen fuel cell), progress ratios are typically on the order of 80 to 95%.

Price Floor. One of the potential drawbacks of this learning curve methodology is that production costs can fall indefinitely if production volumes continually increase. This is not a realistic situation, as total vehicle production costs can never fall beneath the cost of materials and assembly. A way to remedy this situation is to introduce a lower bound, or *price floor*, to the cost reductions. In TOP-HDV, the price floor is a modifiable factor that uses the cost of a conventional diesel vehicle as a reference. For example, a value of 1.1 means that the reductions in retail price over time of a given technology vehicle will stop when the value reaches 10% higher than the cost of a diesel vehicle.

Given the relative uncertainty of how HD vehicle advanced technology costs might decrease over time, a range of plausible values are used for all three of the above parameters in this analysis. See Section 5.8 for the sensitivity analysis of these learning curve variables.

4.3.7.2 Fuel station costs

The second set of capital costs modeled in TOP-HDV are the expenditures related to purchasing and installing the necessary fuel/energy storage and dispensing systems to meet the additional fuel demands (e.g. diesel, NG, hydrogen, electric charging, etc.) of an increasingly diverse HD vehicle fleet. The costs in this module do not include the extensive infrastructure upgrades such as the new distribution pipelines or electrical grid equipment that would be required to support a substantial advanced technology vehicle fleet. Rather, the costs estimated here are meant to represent only the costs that are incurred by typical HD vehicle operators (e.g. a municipality, transit district, trucking firm, private enterprise, etc.).

In the model, the number of new fuel stations that are required in each year as well as the average station sizes (in terms of fuel throughput) and their unit costs are not user inputs, per se. Rather, these fuel station parameters are linked to the scenario outputs—specifically, the total fuel demanded in each year, which is summarized in terms of diesel gallon equivalent (DGE) for each fuel type for each of the six scenarios. Conceptually, the size of new refueling stations is directly proportional to a given fuel's percentage market share in terms of the total fuel demanded by HD vehicles. The average size of new refueling stations is then used to calculate the number of stations needed each year as well as their unit costs for construction. The process for determining the average size, number, and unit cost of new refueling stations are described in more detail in the follow steps.

1. *Average size of new refueling stations*. Each scenario outputs the total fuel consumed in each year in DGE. This fuel demand is met by a certain number of identical refueling stations, whose size is a function of that given fuel's market share. The key assumption of this approach is that the average refueling station size in each year is directly related to the number of vehicles of that type in the fleet and the volume of fuel these vehicles demand. In the real-world, stations sizes are not overly small or large due to market conditions (i.e. fuel retailers tend to size stations to maximize potential revenue) and the need for adequate geographic spacing of stations. Taking these factors into consideration, in the model there are lower and upper bounds on station size of 50,000 and 2,000,000 DGE/year respectively. The lower bound value is the size of a small refueling station that could serve up to roughly five *back-to-base* vehicles (i.e. vehicles with urban drive cycles such as transit buses or delivery trucks that typically return to a central depot after completing daily operations) [270]. The upper bound value is based on the fuel throughput of a moderately sized truck stop that serves LH tractors [271]. The functional form of the station-sizing calculation is given in Equation 4-11. For each year, 2011-2050:

$$\text{If demand for fuel X} \neq 0,$$

$$\text{New refueling station size in DGE/year} =$$

$$\text{Minimum}\{50{,}000 + 50{,}000{,}000 * (\text{demand for fuel X}) / (\text{total fuel demand}); 2{,}000{,}000\}$$

Equation 4-11

2. *Number of new refueling stations required*. Starting in 2011, if there is demand for a given fuel, the first calculation that the model performs is whether or not that fuel demand can be met with existing fuel stations. For each of the five fuel station types

(conventional gasoline and diesel, CNG, LNG, CH_2, and LH_2), there are user inputs for the capacity factor of existing fuel stations.[24] For example, an input of 80% implies that the overall refueling station network can accommodate an additional 20 percentage points of demand before new stations would be required. If new stations are required in a given year, the calculation to determine the number needed is as follows:

Number of new refueling stations =

Roundup{(total demand for fuel X) / (refueling station size, per Equation 4-11)}

Equation 4-12

As a simplification, the model assumes that new refueling stations are built instantaneously to meet the fuel demand in a given year.

3. *Unit costs for each type of refueling station*. The costs estimated in this module include the materials and building expenses that a typical fleet operator would incur in constructing a refueling station. These cost estimates do not include a valuation of the externalities associated with station construction (e.g. emissions, energy use, noise, etc.). Also, annual station operating expenses are not accounted for in the model. The capital costs for each type of refueling station are assumed to be a function of 1) the station size in DGE/year and 2) the cumulative number of stations that have been introduced.[25] The functions that relate capital costs to station size as well as the sources for these estimates are summarized in Table 4-18 and Table 4-19 respectively. With regard to learning

[24] There are also two additional input fields that may be used if a different type of fuel station is being modeled.

[25] An exception is the unit cost of conventional diesel and gasoline stations. As this is the type of station that currently dominates the market, the model assumes that no further cost reductions are possible due to learning effects.

effects, mirroring the approach that is used to model the costs of advanced vehicles as a function of cumulative production, TOP-HDV has a similar method for determining how refueling and recharging station costs decline as a result of increased market penetration over time. As with vehicle costs, initial threshold volume, progress ratio, and price floor user inputs for each of the station types control the profile of cost reductions over the study period. Similar to the case of advanced vehicle retail prices, the literature on HD refueling station costs is sparse, so a variety of values (within reasonable ranges) are utilized for each of these learning curve input parameters as part of the sensitivity analysis (see Section 5.8).

Table 4-18: Refueling station costs (2010$) as a function of annual fuel throughput

HD Vehicle Refueling Station Type	Cost Functions (y = station cost in 2010$; x = annual fuel throughput in DGE)
Conventional gasoline/diesel	y = $135,000 + 0.073x
Compressed NG	y = $1,350,000 + 0.725x
Liquefied NG	y = $2,450,000 + 1.025x
Compressed hydrogen	y = $2,531,250 + 1.359x
Liquefied hydrogen	y = $6,430,788 + 3.279x

Table 4-19: References and methods for estimating the costs of refueling stations

Refueling Station Type	References and Methods for Cost Functions
Conventional gasoline/diesel	Conventional stations are assumed to be 10% the cost of a CNG station. CNG station costs are based on transit buses analyses [211, 272].
Compressed NG	Estimates for CNG station costs as a function of annual fuel throughput are based on the "1/3 each" fleet scenario in the National Renewable Energy Laboratory’s VICE model [270]. This scenario in VICE assumes a fleet mix of transit buses, refuse trucks, and school buses.

Liquefied NG	LNG station costs are based on the estimated cost of a CNG station plus the average installed capital cost of a liquefier in the AVCEM [273]. Also, Johnson (2011) [274] provided an additional data point for LNG station costs.
Compressed hydrogen	Developed using model outputs for hydrogen stations for transit buses [211, 272].
Liquefied hydrogen	The additional cost of hydrogen liquefaction (at a centralized, large-scale facility), truck distribution, and retailing is based on an average of the "High" and "Low" values ($/million BTU) in the AVCEM [273].
Conductive (i.e. plug-in) electrical charging	Assumes that there is one charging outlet/station for each plug-in hybrid or full electric vehicle. Cost information comes from personal communication with Brett Gipe of Smith Electric Vehicles (March 5, 2012) [275]. The $4,700 value represents the total installed cost of a Clipper Creek CS100 Level 2 charger, which retails for $2,195 [276] plus an additional $2,500, which is a rough estimate of the average costs of the minor electrical upgrades that are required for a facility that already has 220/240 alternating current (AC) power.

4.3.7.3 Fuel prices

The third end-user cost module in the model is fuel purchases. These expenses are accounted for on an annual basis. The 2010 fuel retail price estimates that are used in this project as well as the sources and methods for determining these values are given in Table 4-20. Where the data was available, these fuel retail prices represent statewide averages for California. Otherwise, the prices used are US average or western states-based figures.

To model how fuel prices (in 2010$) will change between 2011 and 2050, users enter average annual percent change inputs for each fuel/feedstock combination. Unlike the vehicle and fuel station cost methodologies that employ learning effects to determine the cost reductions, the approach for estimating fuel prices over time is more simplistic. The fuels used by HD vehicles are not exclusive to this specific sector but, rather, are shared across many parts of the economy—transportation and non-transportation alike. Though increases in demand from HD trucks and buses certainly have an effect on fuel markets, there are many other exogenous forces influencing fuel prices. Moreover, energy markets are highly globalized, and increased demand from HD vehicles in California is unlikely to have a substantial impact on prices.

Table 4-20: Fuel retail prices in 2010

Fuel	Feedstock	2010 Estimated Retail Price	Reference
Reformulated gasoline	Crude oil	$3.09/gal	[277]
Ultra-low sulfur diesel	Crude oil	$3.16/gal	[278]
Fischer-Tropsch diesel	Fossil-based NG	$20/gal	[279][a]
Compressed NG	Fossil-based NG	$0.008/SCF	[280]
Compressed NG	Landfill gas (LFG)	$0.013/SCF	b
Compressed NG	Dairy biogas (DBG)	$0.005/SCF	
Liquefied NG	Fossil-based NG	$2.25/gal	[281][c]
Liquefied NG	Landfill gas	$3.88/gal	[282][d]
Liquefied NG	Dairy biogas	$1.26/gal	[283][e]
Biodiesel	Soy	$3.74/gal	[284-286][f]
Ethanol	Corn	$2.60/gal	
Ethanol	Cellulosic	$2.43/gal	[287][g]
Compressed hydrogen	Fossil-based NG	$3.36/kg	[273][h]
Compressed hydrogen	Water	$4.92/kg	
Liquefied hydrogen	Fossil-based NG	$1.82/gal	
Liquefied hydrogen	Water	$2.32/gal	
Electricity	California grid mix	$0.147/kWh	[288]

a) Fischer-Tropsch gas-to-liquids fuel production is still a relatively nascent industry, and, as of this writing, this process is not yet commercial, and there is no production cost or retail price data available. This is a rough estimate based a California Energy Commission fact sheet and the 2010 price of NG.

b) The price ratios for LNG from the three feedstocks (i.e. (LNG from fossil-based NG) / (LNG from LFG) and (LNG from fossil-based NG) / (LNG from DBG)) are used to calculate the price of CNG from LFG and CNG from DBG using the price of CNG from fossil-based NG.

c) This estimate is based on averaging prices from 7 public stations in California (data retrieved on Dec 28, 2011).

d) The $15.5M project cost of the landfill gas-to-vehicle-fuel facility in Altamont, CA is divided by its annual fuel throughput of 4 million gallons to yield $3.88/gal.

e) See Table 8-8 in Krich et al. (2005).

f) Retail price estimates for soy biodiesel and corn ethanol are based on averaging "West Coast" region data points from the April, July, and October 2010 Clean Cities Alternative Fuel Price Reports.

g) In the ARB’s technical support document for the Low Carbon Fuel Standard, corn stover is the feedstock that is assumed in estimating cellulosic ethanol prices (see the “Ethanol Production Cost” comment and response section on page 418).

h) These estimates are derived using $/MMBtu outputs from AVCEM.

4.3.7.4 Maintenance and insurance costs

In addition to fuel, the other expenses related to vehicle operation that are modeled in TOP-HDV are the costs of maintenance and insurance. For maintenance, these costs include periodic expenses such as oil and lubrication, engine and powertrain repair, brake servicing, and tire replacement. The sum of these costs is modeled on a per-mile basis for each technology and vehicle type. There is a fair amount of data in the literature from both industry and academic sources about the operational costs for various types of HD diesel vehicles. The per-mile maintenance costs of conventional diesel vehicles assumed in this project for the year 2010 are summarized in Table 4-21. These cost estimates represent averages across all 30 model years (i.e. MY 1981 to MY 2010).

For non-diesel vehicles, as in the retail price module, TOP-HDV has user input multiplication factors for each technology that control the maintenance costs compared to a MY 2010 diesel vehicle. Perhaps more so than in the case of retail prices, the maintenance costs associated with advanced technology HD vehicles are highly variable, and it is challenging to even cite directional trends versus diesel vehicles. Table 4-22 summarizes eleven real-world testing projects where researchers at the National Renewable Energy Laboratory (NREL) have analyzed—amongst other things—the per-mile maintenance costs of various HD NG and hybrid vehicles in transit bus, parcel delivery, and refuse hauling applications. Looking at the results from this limited set of testing projects, no definitive conclusions can be made about whether conventional diesel vehicles are more or less expensive to maintain. Due to this high degree of uncertainty, multiple maintenance cost scenarios were modeled as part of the sensitivity analysis (see Section 5.8).

Estimates for how maintenance costs may change over the study period (in 2010$) due to learning effects are linked to the retail costs for each of the nine technology groups. This is based on the assumption that new advanced technology vehicles are typically less expensive to maintain over time as learning effects in vehicle design as well as in the field (i.e. with drivers and maintenance technicians) cause maintenance and repair costs to gradually decrease in subsequent model years. This reduction in maintenance and repair costs over time is modeled to occur at the same rate that retail prices decrease. For example, if the retail price of a hybrid MD Urban Vehicle declines 15% between 2020 and 2025 due to an increase in sales volume, then the per-mile maintenance and insurance costs over this time period are assumed to decrease by 15%

as well (insurance rates are a direct function of vehicle price). However, the converse is *not* true for maintenance costs—if per-vehicle retail prices are assumed to increase over time for conventional vehicles (and thus for advanced vehicles as well, since their costs are modeled as a function of diesel vehicle costs), maintenance costs are set to remain constant. This assumption is based on the fact that there is no evidence to support the premise that increased technology adoption rates—say, due to regulation—drive up maintenance costs. This assumption in the model is supported by the analysis done for the US Medium and Heavy-Duty Vehicle GHG and fuel efficiency regulation [189].

Table 4-21: Estimated maintenance costs for conventional diesel vehicles in 2010

Vehicle Type	2010 Estimated Maintenance Cost ($/mile)	Reference	Notes
HD Pickup Truck	$0.07	[273]	Taken from "generic SUV values" on the "Results -- by cost item" sheet in the AVCEM.
Urban Bus	$1.47	[289]	Derived by dividing total vehicle maintenance costs for buses (Table 17) by total miles (Table 8) in APTA (2011).
Other Bus	$0.39	[206]	See page 10 for estimate of per-mile maintenance costs. Engine oil and lubrication costs are assumed to be included in this figure, as 5% of the total, such that maintenance costs + lubrication costs = 39 cents/mile.
MD Urban	$0.11	[290]	Calculated using the values from the “Delivery Fleet Operating Costs” table. In each sub-table, the “Prev. Maint,” “Tires,” and “Repairs” values are summed. The average of the sum of these seven sub-tables are then converted from 2004$ to 2010$.
MD Vocational	$0.14		Calculated using the values from the “Utility/Railroad Fleet Operating Costs” table. The same method is used as for MD Urban vehicles.
HD Vocational	$0.76	[48]	See Figure 13 for the maintenance and engine oil cost per mile estimate ($0.60/mile). This is converted from 2000$ to 2010$.

Vehicle Type	2010 Estimated Maintenance Cost ($/mile)	Reference	Notes
LH Tractor	$0.17	[291]	See Table ES-1, "Q1 2010" column. The costs are assumed to be costs for LH trucking operations. Lubrication is assumed to be 5% [292] of the "Fuel and Oil Costs" line item, which is added to the "Repair & Maintenance" and "Tires" values.
SH Tractor	$0.24	[293]	Per-mile costs are assumed to be 40% higher than that of LH Tractors based on the mileage values in the "Maintenance Intervals" table—35,000 miles for SH and 50,000 for LH.

Table 4-22: NREL real-world testing results of maintenance costs of advanced tech. HD vehicles

Real-World Testing Study	Vehicle and Technology Type	Study Years and Vehicle Model Years	Maintenance Cost Results
Barnitt [294]	FedEx delivery trucks: gasoline hybrid and diesel	2009-2010 Gas-HEV: MY 2008 Diesel: MY 2006	Gas-HEVs: $0.174/mile Diesels: $0.206/mile
Barnitt [295]	Hybrid buses	2005-2007 Gen I: ~ MY 2001 Gen II: ~ MY 2005	"Generation II": $0.75/mile "Generation I" (bus A): $1.23/mile "Generation I" (bus B): $1.42/mile
Barnitt and Chandler [296]	CNG and hybrid buses	2004-2005 CNG: MY 2002 Hybrid: MY 2002	CNG buses: $1.29/mile Hybrid buses: $1.23/mile
Chandler and Proc [49]	LNG and diesel waste transfer trucks	2002-2003 LNG: My 2001 Dsl.: MYs 1999, 2003	LNG trucks: $0.096/mile Diesel trucks: $0.042/mile
Chandler and Walkowicz [297]	Diesel hybrid and conv. diesel articulated buses	2005-2006 Hybrid: MY 2004 Diesel: MY 2004	Hybrid buses: $0.46/mile Diesel buses: $0.44/mile

Real-World Testing Study	Vehicle and Technology Type	Study Years and Vehicle Model Years	Maintenance Cost Results
Chandler et al. [50]	UPS delivery trucks: CNG and diesel	1997-2000 CNG: MY 1997 Diesel: MY 1996	Hartford CNG trucks: $$0.215/mile Waterbury CNG trucks: $0.157/mile Windsor diesel trucks: $0.167/mile
Chandler et al. [48]	LNG and diesel refuse trucks	1998-2000 LNG: MYs 1997-1999 Diesel: MY 1997	LNG trucks: ~ $0.80/mile Diesel trucks: ~ $0.60/mile
Chandler et al. [298]	LNG and diesel tractors	1997-1998 LNG: MY 1997 Diesel: 1996	LNG tractors: $0.096/mile Diesel tractors: $0.048/mile
Chandler et al. [47]	LNG and diesel buses	1999-2000 LNG: MYs 1998, 1999 Diesel: MY 1998	"Original LNG": ~ $0.45/mile "New LNG": ~ $0.39/mile Diesel buses: ~ $0.53/mile
Lammert [299]	Gasoline hybrid and diesel buses	2005-2007 HEVs: MYs 2004, 2005 Diesel: My 2002	Hybrid buses: $0.31/mile Diesel buses: $0.54/mile
Lammert and Walkowicz [300]	UPS delivery: diesel hybrid and conv. diesel	2008-2010 Hybrid: MY 2007 Diesel: MY 2006	Hybrid trucks: $0.141/mile Diesel trucks: $0.130/mile

For HD vehicles, only one source was found in the literature that provides a breakdown of operational costs that includes a specific line item for insurance. This ATRI report [291] focuses on motor carrier operations, so the costs are most applicable to LH Tractors. As with maintenance costs, insurance expenditures are estimated on a per-mile basis. To determine the insurance costs for the other seven vehicle categories, a key assumption is that insurance costs are directly proportional to the value of the vehicle. To determine the relative value of each of the eight vehicle types, the retail price for MY 2010 diesel vehicles is used as a proxy. Equation 4-13 summarizes how insurance costs are derived for non-LH Tractors.

Insurance costs for non-LH Tractors in 2010 ($/mile) =

(ATRI value for "Truck Insurance Premiums") * (2010 retail price of diesel vehicle *A*) / (2010 retail price of diesel LH Tractor)

Equation 4-13

4.3.8 Valuation of externalities

Generally, lifecycle analysis involves translating the results from the inventory development portion of the project into meaningful metrics that provide an indication of a system's impact on the environment and/or human health. During the impact assessment phase of LCA, *valuation* is typically the final step in the process in which the impacts are integrated across categories[26] to allow for greater ease of comparison. One method of valuation is to transform the inventory results into monetary values such that all of the positive and negative outcomes of the study are accounted for in overall societal benefits and costs in monetized terms. In TOP-HDV the inventory results for each year are translated into 2010 US dollars. Therefore, the comparative results for each of the vehicle technology options as well as the six long-term scenarios are presented in terms of relative net costs to society.

Four externality impact categories were chosen for this project: 1) air pollution and human toxicity, 2) global warming, 3) energy insecurity, and 4) noise pollution. For all four of these impacts, there are no direct monetary costs to end-users (i.e. HD vehicle operators). However, as there are consequences that society as a whole must incur, these impacts are *externalities*. With regard to the impact of HD vehicles, this is not an exhaustive list, as categories such as vehicle accidents, time lost due to traffic congestion, or pavement damage could have been included as

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[26] For example, global warming, human toxicity, and ozone depletion are a few of the many impact categories that an analyst may select.

well. The rationale for omitting accidents, congestion, and pavement damage from the analysis is that there are no compelling reasons to believe that the rate of occurrence or magnitude of these events change as a result of switching fuels or propulsion technologies in HD vehicles.

All of the unit valuation factors in this project are based on data from the AVCEM, and the methodologies for deriving the values for the four impact categories are described in the following sections.

4.3.8.1 Tailpipe and upstream emissions

The first externality that is valuated in the model is air pollution resulting from the lifecycle emissions of HD vehicles. As explained earlier in this chapter, these emissions are generated from vehicle production, operation, and scrappage as well as the production and delivery of fuels (and/or electricity) that power these vehicles. Air pollution imparts a multitude of negative effects on ecosystems and human beings. Some of these impacts include both chronic and acute health effects such as cancer, asthma, and cardiovascular and respiratory disease as well as damage to the environment, which manifests in a variety of ways—agriculture and forest degradation, reduced visibility, and acidification are such examples.

In the AVCEM, the total costs due to each air pollutant are a function of 1) vehicle activity (VMT), 2) emission rates (grams/mile), and 3) damage cost factors ($/gram). The valuation methodology is identical in TOP-HDV. The damage cost factors used in AVCEM were estimated in detail by McCubbin and Delucchi [301, 302] and then updated by Delucchi [6]. These factors encompass a number of complex relationships:

- Vehicular emissions → ambient concentrations
- Ambient concentrations → exposure (both human and environmental exposure)

- Exposure → physical responses
- Physical responses → societal cost valuation

There is a high level of uncertainty in each of these analytical steps, and ideally, each of these processes would be modeled in detail for each pollutant, vehicle category, exposure setting (e.g. urban, rural, "hot-spot"), meteorology profile, etc. However, performing these rigorous analyses is beyond the scope of this project. Nevertheless, as an attractive alternative for LCA projects such as this study, Delucchi [6] remarks that urban-area damage cost estimates for vehicular emissions can provide a useful starting point to which adjustments can be made based on the parameters of the particular research project.

Following this approach, adjustments were made to the pollutant damage factors from AVCEM to better represent the impacts from HD vehicle activity in California. The first step in the process was to use a scalar to modify the US urban area $/gram damage factors from AVCEM to values based on average exposure from trucks and buses across all areas in California—urban, suburban, and rural. This scaling factor was developed by using population density as a proxy for relative exposure. The average population density for urban areas used in the AVCEM calculations is 2,150 persons/mi^2. To estimate the exposure from HD vehicles in California, an ARB report [201], which estimates heavy HD truck (i.e. Class 8) VMT percentages by county, is used to approximate of total HD vehicle VMT spatial distribution. A drawback of this approximation is that Class 8 vehicle VMT is dominated by LH trucks, which spend a much larger percent of time operating on highways and rural areas than other HD trucks and buses, which more frequently operate in more densely populated regions that are more susceptible to the human health impacts of criteria pollutant emissions.

Multiplying each county's population density [303] with its respective VMT percentage produced a truck activity-weighted population density of 665 persons/mi^2. For the five pollutant species for which damages are assessed—$PM_{2.5}$, NOx, NMHC, CO, and SOx—the exposure scalar is 665/2,150 = 0.31.

The second modification step is meant to scale from US values to California values. Following Delucchi's [6] methodology, the valuation scalar is a ratio of median household incomes. From the US Census Bureau, the California-to-US ratio for median household income in 2010 is $60,883/$51,914 = 1.17. So, to transform the AVCEM pollutant damage cost factors for this analysis, the following formula was used:

TOP-HDV damage cost factor ($/gram) = (AVCEM damage cost factor) * 0.31 * 1.17

Equation 4-14

In the model's valuation calculations, estimates are generated for both tailpipe and upstream (i.e. non-tailpipe) emissions. This distinction is made to reflect the fact that human exposures are typically much higher from vehicle emissions than from industrial processes due to the close proximity of vehicle exhaust to areas that are often densely populated. To model the reduced exposure from upstream emissions, a user input scaling factor controls the ratio of upstream damage factors to tailpipe damage factors. This scalar is based on the ratio of average particulate matter intake fractions from "stack" and "ground-level" pollution that are reported in Humbert et al. (2011) [304]. This intake scaling factor (i.e. "stack" / "ground-level") is roughly 30% and is applied to all five pollutants, with the assumption that the intake fraction ratio for PM is a reasonable approximation for the other pollutants.

4.3.8.2 Climate change

The second consequence of vehicle emissions that is valuated in TOP-HDV is climate change. Rising average global temperatures are detrimental to the environment in a variety of ways, and the effects are often highly interrelated in complex ways that can often exacerbate warming. Examples include sea level rise, increased incidence of extreme conditions such as hurricanes or droughts, melting of polar ice caps, and destruction of sensitive ecosystems such as coral reefs.

As evidenced by the wide distribution of climate change damage costs reported in the literature (for example, see Table 2 in [305], Table 7 in [7]), it is challenging to monetize the costs related to climate change with a high degree of confidence for number of reasons. Nevertheless, this study draws on the other climate-related research in the methodology for estimating the combined climate effects of the various pollutant species as well as the costs of the damages imposed by these effects.

Each of the pollutants inventoried in the model has a different effect on the global climate based on factors such as residence time in the atmosphere, radiative forcing, and effects on other emitted species. The first step in the valuation process involves evaluating all of the individual pollutants on an *equivalent* basis. In analysis involving the impact assessment of emissions, it has become commonplace to use carbon dioxide as the basis for establishing equivalency. In order to estimate the combined impact of non-CO_2 emissions, the mass emissions of non-CO_2 gases and aerosols are converted into the mass amount of CO_2 that would have the same impact on some measure of interest—say, global climate or the global economy. The first CO_2 equivalency factors were published in 1990 by the Intergovernmental Panel on Climate Change (IPCC) [306] and based on integrated radiative forcing and were called *global warming potential* (GWP) factors.

In estimating a GWP factor for a particular pollutant, one needs to know the:

- Relationship between radiative forcing and atmospheric concentration
- Relationship between an increase in yearly emissions and the increase in the equilibrium atmospheric concentration
- Interaction between the pollutants
- Ultimate fate of the gases
- Period of time over which to do the analysis (e.g. 10 years, 100 years, etc.)

The use of GWPs in emissions impact assessment is quite prevalent; however, as summarized by Delucchi [307], there are some drawbacks to using GWPs for policy analysis:

- GWPs compare radiative forcing rather than the impacts of climate change.
- GWPs arbitrarily ignore radiative forcing, and hence, climate change impacts beyond the chosen time horizon.
- GWPs assume a constant radiative forcing per unit for all gases, whereas in reality the radiative forcing per unit of some gases is a function of the concentration, which changes over time.

To mitigate these shortcomings, Delucchi developed *CO_2 equivalency factors* (CEFs) [307], which are based on the impacts of radiative forcing rather than on radiative forcing itself and also apply a non-zero discount rate to these impacts over a long period of time. Each CEF is a function of:

- Rate of decay of a unit emission of a gas (function of the concentration)

- Unit radiative forcing of the gas remaining in the atmosphere (function of the concentration)
- Relationships between temperature and radiative forcing
- Relationships between damages and temperature changes
- A discount factor which declines over time

In TOP-HDV, there is a toggle control on the *Scenario Builder* sheet that allows users to choose between the IPCC GWP factors (the 100-yr or the 500-yr values) and Delucchi's CEFs. If the GWP values are used, these factors are assumed to be constant over the study period, whereas the CEFs change from year-to-year.

Though the climate impacts of emissions are generally global in scale, this analysis is focused on the damage costs for California in particular. As such, the "US" damage cost factors ($/$CO_2$-equivalent metric tonne) from AVCEM are the utilized rather than the "global" values. To estimate the differing valuation of damage costs in California versus the nation as a whole, the 1.17 valuation scalar based on the ratio of median household incomes is used in the calculation, as was done for air pollution damage costs.

4.3.8.3 Oil use

There are a number of costs related to petroleum use in transportation that are generally not included in the market price of a barrel of oil. Adapting the methodology that has been developed and updated by Delucchi for the AVCEM, the external costs related to oil use that are valuated in the model include:

- Expenses related to the US Strategic Petroleum Reserve

- Military defense spending in the Persian Gulf region
- Wealth transfer from US consumers to foreign oil producers
- Macroeconomic price shocks due to reliance on oil imports
- Ground water and marine water pollution caused by oil spills and leakage

Each of these cost areas is described in detail in these references [5-7].

Mirroring the AVCEM approach, the sum of all of these externalities are modeled as a $/gallon damage cost factors and applied to both gasoline and diesel fuel use totals for each year in the analysis. As before, the California-to-US valuation factor of 1.17 is applied to the AVCEM values. Factors are also included to take into account the petroleum content of reformulated gasoline (which contains ethanol as an oxygenate) and diesel as well as upstream oil use. The ratio of total fuel-cycle (i.e. upstream + end-use) oil use to end-use oil that is used in this project is 1.1 and is taken from the LEM ("best" case) [214].

4.3.8.4 Noise

The final category of externality costs that is modeled in TOP-HDV is the negative impact of noise pollution. Noise can impose costs such as reduced productivity, interrupted sleep, and disrupted tasks. Trucks and buses are often much louder than light-duty vehicles due to their larger size and the prominence of diesel engines, which are typically noisier than their gasoline counterparts.

In the model, noise costs are estimated on a per-mile basis using the marginal damage costs developed by Delucchi and Hsu. In their analysis, Delucchi and Hsu calculate "low-cost," "high-cost," and "base case" $/VMT factors for seven road types (Interstate, Other Freeway, Principal Arterials, Minor Arterials, Collectors, Local Roads, and Rural Highways) and four vehicle types

(LDAs – light-duty autos; MDTs – MD trucks; HDTs – HD trucks; and Buses). Using this data as a basis, estimates of average damages over all road types for each of the eight vehicle types in TOP-HDV were derived in three steps.

1. Noise levels from pickup trucks and vans are estimated using data from a Federal Highway Administration (FHWA) external cost study (see Table V-22 in [308]). In effect, an additional row was added in the "low-cost," "high-cost," and "base case" sub tables in Delucchi and Hsu's Table 7 ("The Marginal Cost of Noise from a 10% Increase in VMT, for Different Types of Vehicles on Different Types of Roads, in Urbanized Areas") for HD Pickup Trucks and Vans using the following formula:

   Marginal cost of noise, HD Pickups = (Delucchi & Hsu value for MDTs) * (FHWA value for "Pickup and Van" for "Urban Highways") / (FHWA value for "Single Unit Trucks" for "Urban Highways")

   Equation 4-15

2. The FHWA (1999) report [309] was used to estimate the fraction of VMT allocated to each type of road for HD vehicle activity in California (see Table C-7, "Urban Versus Rural VMT by Functional Class").
3. For the "low-cost," "high-cost," and "base case" tables from Delucchi and Hsu (plus the additional rows for HD Pickups), the damage cost estimate for each road type was multiplied by the corresponding VMT percentage (based on the FHWA (1999) data) and then summed to produce average noise damage cost factors for each of the eight TOP-HDV conventional diesel vehicle types. Finally, the costs are then transformed into

2010$ and multiplied by the 1.17 California-to-US valuation factor. In TOP-HDV, users may select “low cost,” “high cost,” or “best estimate” noise damage factors (Table 4-23), which correspond to the “low-cost,” “high-cost,” and “base case” tables of Delucchi and Hsu.

Table 4-23: Noise-related damage costs for conventional diesel vehicles in 2010$ (cents/mile)

	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
Low cost	0.0	0.0	0.1	0.0	0.0	0.2	0.1	0.2
High cost	1.3	18.9	14.8	15.4	15.0	45.3	28.1	39.7
Best estimate	0.1	0.9	1.0	1.1	1.1	3.1	2.0	2.8

There is very little data in the literature that estimates noise levels from advanced HD vehicles. One reference [310] was found that reports the relative decibel levels of a NG engine to a diesel engine, but no sources were found that estimate overall noise level differences for hybrids or other advanced technology HD vehicles as compared to diesels. To model the differences in noise damages per mile, there is an input matrix where users enter scaling factors that control the $/mile noise costs for each technology by vehicle type as compared to conventional diesel vehicles. The values in Table 4-24 are the author’s best estimates, but due to the uncertainty in relative noise levels, a range of values were modeled in the sensitivity analysis (see Section 5.8).

Table 4-24: Noise damage factors compared conventional diesel vehicles

	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
Gasoline (gsl.)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Diesel (dsl.)	1	1	1	1	1	1	1	1
NG	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9

Gsl. hybrid	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Dsl. hybrid	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Gsl. PHEV	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Dsl. PHEV	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
BEV	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
FCV	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

5 SCENARIO DESCRIPTIONS AND RESULTS

5.1 Introduction

Each of the six scenarios in this project are meant to illustrate the relative costs and benefits associated with distinct pathways for the California HD vehicle fleet based on certain assumptions about the rates of non-conventional fuel and technology adoption. For example, the Fuel Cell Vehicles scenario is premised on the assumption that hydrogen fuel cell vehicle technology grows to dominate the HD vehicle market, while other advanced fuels and technologies see only modest adoption. Each scenario is a distinct vision of the future California HD fleet, and the results provide estimates of the relative differences in emissions, fuel use, and total societal costs. The six scenarios are as follows:

- Baseline
- High Efficiency
- Plug-in Hybrids and Electric Vehicles ("PHEVs+EVs")
- Fuel Cell Vehicles ("FCVs")
- Alternative Fuels
- 80% Reduction in CO_2-equivalent Emissions by 2050 ("80in50")

In the first part of the chapter, each of the six scenarios is described in terms of model inputs for technology adoption across the eight vehicle categories as well as fuel and feedstock assumptions. Following the discussion of each scenario's input parameters, results are presented for emissions, fuel consumption, and costs for each scenario. The chapter concludes with a sensitivity analysis that discusses the uncertainty associated with the model inputs and examines how scenario NPV results change in response to altering key variables across a range of plausible values.

5.2 Baseline Scenario

The Baseline scenario is an estimate of the future of the California HD vehicle fleet in the absence of any regulation targeting fuel efficiency or GHGs. This scenario assumes that conventional petroleum-based fuels and vehicles continue to represent a sizeable percentage of the market. However, the scenario assumes increased adoption of NG vehicles due to favorable NG prices compared to diesel that continue throughout the entire study period. Conventional diesel and gasoline, NG, and hybrid vehicles are the only technology types modeled in this scenario. This does not imply that advanced technologies such as full electric or fuel cell vehicles do not exist in the HD fleet; rather, advanced technologies such as these only experience marginal adoption (i.e. on the order of 0.5% or less of new vehicle sales in any given year) in niche markets. As a simplification, these small adoption rates are not modeled.

5.2.1 Vehicle Population and Activity Summary

The vehicle population and activity controls as well as the resulting summary statistics for the Baseline scenario are shown in Table 5-1 through Table 5-3. These input controls and results are identical for each of the six scenarios.

An assumption in this analysis is that per-vehicle annual VMT remains constant over the entire study period. Thus, the rate of growth in total fleet VMT is identical to the rate of vehicle population growth, which is controlled by the sales-to-scrappage ratio inputs that are set at 5-year intervals (see Table 5-1). As described in Section 0, a sales-to-scrappage ratio greater than 1 means that for that given year, more vehicles are sold than are retired from the fleet.

For this analysis, the inputs for vehicle sales-to-scrappage ratio and annual VMT for each vehicle type are estimates so that total fleet VMT between 2010 and 2050 grows at an annual rate that is somewhat lower than the annual rates derived from the EMFAC2007 model [191] in order to take account for the recession, which has had significant impacts on HD vehicle activity in California[311]. In EMFAC2007, which was released prior to the recession, total VMT for the HD fleet grows at a rate of roughly 1.5% between 1990 and 2010. In this analysis, the sales-to-scrappage ratios are set to 1.1 for the years 2011 to 2020 to model the ongoing recession effects, and in subsequent years, out to 2050, the ratio is set to 1.2. Altogether, total fleet population and VMT increase at roughly 0.9% per year, and in 2050, there are nearly 45% more vehicles and total miles driven (as well as hours of idling and PTO operations) than in 2010.

Table 5-1: Vehicle sales-to-scrappage ratio input values

Year	Vehicle Sales-to-Scrappage Ratio
2011-2015	1.1
2016-2020	1.1
2021-2025	1.2
2026-2030	1.2
2031-2035	1.2
2036-2040	1.2
2041-2045	1.2
2046-2050	1.2

Table 5-2: Assumed year-one VMT values by vehicle type

HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
25,000	30,000	50,000	25,000	23,000	27,500	125,000	50,000

Table 5-3: 2050 vs. 2010 fleet-wide population and activity summary statistics

Ratio of 2050 to 2010 vehicle population	1.45
Total VMT, 2010 (million miles)	14,191
Total VMT, 2050 (million miles)	20,530
Average Annual Increase in Total VMT	0.93%

5.2.2 Fuel and technology evolution

In the Baseline scenario, advances in vehicle fuel efficiency are assumed to occur as a result of *natural* technology improvements, consumer demand for increasingly fuel-efficient vehicles, manufacturer competition, and cost reduction in advanced vehicle components (e.g. energy storage systems, power systems, etc.). In the absence of regulation, historical per-vehicle fuel consumption rates for vehicles in the US and Europe have decreased by roughly 1% per year since the 1960s [212]. This fuel efficiency progress rate of 1% per year is assumed for each technology across all eight vehicle types.

The input parameters that control the market shares over time for conventional, NG, and hybrid vehicles are shown in Table 5-5. For the introduction of advanced (i.e. non-conventional diesel or gasoline) vehicles over time, the eight vehicle groups fall into three broad categories, which are summarized in Table 5-4. These three groups are applicable to all six scenarios.

Table 5-4: Technology adoption rate categories for the TOP-HDV scenarios

Vehicle Type	Technology Adopter Category
Urban Bus	Early adopters
HD Vocation	
MD Urban	Intermediate adopters
MD Vocation	
HD Pickup	Late adopters
Other Bus	
LH Tractor	
SH Tractor	

1. *Early adopters: urban fleets with existing advanced vehicle penetration*. Within the HD vehicle market, fleets such as transit buses and refuse trucks have been early adopters of advanced technology—specifically, NG vehicles—since the early 1990s. Also, since the mid to late 2000s, transit buses have been the one of the first markets for HD hybrid vehicles. Transit bus and refuse truck drive cycles are typically very transient, thus the opportunity for recovering energy via regenerative braking makes hybridization attractive from an efficiency and fuel savings perspective. As discussed in Section 3.2.2.1 and 3.2.2.2, ARB regulations targeting transit buses and refuse trucks have certainly been a significant factor in accelerating the adoption of advanced technologies—particularly NG vehicles—since the early 2000s.

   Recognizing that NG and hybrid vehicles made up a sizeable percentage of transit buses and refuse truck fleets in 2010, the Initial year of AV adoption is set to 2011 for the Urban Bus and HD Vocation categories. In this scenario, the estimated percent split between the two technology types—75% for NG and 25% for hybrids—is assumed to be constant between 2011 and 2050 based on current market trends [312] and the assumption that the magnitude of the price advantage of NG compared to diesel remains relatively stable in the future [260, 313] and results in a preference for NG vehicles over hybrids.[27]

   The inputs for Pivot year 1 and 2 are 2020 and 2030 for Urban Buses and 2025 and 2035 for HD Vocational Vehicles (see Section 4.3.4 for a description of the vehicle market controls methodology). Between 2011 and 2050, conventional Urban Buses are assumed to

[27] On an energy-equivalent basis, NG is currently about half the price of diesel. Estimates from state and federal agencies forecast that this price delta continues in the future.

lose new vehicle market share at a rate of 5% per year. This annual rate of change is based on the fact that 4 of the 10 largest transit operators in California (including Los Angeles Metropolitan Transportation Authority, which has the largest fleet of buses by a factor of 3) are on the “Alternative Fuels” compliance pathway for the Urban Bus regulation (see Section 3.2.2.1) and are expected to purchase an increasing number of NG buses over time [122]. For HD Vocational Vehicles, the annual percent reduction for conventional vehicles is assumed to be 2% between 2011 and 2025 and then 5% until 2050 based on current penetration rates and the author’s best judgment. These pivot year and annual percent change in market share inputs reflect the fact that transit buses tend to be the first adopters for advanced technologies in the HD vehicle market, and it is assumed that Urban Buses have the highest penetration rates of NG and hybrids over the entire study period.

With these input parameters, the evolution of the new vehicle market shares for Urban Buses and HD Vocational Vehicles is shown in Figure 5-1 and Figure 5-2. Figure 5-1 shows that NG Urban Buses gradually become the majority of the new vehicle market—roughly two-thirds of sales in 2050—and outsell hybrids by a factor of 3 to 1. For HD Vocational Vehicles, NG vehicles represent 60% of sales in 2050, and hybrids and conventional vehicles each have roughly 20% of the market. In the market share figures, the “Diesel” category represents the sum of conventional diesel and gasoline vehicles, and the “HEV” category represents the sum of hybrid-electric and hydraulic hybrids.

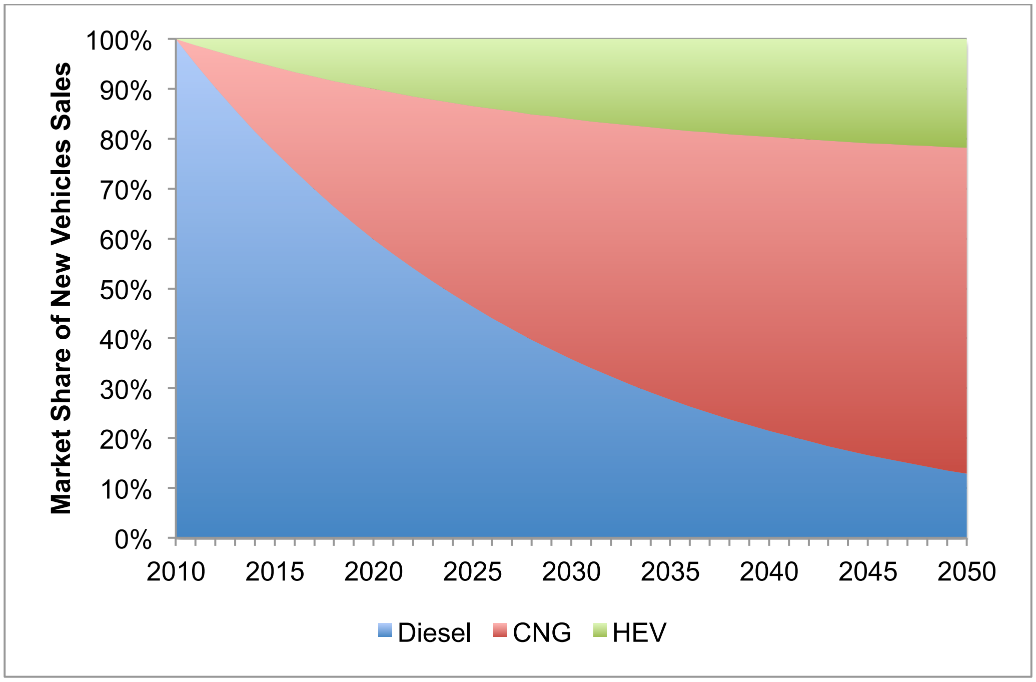

Figure 5-1: Urban Bus new vehicle market share in the Baseline scenario

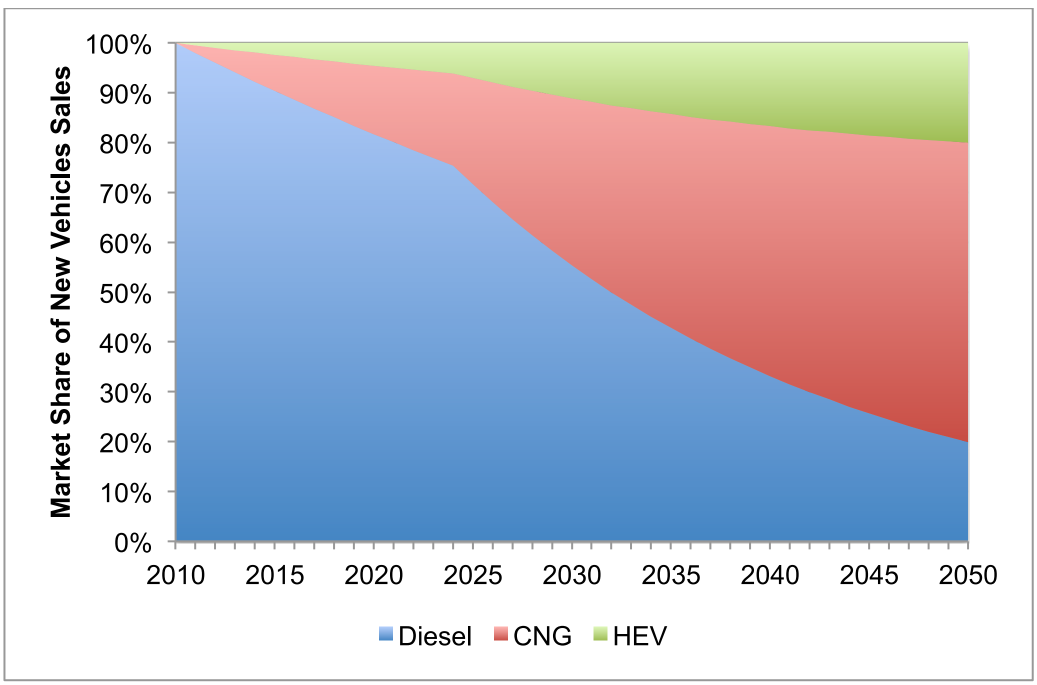

Figure 5-2: HD Vocational Vehicle new vehicle market share in the Baseline Scenario

For Urban Buses, 90% of the NG vehicles over the study period are assumed to carry fuel onboard as compressed gas. This assumption reflects recent trends for NG onboard storage in transit buses, where CNG has the large majority of the market [314]. For hybrids, 95% urban buses are assumed to be hybrid-electrics. This assumption is based on the fact that, as of this writing, only one hydraulic hybrid transit bus has been introduced as a prototype [315].

For HD Vocational Vehicles, the percentage breakdown of CNG versus LNG is based on the current trends present in the refuse truck market. The percent of NG HD Vocational Vehicles that are LNG is set at 40%, based on the approximate breakdown within Waste Management's trucks, which is the largest NG refuse fleet both in California and N. America [316]. With regards to hybrids, hydraulic hybrids have been commercially available in the refuse market since 2008. Hydraulic systems are very attractive in the refuse sector due to their ability to recapture much more braking energy than electric systems and provide high power density and energy transfer [68]. In additional to refuse trucks, the HD Vocational Vehicle category includes other trucks such as cement mixers and worksite support vehicles that typically have less transient drive cycles than refuse trucks and are therefore less suited for a hydraulic system. Also, electric hybrids can more easily provide an auxiliary power source, which is very attractive in many vocational applications. The estimated percentage of hydraulic hybrids in the HD Vocational Vehicle fleet is set at 10% and is based on the assumption that while the penetration of hydraulic hybrids in the refuse sector could be quite high (on the order of 50% or more), hybrid electric systems gain a large majority of the market share in other HD vocational truck types (e.g. fire trucks, utility trucks, boom cranes, etc.). From the CEC population data, refuse trucks make up roughly one-fifth of the vehicles that are categorized as HD Vocational Vehicles [197].

2. *Intermediate adopters: medium-duty captive fleets*. MD Urban and MD Vocational Vehicles are in this category and include vehicle types such as box trucks, parcel delivery vehicles, and worksite support trucks. The large majority of vehicles in this category operate on city and suburban driving routes and typically return to a central depot at the end of a shift. This link to a *home base* fueling and maintenance facility makes these vehicles more suitable for advanced technologies, which often require specialized refueling systems and/or service technicians that have skills that extend beyond conventional vehicles. Commercialization of medium-duty NG and hybrids began in the late 2000s, and adoption to date has been limited [312].

   Though there are a small number medium-duty NG and hybrid vehicles currently in operation, as a simplification, the *Initial year of AV adoption* is set to 2015 for the MD Urban and Vocation categories. For both MD vehicle types, NG and hybrids are assumed to split the advanced vehicle market share evenly over the entire study period. This assumes that current sales trends [312] continue in the future. The inputs for Pivot year 1 and 2 are 2025 and 2035. The annual rate of reduction of the conventional vehicle market share is set to 2% in Period 1 (2015-2025) and then 5% for the remainder of the study period. Assuming these pivot year and adoption rate inputs, the medium-duty sales market over the study period is depicted in Figure 5-3. In 2050, the new vehicle market share for NG and hybrid vehicles are roughly 39% each, and conventional vehicles make up the remaining 22%.

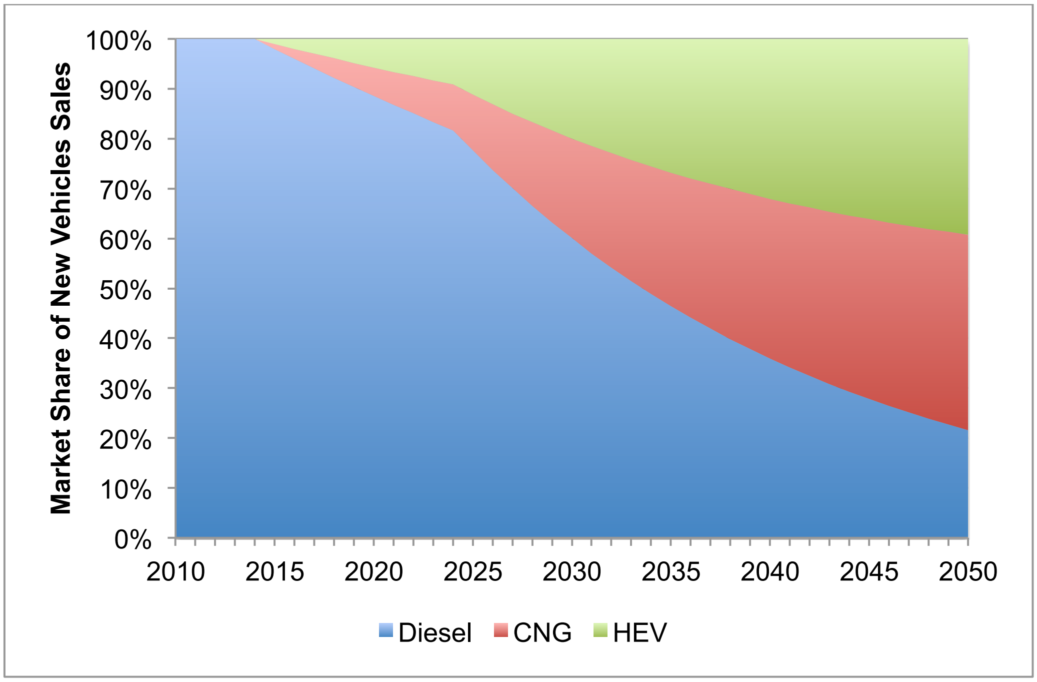

Figure 5-3: MD Urban and MD Vocational Vehicle new vehicle market share in the Baseline scenario

Compared to the heavier vehicle classes (i.e. Class 7 and 8), the higher costs imposed by cryogenic LNG storage tanks and pumping systems represent a larger percentage cost premium for vehicles in the medium-duty sector. As a result, CNG vehicles are assumed to dominate the medium-duty NG market, accounting for 95% of all NG vehicle sales. In the hybrid market, hydraulic hybrids are assumed to make up 10% and 5% of the MD Urban and Vocational categories respectively. Hydraulic hybrids were first adopted commercially in parcel delivery applications [67, 317, 318], and it is assumed that hydraulic hybrids will be more attractive in the MD Urban segment than in the Vocational category, where there is more of a premium placed on exportable electricity for jobsite support.

3. *Late adopters: non-captive fleets*. Advanced fuels and technologies are often last to appear in the following vehicle categories: Long- and Short-Haul Tractors, Other Buses, and HD Pickup Trucks. For tractors and Other Buses (which represent coach buses), two significant factors challenge advanced vehicle deployment: typical driving patterns in these vehicle categories and the lack of publically available NG refueling stations. Tractors and coach buses are typically involved in regional and long-distance travel at highway speeds, for which the benefits of hybridization are much smaller compared to city driving. Also, NG vehicles traveling long distances are routinely dependent on public refueling stations (e.g. truck stops) in remote areas along highways, and, to date, the network of NG stations has been primarily limited to urban centers. However, given the current upswing in demand for NG heavy-duty vehicles (and, in particular, tractor trucks), many energy companies and fuel retailers are currently working to construct a nationwide network of NG fueling centers [319, 320].

The *Initial year of AV adoption* is set to 2020 for all of the late adopter vehicle types except SH Tractors, where this value is set to 2015. The SH Tractor segment includes vehicles such as beverage tractors, which primarily operate in urban areas and, as of this writing, have had hybrid and NG vehicles enter into the fleet in relatively small numbers since the late 2000s [312]. For all four vehicle types, the Pivot year 1 and 2 inputs are 2030 and 2040, and the annual rate of reduction of the conventional vehicle market share is set to 2% in Period 1 and then 5% for the remainder of the study period. The percentage of NG and hybrid vehicles over the study period is set at 10% and 90% respectively, based on the author's best judgment. Assuming these pivot year and adoption rate inputs, the evolution of the sales market during the study period is depicted in Figure 5-4 for SH Tractors and Figure 5-5 for the other three late adopter vehicle categories.

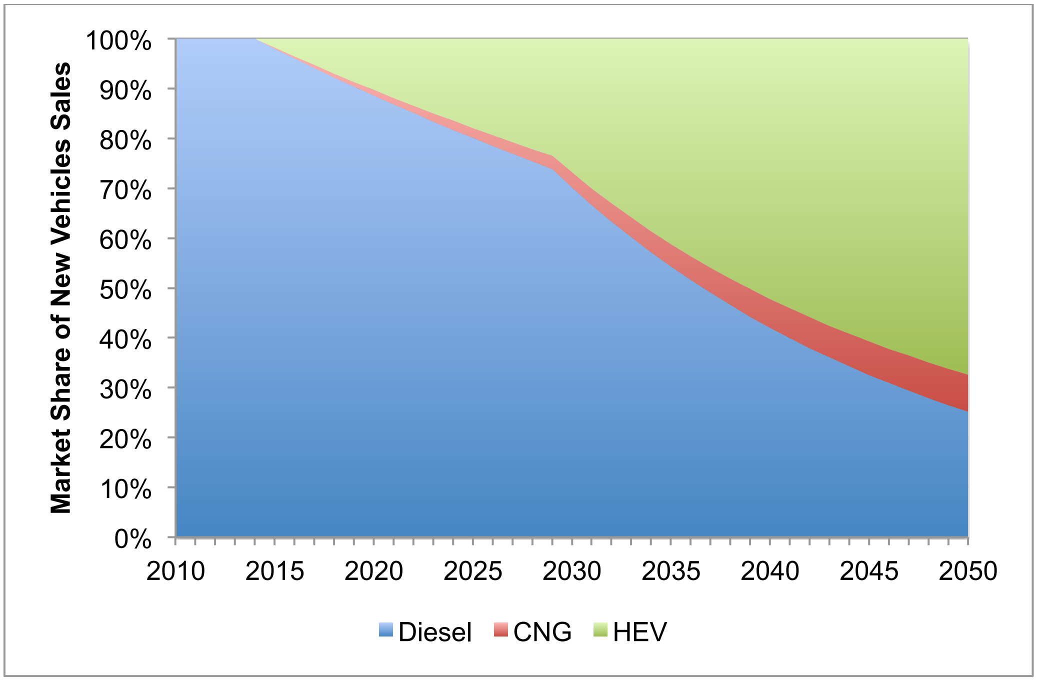

Figure 5-4: SH Tractor new vehicle market share in the Baseline scenario

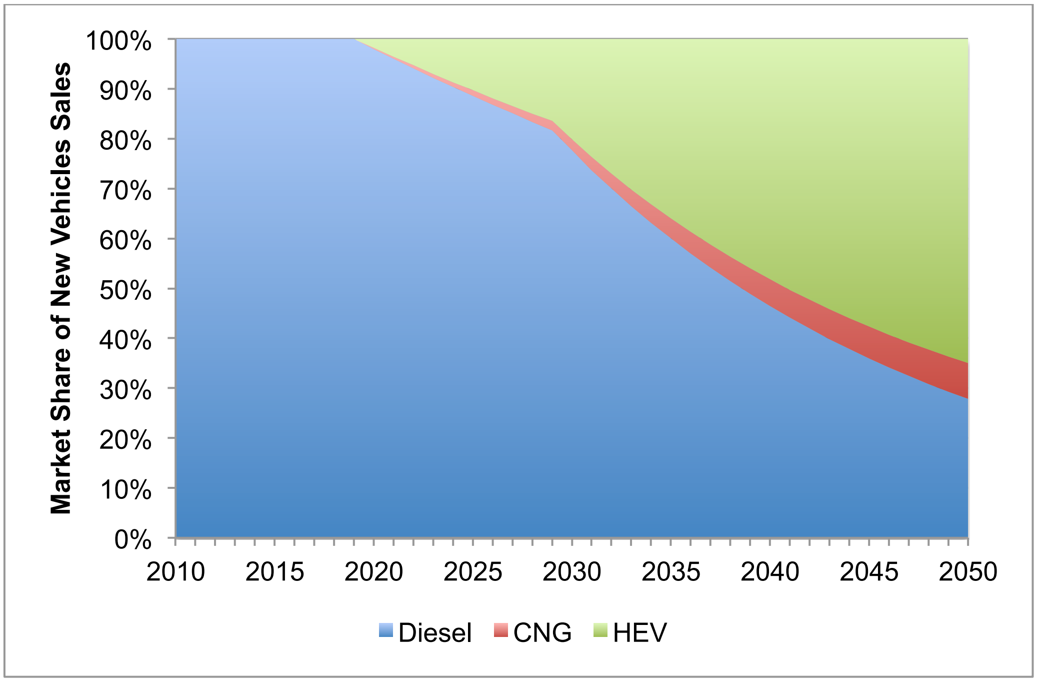

Figure 5-5: HD Pickup, Other Bus, and LH Tractor new vehicle market share in the Baseline scenario

For the HD Pickup Trucks category, the higher additional cost and weight of onboard LNG tanks are assumed to make CNG the predominant design choice for these NG vehicles. As such, for NG HD pickups, the percentage of CNG vehicles is set to 100%. For the other three late adopter vehicle types, the additional costs of LNG tanks are justified due to the superior driving range that the energy-dense liquid fuel provides, and the LNG market share is set to 100%. For the late adopter hybrid market, hybrid-electrics are assumed to make up 100% of sales due to the larger percentage of highway driving for these vehicle types and the high value of having exportable electricity for powering auxiliaries (e.g. air conditioning loads, cabin electronics, etc.).

The market share control inputs for the Baseline scenario are summarized in Table 5-5.

Table 5-5: Market share controls for the Baseline scenario

	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
Adoption Controls								
Initial yr. of AV adoption	2020	2011	2020	2015	2015	2011	2020	2015
Pivot year 1	2030	2020	2030	2025	2025	2025	2030	2030
Pivot year 2	2040	2030	2040	2025	2025	2035	2040	2040
Conv. Vehicle Change in Market Share								
Period 1 annual change in MS (percentage)	-2%	-5%	-2%	-2%	-2%	-2%	-2%	-2%
Period 2 annual change in MS (percentage)	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%
Period 3 annual change in MS (percentage)	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%
Natural Gas Controls								
Initial % of AV market	10%	75%	10%	50%	50%	75%	10%	10%
Period 1 annual change in MS (percentage points)	0%	0%	0%	0%	0%	0%	0%	0%
Period 2 annual change in MS (percentage points)	0%	0%	0%	0%	0%	0%	0%	0%
Period 3 annual change in MS (percentage points)	0%	0%	0%	0%	0%	0%	0%	0%
Hybrid Controls								
Initial % of AV market	90%	25%	90%	50%	50%	25%	90%	90%
Period 1 annual change in MS (percentage points)	0%	0%	0%	0%	0%	0%	0%	0%
Period 2 annual change in MS (percentage points)	0%	0%	0%	0%	0%	0%	0%	0%
Period 3 annual change in MS (percentage points)	0%	0%	0%	0%	0%	0%	0%	0%

5.2.3 Emission Results

The emissions results for the Baseline scenario are summarized in Figure 5-6. The breakdown of the individual species contribution to CO_2e in 2010, 2020, 2030, 2040, and 2050 as well as the CO_2-equivalent (CO_2e) emissions by lifecycle phase are shown in Figure 5-7 and Figure 5-8 respectively.

For non-CO_2e emissions, in general, all of the emitted species display a steady decrease over time. This is a result of emission factor reductions in all four lifecycle phases: tailpipe (grams/mile), upstream fuels production and transportation (grams/MMBtu), vehicle manufacturing (grams/vehicle), and vehicle scrappage (grams/vehicle). Particulate matter ($PM_{2.5}$) and black carbon emissions have the most dramatic reduction, which is primarily due to fleet turnover and an increasing percentage of the fleet that is equipped with diesel particulate filters (DPFs) that were implemented across the entire fleet starting in model year 2007 as a result of a 90% reduction in the engine emission standard for PM mass. As discussed in Section 2.1.3.1, DPFs typically reduce particulate and black carbon emissions by an order of magnitude or more. The large decline in SOx over time is mainly due to reductions in upstream fuel and vehicle manufacturing emissions, which together make up more than 99% of total SOx emissions. For the Baseline scenario, a breakdown of each emitted species over the study period by lifecycle phase is shown in the Appendix.

For CO_2e emissions, there is an increase of approximately 11% between 2010 and 2020 followed by a downward trend out to 2050. As shown in Figure 5-8, the increase between 2010 and 2020 is due to an increase in upstream fuel and vehicle manufacturing emissions. The early escalation for these two sets of CO_2e emissions is primarily due a decrease in SOx emissions, which have a strong net cooling effect per unit mass. Total CO_2e emissions in 2050 are roughly 31.6 million metric tonnes (MMT), which is 5.6% higher than the 2010 value of 29.9 MMT.

The percentage contribution to lifecycle CO_2e by each of the vehicle and technology types in 2020 and 2050 is shown in Figure 5-9 and Figure 5-10. Over the study period, LH Tractors emit the largest portion of CO_2e emissions at 29%, followed by HD Pickups and MD Urban Vehicles at 17% and 16% respectively. The remaining five vehicle categories contribute roughly 10% or less to overall CO_2e emissions. In 2020, conventional gasoline and diesel vehicles are the principal contributor to CO_2e emissions, accounting for 96% of the total. In 2050, conventional, NG, and hybrid vehicles account for 37%, 20%, and 43% of the total CO_2e emissions respectively.

Official state inventory data from the California Air Resources Board was utilized to validate the criteria pollutant and GHG emissions results of the model. In general, the results from TOP-HDV are within a reasonable proximity to the data reported by the ARB, given that the two sets of model results are calculated using different assumptions for critical inputs such as vehicle population, per-vehicle VMT, and emission factors. Table 5-6 summarizes the differences in results for tailpipe $PM_{2.5}$, NOx, and CO_2 emissions for 2010. The TOP-HDV results for $PM_{2.5}$ and NOx are roughly 30% lower than the ARB figures, which are derived from the EMFAC2011 model [321]. The ARB data for CO_2 emissions is from the official statewide GHG inventory for 2008 [322], which is the latest year that data is available.

Table 5-6: Tailpipe emissions validation for 2010 compared to ARB inventory results

	ARB Inventory (1,000 metric tonnes)	TOP-HDV (1,000 metric tonnes)	Difference (1,000 metric tonnes)	% Difference
$PM_{2.5}$	9	6	3	-33%
NOx	269	198	71	-26%
CO_2	34,200	27,600	6,600	-19%

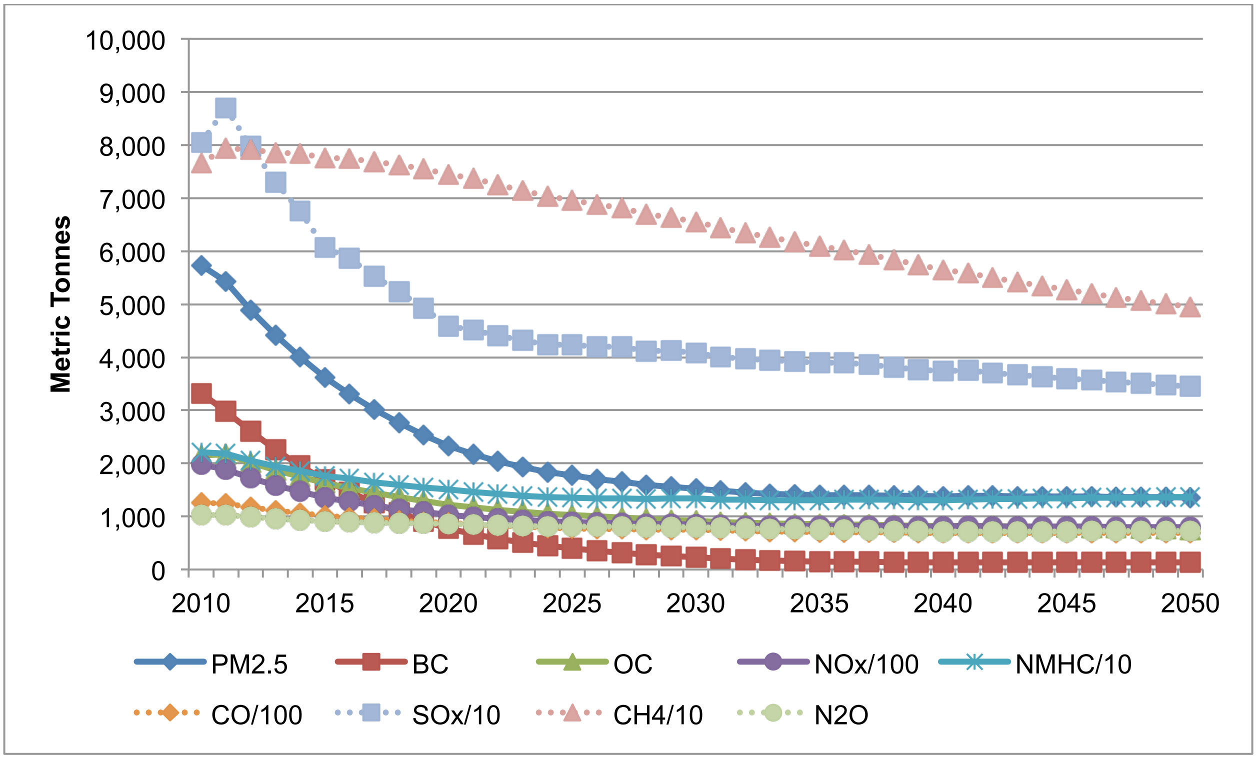

Figure 5-6: Emissions results of the Baseline scenario

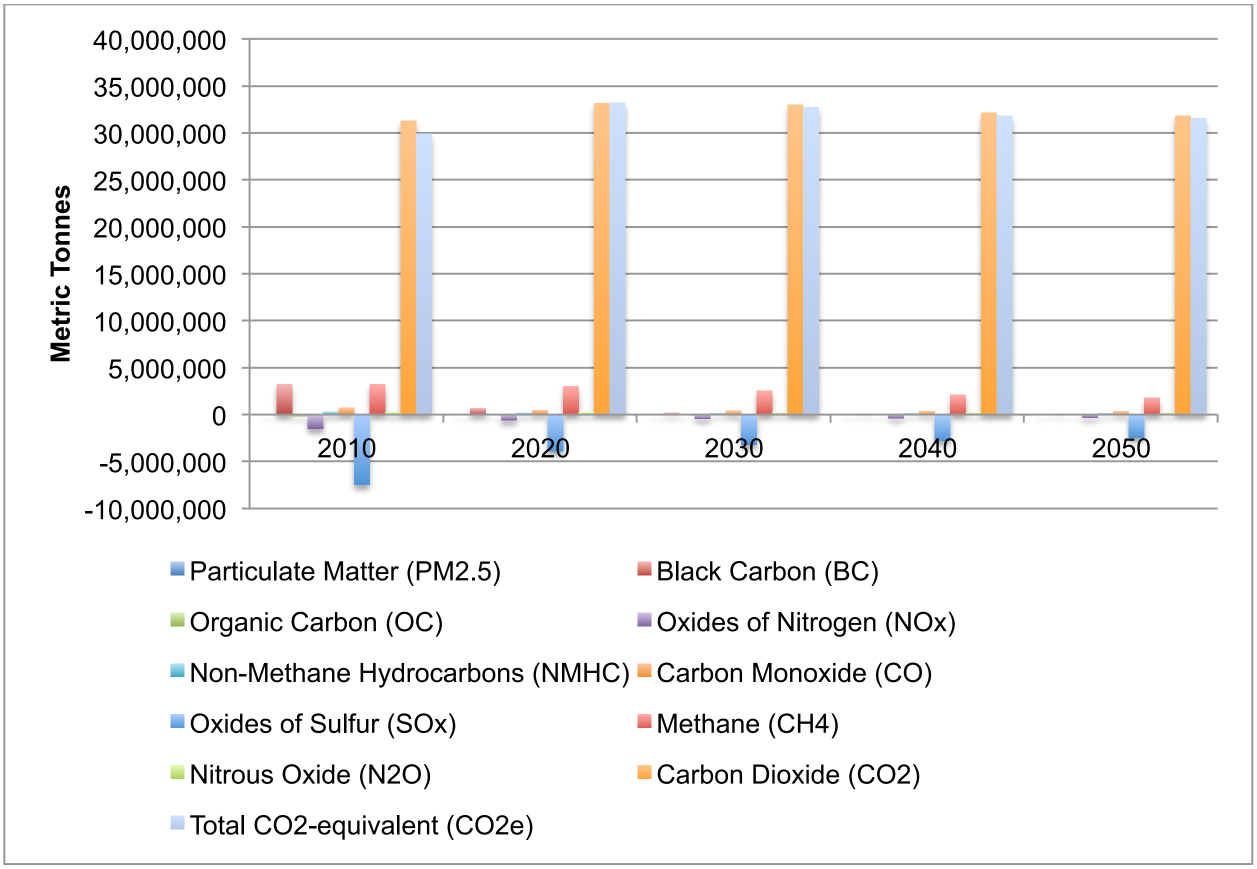

Figure 5-7: CO_2e emissions breakdown for the Baseline scenario

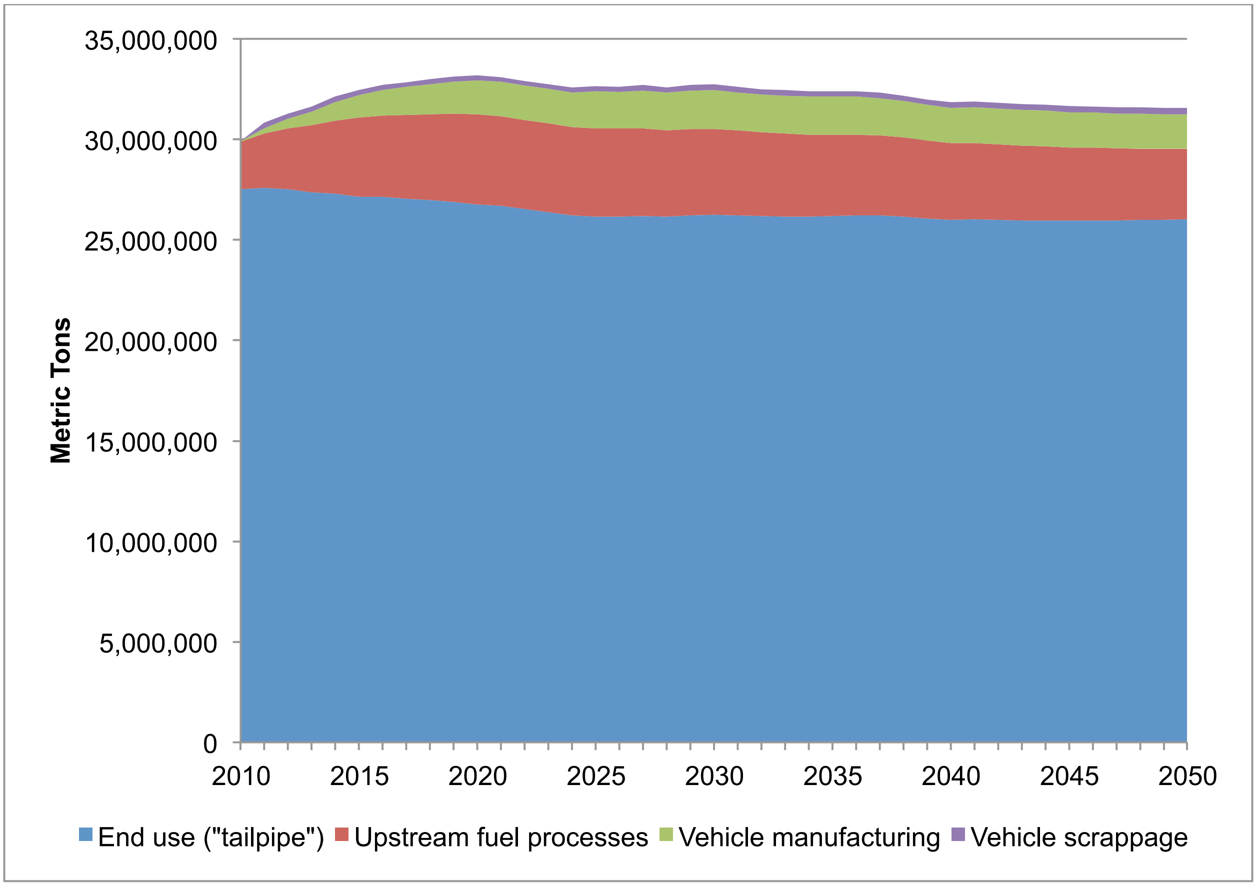

Figure 5-8: CO_2e emissions by lifecycle phase in the Baseline scenario

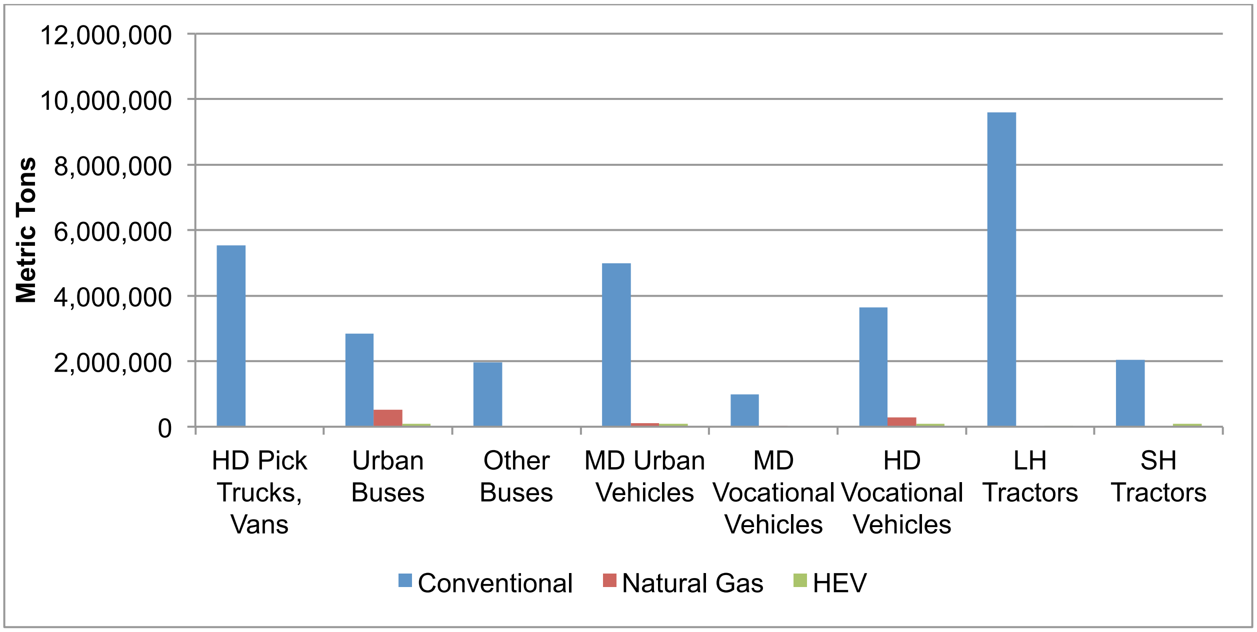

Figure 5-9: CO_2e emissions by vehicle technology type in 2020 in the Baseline scenario

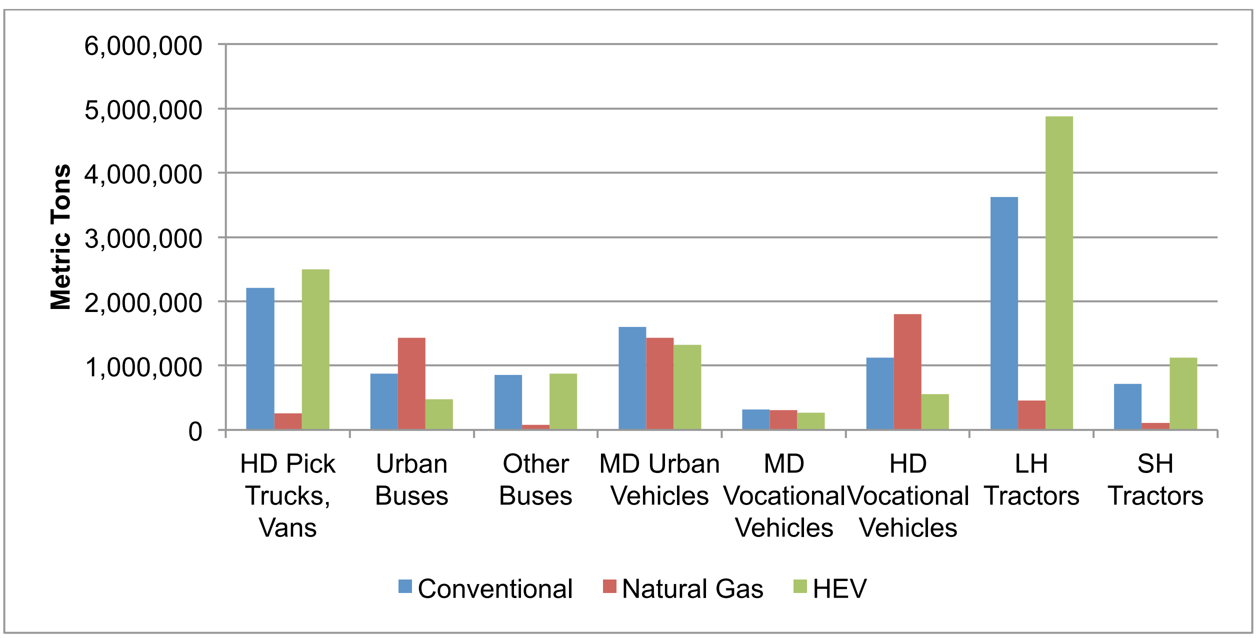

Figure 5-10: CO_2e emissions by vehicle technology type in 2050 in the Baseline scenario

5.2.4 Fuel Use Results

The fuel use results (units are diesel gallon equivalent, DGE) for the Baseline scenario are shown in Figure 5-11. Diesel and gasoline are the dominant fuels over the study period; however, over time, the NG market share increases by a factor of ten, growing from 2.5% in 2010 to 25% in 2050. Total fuel consumption for the fleet is relatively constant over the 40 years, as the growth in vehicle population and VMT is counter-balanced by increasing new vehicle fuel efficiency (1% reduction in fuel consumption per year) and an increased market share of hybrid vehicles, which are estimated to use between 5 to 35% less fuel per mile, depending on the vehicle type and type of hybrid (i.e. electric or hydraulic).

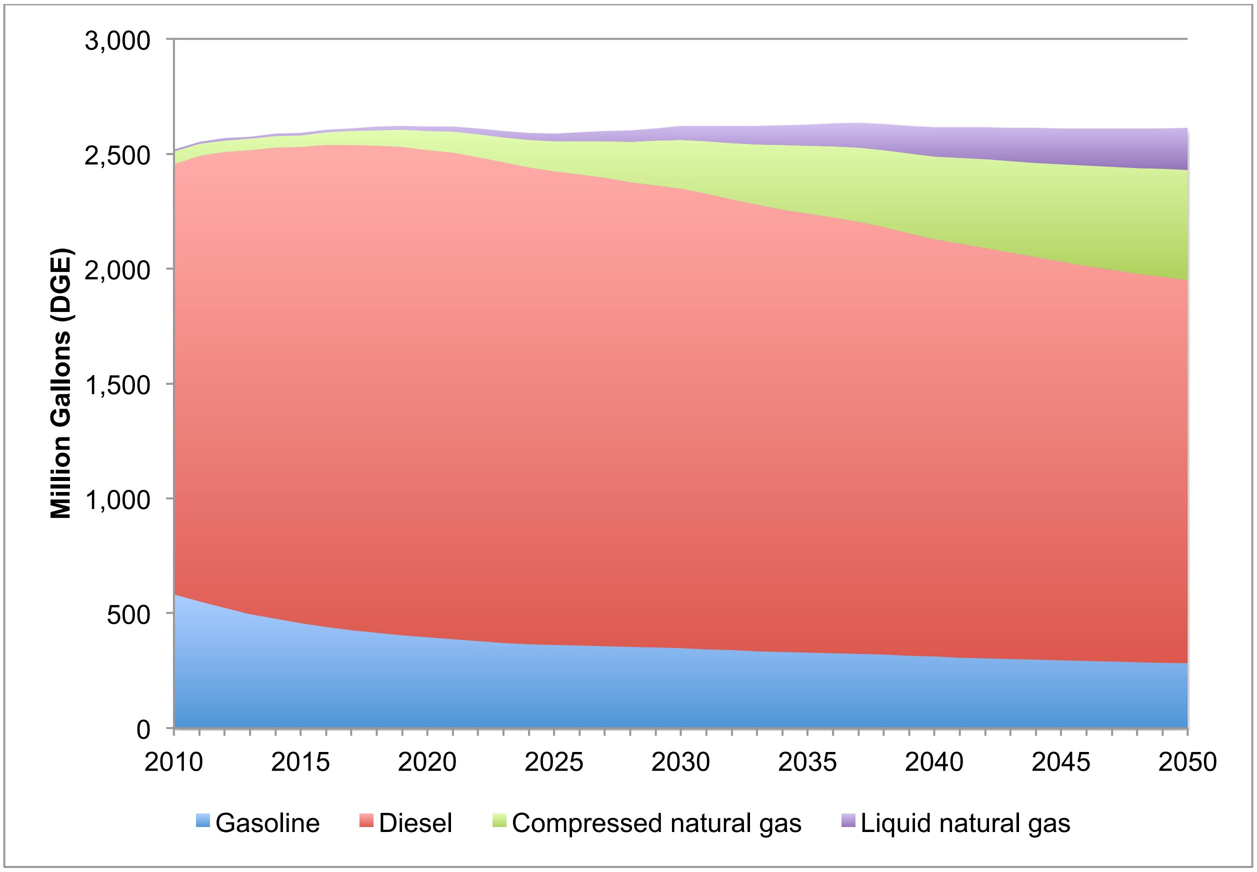

Figure 5-11: Fuel use trends of the Baseline scenario (million diesel gallon equivalents)

5.2.5 Cost Results

The lifecycle cost totals for the Baseline scenario are summarized in Figure 5-12. All together, the lifecycle costs estimated in TOP-HDV are estimated to grow from roughly $19.2 billion in 2010 to $28.9 billion in 2050, which is an average annual growth rate of 1.0%. The cost totals are dominated by end-user costs: vehicle retail, fuel, and maintenance and repair (i.e. "Non-fuel Operating" costs in Figure 5-12). Together, end-user costs make up 89% of the total in 2010 and grow to 97% in 2050. The percentage contribution of each of the eight cost items in 2010 and 2050 are summarized in Table 5-7.

Table 5-7: Cost breakdowns in 2010 and 2050

Cost Item	Percent of Total Costs	
	2010	2050
Vehicle Retail	19.4%	33.6%
Fuel	42.2%	36.5%
Non-fuel Operating	27.6%	26.4%
Tailpipe Emissions	3.5%	0.6%
Upstream Emissions	3.4%	1.0%
Energy Security	3.3%	1.4%
Noise	0.5%	0.5%
Fuel Station Construction	0.0%	0.04%
TOTAL	100.0%	100.0%

The increase in vehicle retail costs is due to two factors: 1) growth in overall fleet size, and 2) increased adoption of advanced vehicles—that is, NG and hybrid vehicles. As described in Section 4.3.7.1, the purchase costs for each technology are controlled with learning curve effects controls on the *Scenario Builder* sheet. The capital cost premiums for each vehicle type and technology in 2010 are summarized in Table 4-16. The input estimates for the initial production volume threshold for each advanced vehicle type are summarized in Table 5-8. The threshold volume inputs are steadily lower for plug-in hybrids and fully electric vehicles (both battery electric and fuel cell vehicles) based on the assumption that the large uptake of hybrid vehicles drives the costs down for electric components (e.g. batteries, motors, inverters, etc.) that are shared across PHEVs, EVs, and FCVs. Thus, the cost reductions for PHEVs, EVs, and FCVs occur at a faster rate than for hybrid vehicles. The threshold volume assumptions are identical for each of the six scenarios.

The Progress Ratio for all vehicle and technology types is set at 95% based on estimates from the light-duty advanced vehicle market [265, 266]. The Price Floor NG vehicles—that is, the lowest that retail prices are allowed to go—is assumed to be equal to the cost of a conventional diesel vehicle. For NG vehicles, this Price Floor value is based on the assumption that the cost premiums associated with fuel storage tanks and the cryogenic pumping system in the case of LNG vehicles decrease over time as a result of increasing sales volumes. For hybrids, a Price Floor value of 1.1 is an estimate based on the assumption that though there are additional design complexities and material costs presented by power electronics and energy storage systems, these additional costs decrease over time as hybrid production increases. However, due to the hybrid vehicle's inherent increased complexity compared to a conventional vehicle, it is assumed that costs never fully reach parity with diesels.

These values for Production Volume Threshold, Progress Ratio, and Price Floor are used in all six scenarios for NG and hybrid vehicles but are highly uncertain—reasonable ranges for each parameter are tested as part of the sensitivity analysis (Section 5.8). In the Baseline scenario, retail prices of conventional diesel and gasoline vehicles are assumed to be constant (in 2010$) over time.

Table 5-8: Initial production volume threshold values used for all six scenarios

	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
Natural gas	15,000	2,000	1,000	5,000	2,500	3,000	5,000	5,000
HEV/HHV	15,000	2,000	1,000	5,000	2,500	3,000	5,000	5,000
Plug-in hybrids	5,000	1,000	500	2,500	1,000	1,000	2,000	2,000
Battery electric	2,000	500	500	1,000	500	500	1,000	1,000
Fuel cell	2,000	500	500	1,000	500	500	1,000	1,000

Based on the assumed adoption rates of NG and hybrid vehicles in the Baseline scenario, the resulting per-vehicle retail costs for each vehicle and technology type compared to a conventional diesel are shown in Figure 5-13 and Figure 5-14. For NG vehicles, per-vehicle purchase costs begin to decrease immediately for the early adopter (i.e. Urban Buses and HD Vocational Vehicles) fleets, in the 2020 to 2025 timeframe for the medium-duty fleets, and around 2035 for the remaining four vehicle categories. For hybrids, the commencement of unit cost reductions across all eight vehicle categories is more tightly clustered and occurs roughly between 2020 and 2025. For both NG vehicles and hybrids, the rate of cost reductions is similar across all of the vehicle categories. For advanced vehicles with price premiums of 40 or more percent over diesels, it takes approximately 6 to 8 years until costs reach the price floor, which is cost parity with diesels for NG vehicles and a 10% premium for both electric and hydraulic hybrids. For NG and hybrid vehicle types with initial price deltas in the 10-25% range, cost reductions to the price floor typically take about 3 to 5 years.

For NG Urban Buses, there is a steep decline from a 15% purchase price premium in 2010 to price parity with diesels in 2011, which represents a significant reduction in capital costs (~ $50,000) over one year, which is likely not plausible. In order to extend the cost reduction time period for NG Urban Buses to better reflect more realistic purchase price reductions over time, values for the initial production volume threshold (IPVT) were doubled as part of the sensitivity analysis. In doubling the IPVT values, the time needed for NG Urban Buses to reach price parity with diesels increases to roughly four years. However, as shown in the sensitivity analysis results, the NPV for the Baseline scenario is only marginally impacted by doubling (or halving) the IPVT values for NG vehicles and hybrids.

Fuel prices (2010$) for gasoline and diesel over the study period are assumed to increase at 1.2% per year based on the California Energy Commission's "High Price" scenario for 2011 to 2030 [313]. For transportation CNG, the CEC High Price scenario shows an annual increase of 0.4%. For this analysis, the price of LNG is assumed to grow at this rate as well. In the CEC's "Low Price" scenario, prices for gasoline, diesel, and NG are relatively constant over the 20-year period—this no price growth scenario is evaluated in the sensitivity analysis (see Section 5.8).

Non-fuel operating costs increase by roughly 50% over the study period. As these costs are a linear function of vehicle mileage, the annual rate of growth in these costs is directly linked to the increase in fleet-wide VMT, which also grows by approximately 50% between 2010 and 2050.

The steep 12% increase in total costs from 2010 to 2011 is primarily due to a jump in vehicle retail costs. The stock turnover model for each of the eight vehicle types is designed such that the sales for a given year is based on the sales-to-scrappage ratio, which is input in the *Vehicle Population and Activity* section on the *Scenario Builder* sheet. The survival rates assumed in the model make it such that the number of vehicles scrapped (and sold) on January 1st 2011 is larger than the estimated number of vehicles sold in 2010. Assuming a sales-to-scrappage ratio of 1.1, there are 63,613 new MY 2011 vehicles in 2011 as compared to 52,277 MY 2010 vehicles in 2010. This sales differential accounts for the large increase in retail costs in 2011.

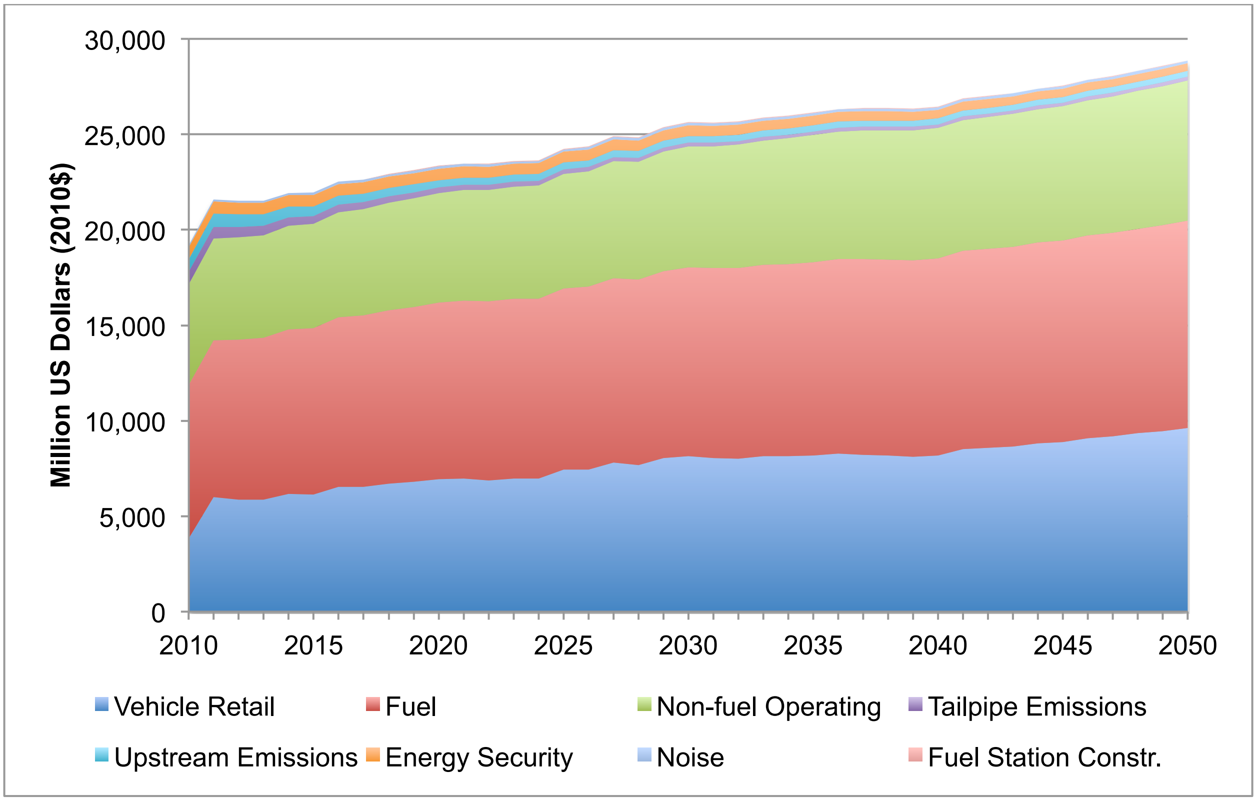

Figure 5-12: Total costs breakdown for the Baseline scenario

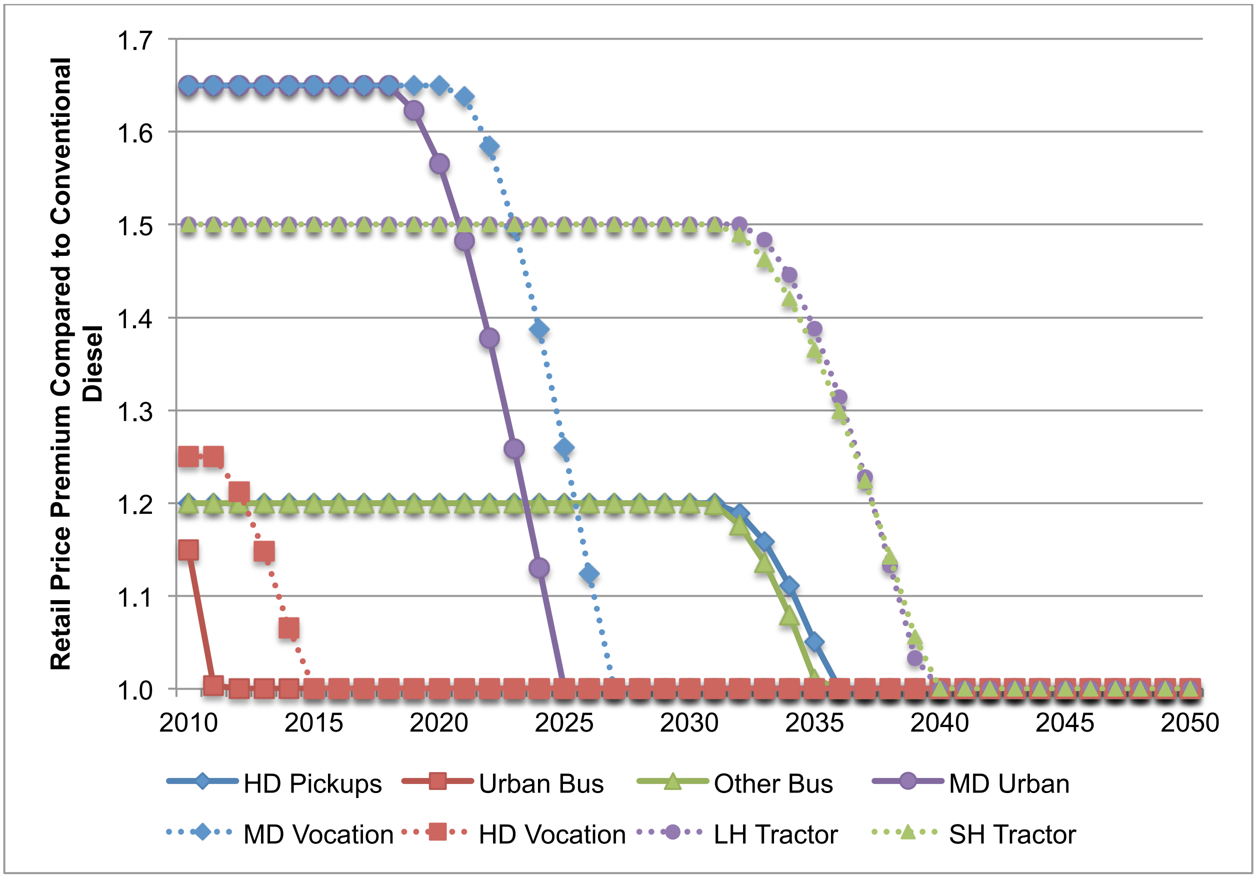

Figure 5-13: Retail price premiums for NG vehicles in the Baseline scenario

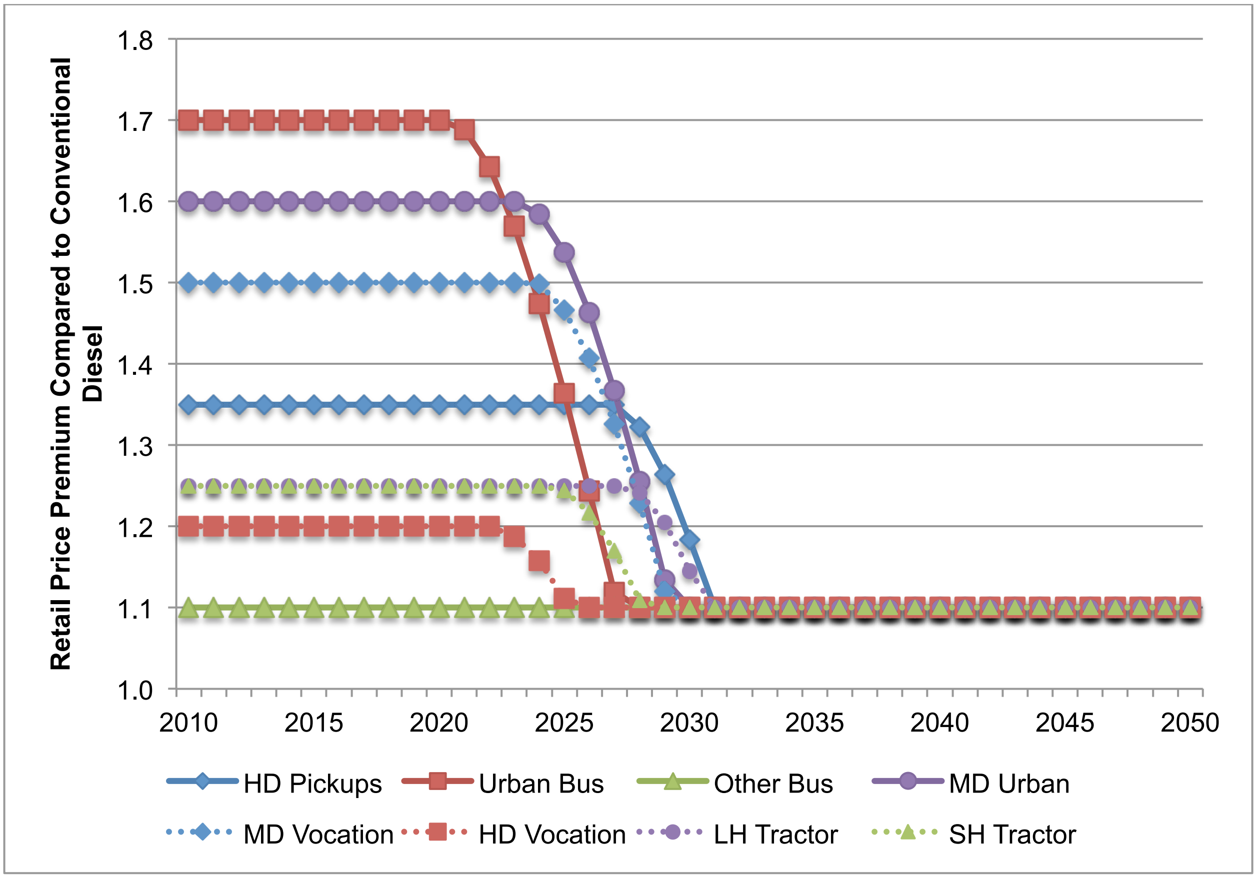

Figure 5-14: Retail price premiums for hybrid vehicles in the Baseline scenario

5.3 High Efficiency Scenario

The High Efficiency scenario is a future in which the HD vehicle fleet in California is subject to increasingly stringent performance-based fuel efficiency/GHG regulations, and the market penetration of hybrids happens at a much faster rate than the Baseline scenario. As with the Baseline scenario, conventional diesel and gasoline, NG, and hybrid vehicles are the only technology types modeled in this scenario.

5.3.1 Fuel and technology evolution

In the High Efficiency scenario, improvements in vehicle fuel efficiency are assumed to accelerate as a result of technology-forcing policy measures. The per-vehicle fuel consumption rates for new vehicles are assumed to decrease by between 2% and 4% per year and are summarized in Table 5-9. These annual rates of fuel consumption reduction for new vehicles are based on technology potential estimates for the 2015 to 2020 timeframe that were published by a National Academy of Sciences (NAS) committee in 2010 [36]. In this NAS study, the per-vehicle fuel consumption potential for 2015 to 2020 compared to a 2008 baseline ranged from roughly 30% to 50%, depending on the vehicle category. As a simplification, the total technology potential for each vehicle type—*without* including hybridization[28]—is assumed to occur over a 10-year time horizon between 2010 and 2020. The resulting annual percentage reduction rates from this calculation are then rounded based on the author's best judgment to result in the values in Table 5-9. A key assumption in this analysis is that the annual fuel consumption benefits coming from improvements in aerodynamics, engines, weight reduction, tires, and transmissions remain constant over the entire 40-year study period. Using the percent reduction assumptions of Table 5-9, the resulting fuel consumption profiles for new vehicles over time are shown in Figure 5-15. By 2050, the per-vehicle fuel consumption decreases substantially—by 55% to 80%, depending on the vehicle category. A core assumption in this analysis is that the annual fuel consumption reductions estimated from the NAS study remain constant over the entire study period. For context, the EPA and NHTSA's greenhouse gas and

[28] In the NAS study, technology potential estimates are broken down into the following categories: aerodynamics, engines, weight reduction, tires, transmissions, and hybridization.

fuel efficiency regulations that were finalized in the summer of 2011 are estimated to cut per-vehicle GHGs and fuel consumption by 1-3% per year over the course of the 5-year program (model years 2014 to 2018), depending on the vehicle category [189]. So, the continuous efficiency improvements shown in Figure 5-15 represent the steady implementation of fuel efficiency standards (and other policy measures) over time that are more stringent than the current federal regulations that have been put in place.

Table 5-9: Annual fuel consumption reduction in new vehicles for all five non-Baseline scenarios

HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
3.0%	2.5%	3.0%	3.0%	2.0%	2.0%	4.0%	4.0%

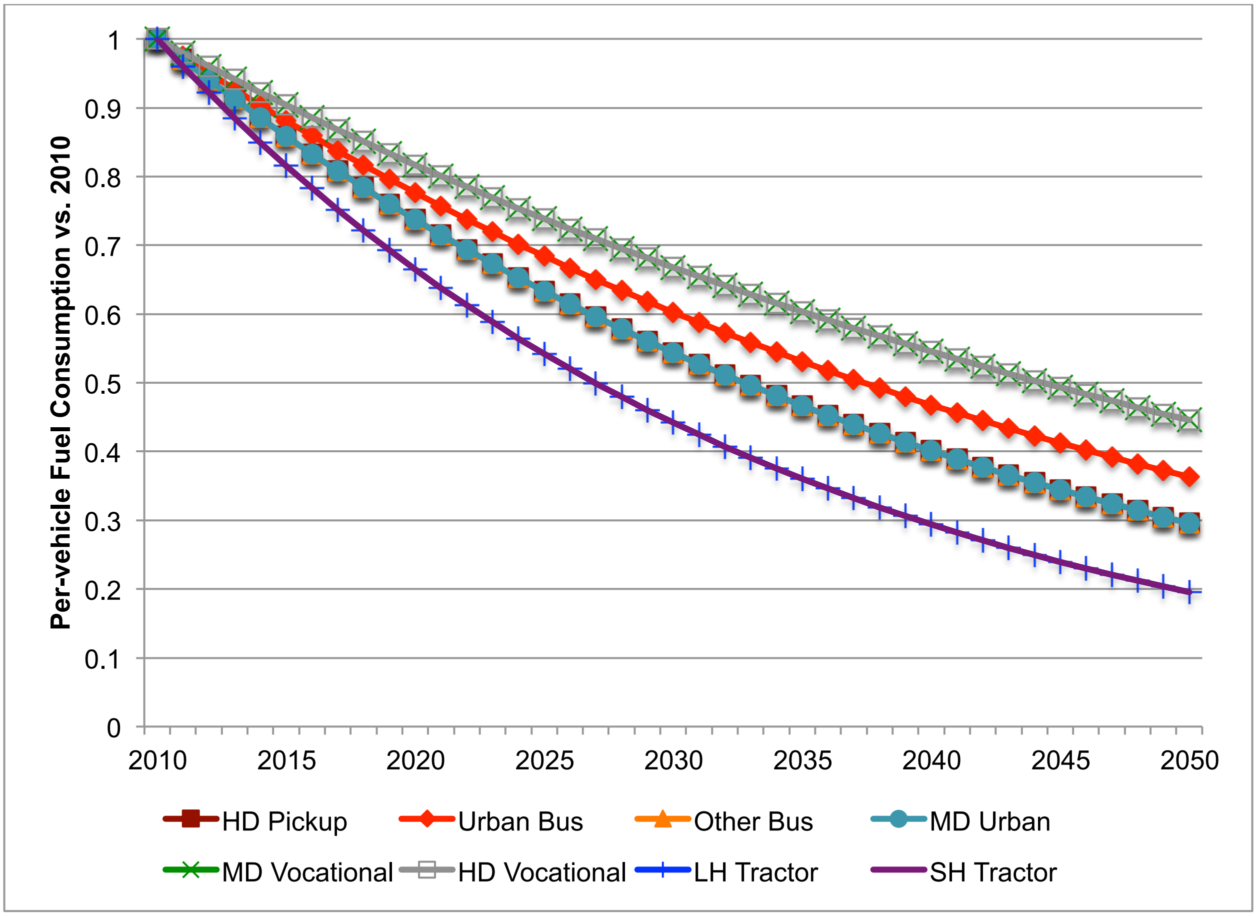

Figure 5-15: Fuel consumption reductions in new vehicles compared to 2010 vehicles for all of the non-Baseline scenarios

In addition to larger annual improvements in fuel efficiency, advanced vehicles are assumed to enter the market more quickly in the High Efficiency scenario compared to the Baseline. Though the pivot years are identical between the two scenarios[29], the decrease in market share for conventional vehicles accelerates at a higher rate over time in the High

[29] The pivot years are assumed to be roughly identical for all six scenarios. The exceptions are in the PHEVs+EVs and FCVs scenarios, where the Pivot year 2 is 2031 for Urban Buses and 2036 for HD Vocational Vehicles.

Efficiency scenario. As shown in Table 5-10, the change in market share for conventional vehicles in Periods 1, 2, and 3 is 3% (5% for Urban Buses), 7.5%, and 15% respectively.

Relative to the Baseline, the High Efficiency scenario assumes that hybrids have a growing percentage of the advanced vehicle market share over time. For Urban Buses, MD Urban, MD Vocational, and HD Vocational Vehicles, the initial percentage split between NG and hybrid vehicles is identical to the Baseline scenario. However, during Periods 1, 2, and 3, hybrids gain advanced vehicle market share at a rate of 1 percentage point per year. For the remaining four vehicle categories, hybrids and NG vehicles are assumed to have 95% and 5% of the advanced vehicle market over the study period. The increasing preference for hybrids over time is driven by their superior fuel efficiency and the assumption that incentive programs and stringent regulations accelerate hybridization into the HD market across all of the vehicle categories.

Table 5-10: Market share controls for the High Efficiency scenario

	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
Adoption Controls								
Initial yr. of AV adoption	2020	2011	2020	2015	2015	2011	2020	2015
Pivot year 1	2030	2020	2030	2025	2025	2025	2030	2030
Pivot year 2	2040	2030	2040	2025	2025	2035	2040	2040
Conv. Vehicle Change in Market Share								
Period 1 annual change in MS (percentage)	-3%	-5%	-3%	-3%	-3%	-3%	-3%	-3%
Period 2 annual change in MS (percentage)	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%
Period 3 annual change in MS (percentage)	-15%	-15%	-15%	-15%	-15%	-15%	-15%	-15%
Natural Gas Controls								
Initial % of AV market	5%	75%	5%	50%	50%	75%	5%	5%
Period 1 annual change in MS (percentage points)	0%	-1%	0%	-1%	-1%	-1%	0%	0%
Period 2 annual change in MS (percentage points)	0%	-1%	0%	-1%	-1%	-1%	0%	0%

	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
Period 3 annual change in MS (percentage points)	0%	-1%	0%	-1%	-1%	-1%	0%	0%
Hybrid Controls								
Initial % of AV market	95%	25%	95%	50%	50%	25%	95%	95%
Period 1 annual change in MS (percentage points)	0%	1%	0%	1%	1%	1%	0%	0%
Period 2 annual change in MS (percentage points)	0%	1%	0%	1%	1%	1%	0%	0%
Period 3 annual change in MS (percentage points)	0%	1%	0%	1%	1%	1%	0%	0%

The new vehicle market shares for each technology type over the study period are summarized in the figures below. Across all eight vehicle categories, advanced technology vehicles come to dominate the sales market, and by 2050, conventional diesel and gasoline vehicles only represent between 1% and 6% of new vehicle sales, depending on the vehicle type.

In each of the eight vehicle categories, the split between CNG and LNG as well as hybrid-electric and hybrid hydraulic vehicles is identical to the Baseline scenario. This is true for all five of the non-Baseline scenarios.

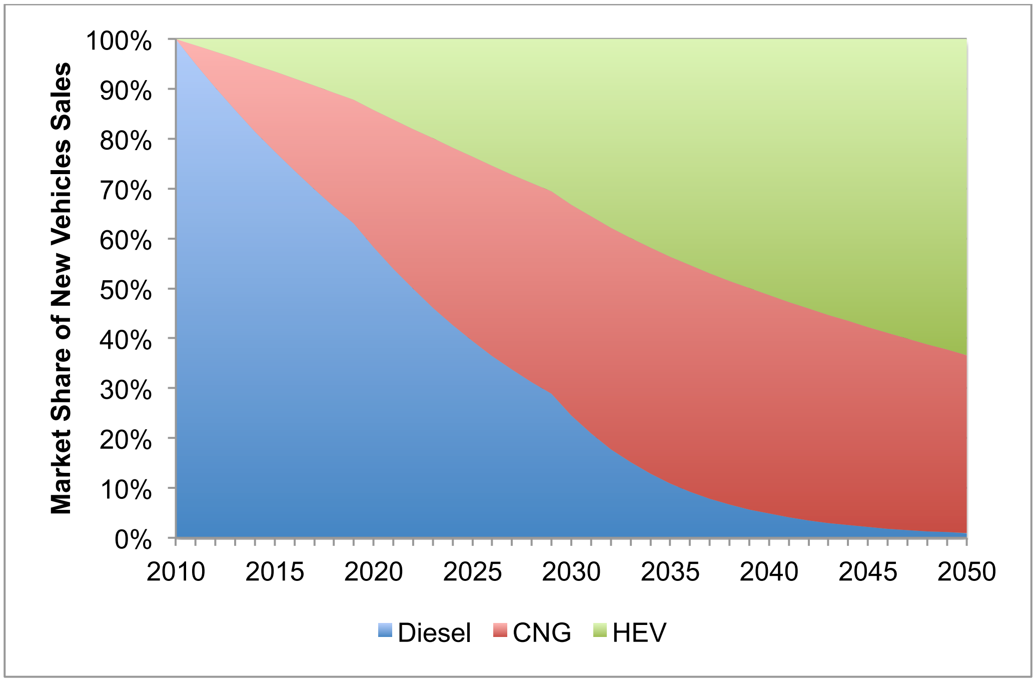

Figure 5-16: Urban Bus new vehicle market share in the High Efficiency scenario

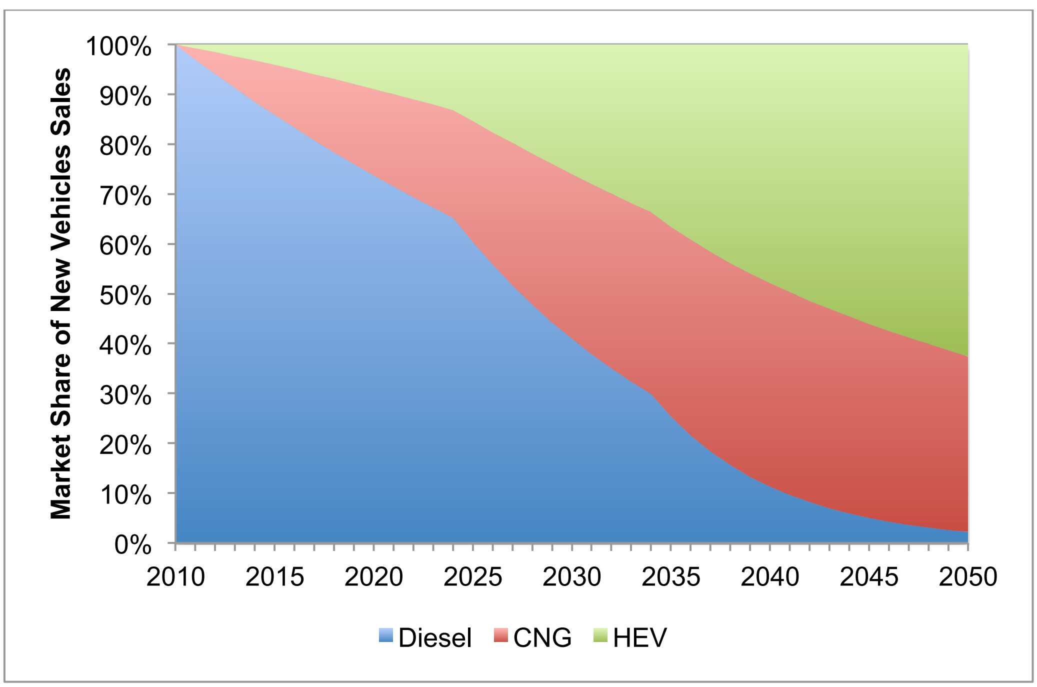

Figure 5-17: HD Vocational Vehicle new vehicle market share in the High Efficiency Scenario

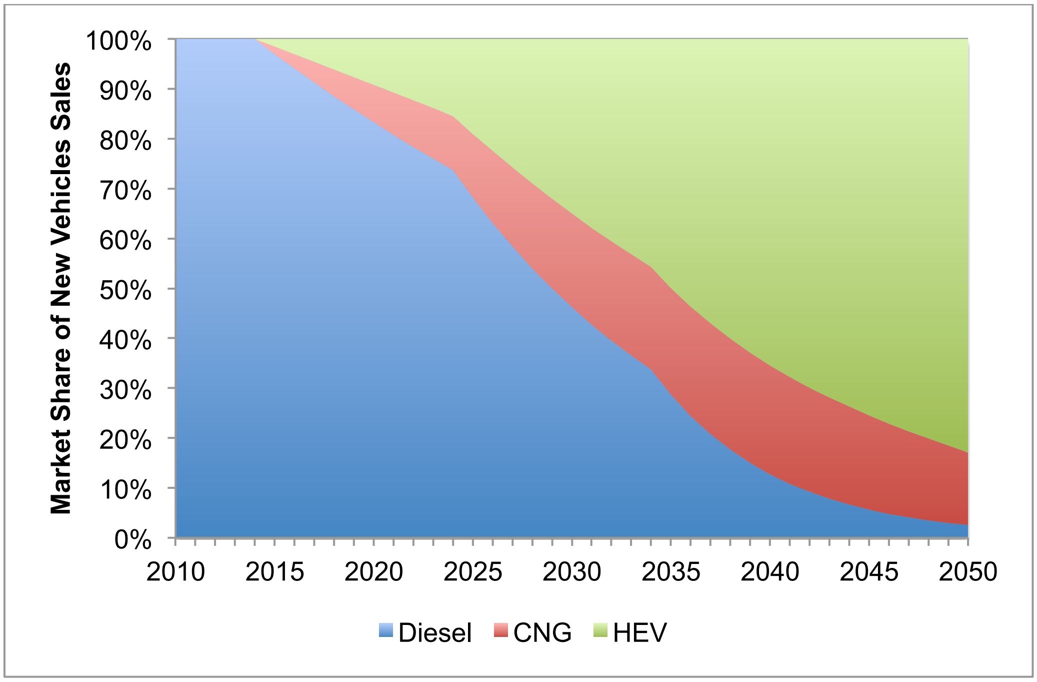

Figure 5-18: MD Urban and MD Vocational Vehicle new vehicle market share in the High Efficiency scenario

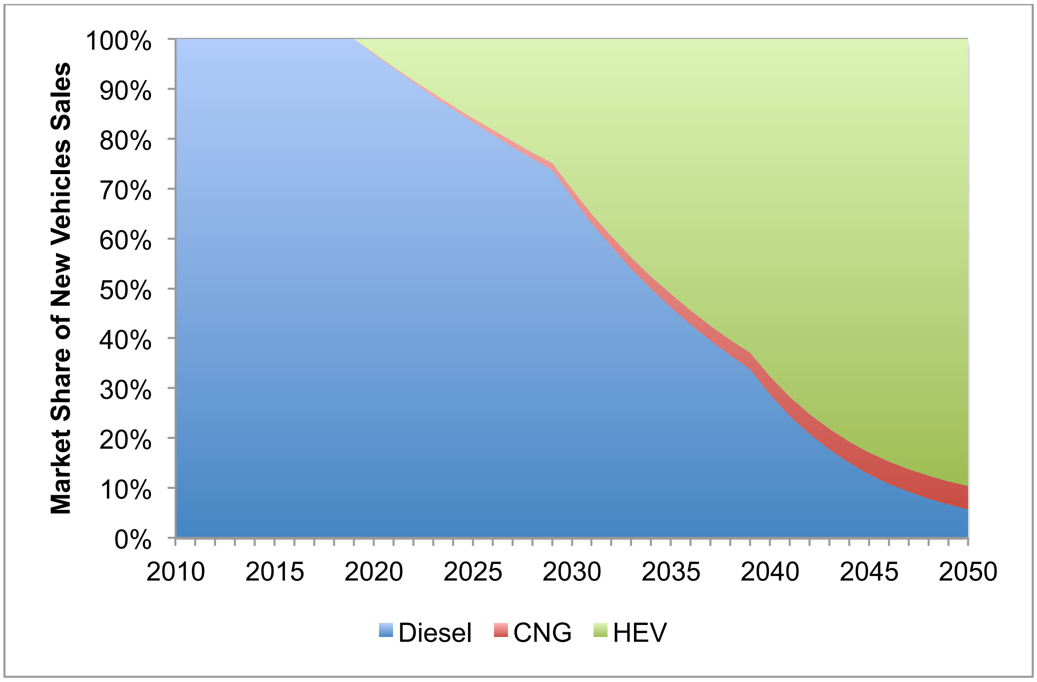

Figure 5-19: SH Tractor new vehicle market share in the High Efficiency scenario

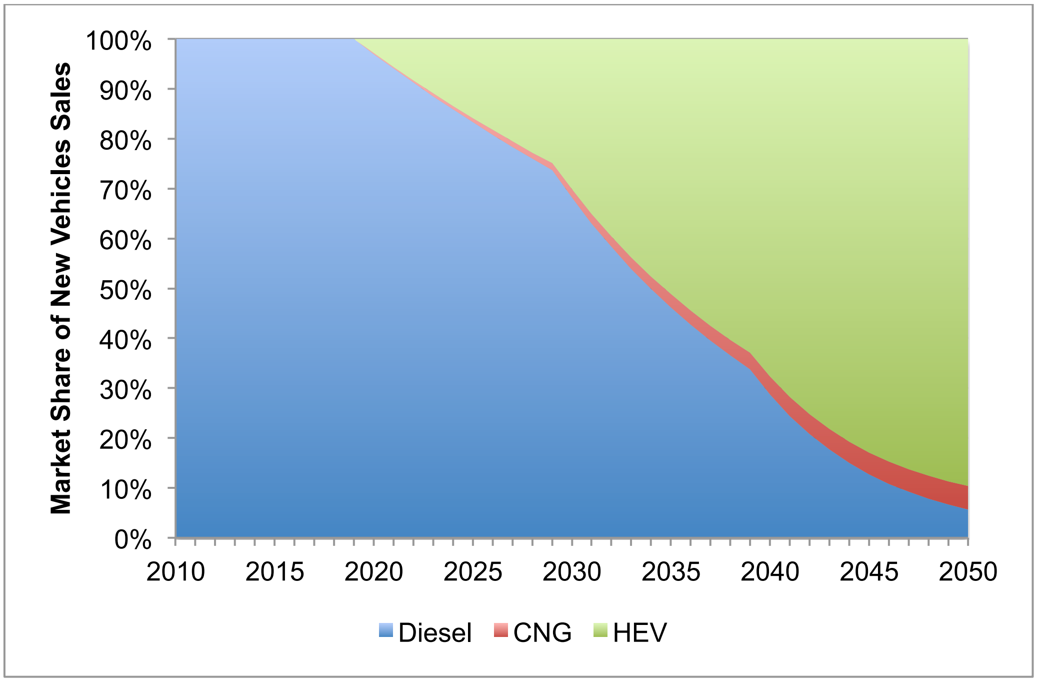

Figure 5-20: HD Pickup, Other Bus, and LH Tractor new vehicle market share in the High Efficiency scenario

5.3.2 Emission Results

The emissions reductions of the High Efficiency scenario compared to the Baseline are summarized in Figure 5-21, Figure 5-22, and Figure 5-23. The breakdown of the individual contributions to CO_2e in 2010, 2020, 2030, 2040, and 2050 as well as the CO_2e emissions by lifecycle phase are shown in Figure 5-24 and Figure 5-25 respectively.

For non-CO_2 emissions, fleet modernization results in decreasing emissions over time that mirrors the trends Baseline due to identical assumption about declining emission rates (2% per year for all species except SOx, which is primarily a function of the sulfur level in fuels) for new vehicles. However, the accelerated adoption of hybrids causes more rapid reductions, as hybrids are assumed to emit 20% less per unit of activity, which is an estimate based on the analysis done by Wayne et al. [323] and the author's best judgment. The percentage emission reductions of the High Efficiency scenario versus the Baseline are shown Figure 5-22 (cumulative reductions) and Figure 5-23 (annual reductions in 2020 and 2050). The emissions performance of hybrids compared to conventional vehicles is highly variable based on driving patterns, payload, and other factors. Also, since both hybrids and conventional diesel vehicles employ DPFs and SCR systems to meet the stringency requirements of the MY 2010 PM and NOx standards, the marginal criteria pollutant benefits of hybridization are likely less than what was evident in earlier model year analyses [324, 325]. As such, this blanket 20% reduction factor is a rough simplification that is set to zero as part of the sensitivity analysis. Eliminating the criteria pollutant benefits of hybridization results in emissions trends for the High Efficiency scenario that are very similar to the Baseline, with annual emissions for each species within ±5% of the Baseline.

For CO_2e emissions, the reduction over the study period as compared to the Baseline is a result of increased annual efficiency gains for new vehicles (2-4% per year for High Efficiency versus 1% per year for Baseline) and an escalating presence of hybrid vehicles in the fleet. In comparison to Baseline levels, the annual reduction in CO_2e emissions is 9% in 2020 and 44% in 2050, and the cumulative reductions are 4% and 22% in 2020 and 2050 respectively.

As shown in Figure 5-24, individual species contribution to total CO_2e emissions is nearly identical to the Baseline. Total CO_2e is roughly equal to CO_2 emissions, as the net total of the warming and cooling non-CO_2 emissions is close to zero.

Figure 5-25 is the breakdown of CO_2e emissions over time, and the reduction versus the Baseline is shown in the gray area. Approximately 80% of the decrease in CO_2e is due to reduced tailpipe emissions, with the remaining 20% coming from upstream fuels processes since the High Efficiency scenario has reduced fuel consumption compared to the Baseline, and there is less need for fuel production, refining, and transportation. The CO_2e emissions from vehicle manufacturing and scrappage are nearly identical between the two scenarios, and this is true of the remaining four scenarios as well.

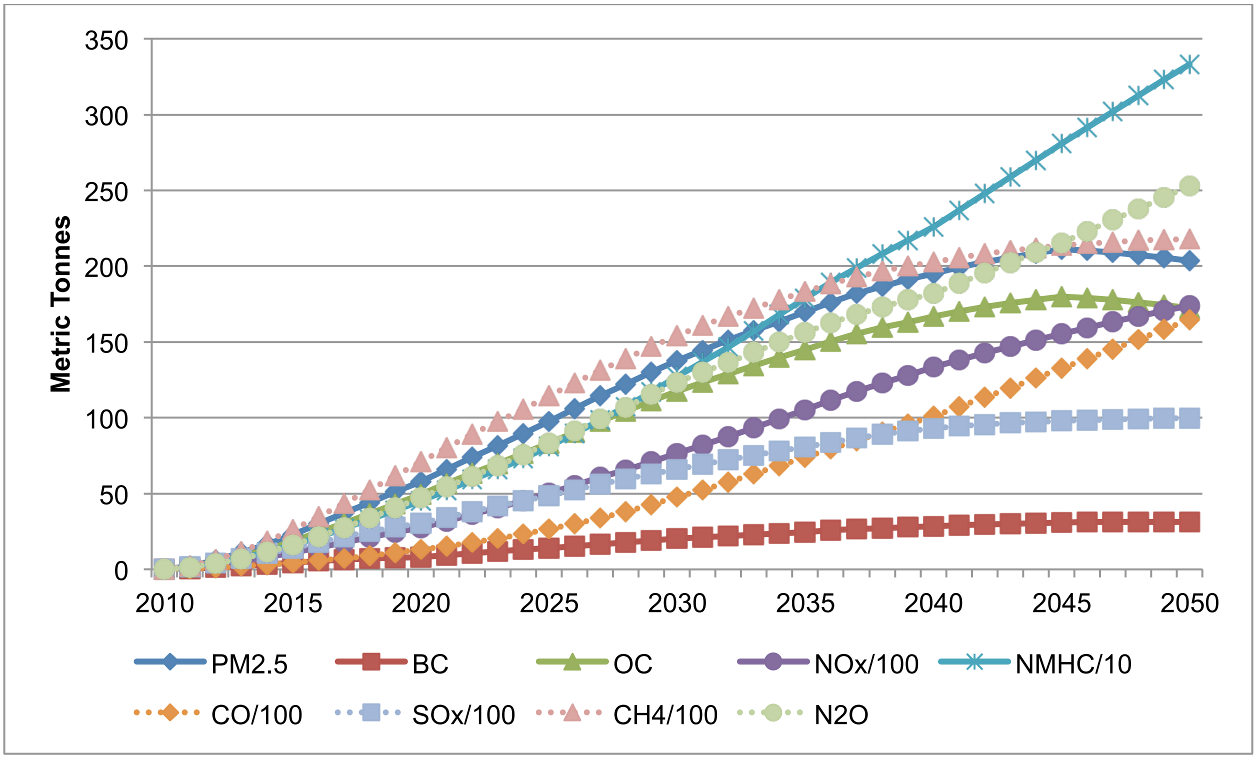

Figure 5-21: Emissions reductions of the High Efficiency scenario compared to the Baseline

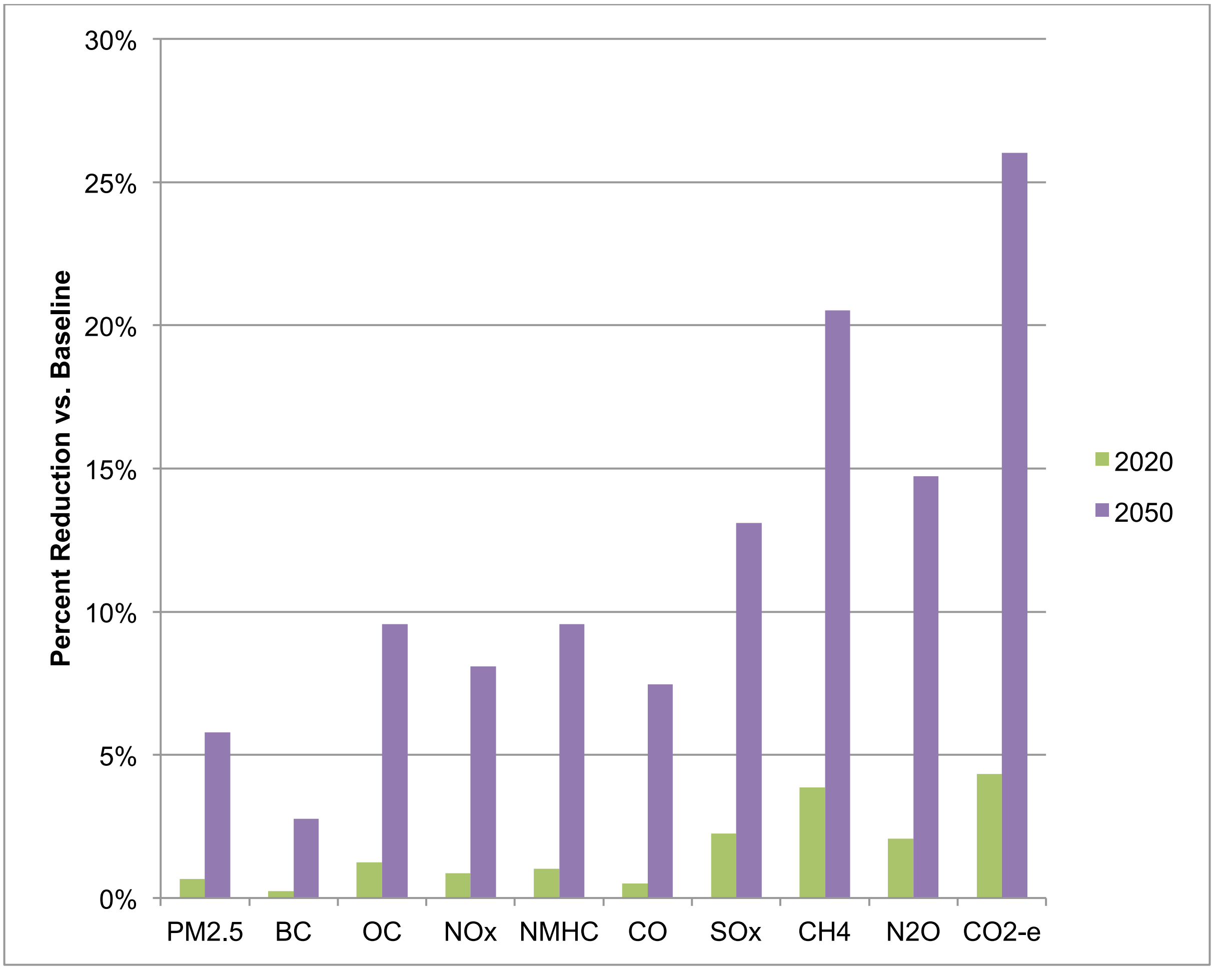

Figure 5-22: Percent reduction in cumulative emissions in 2020 and 2050 for the High Efficiency scenario as compared to the Baseline

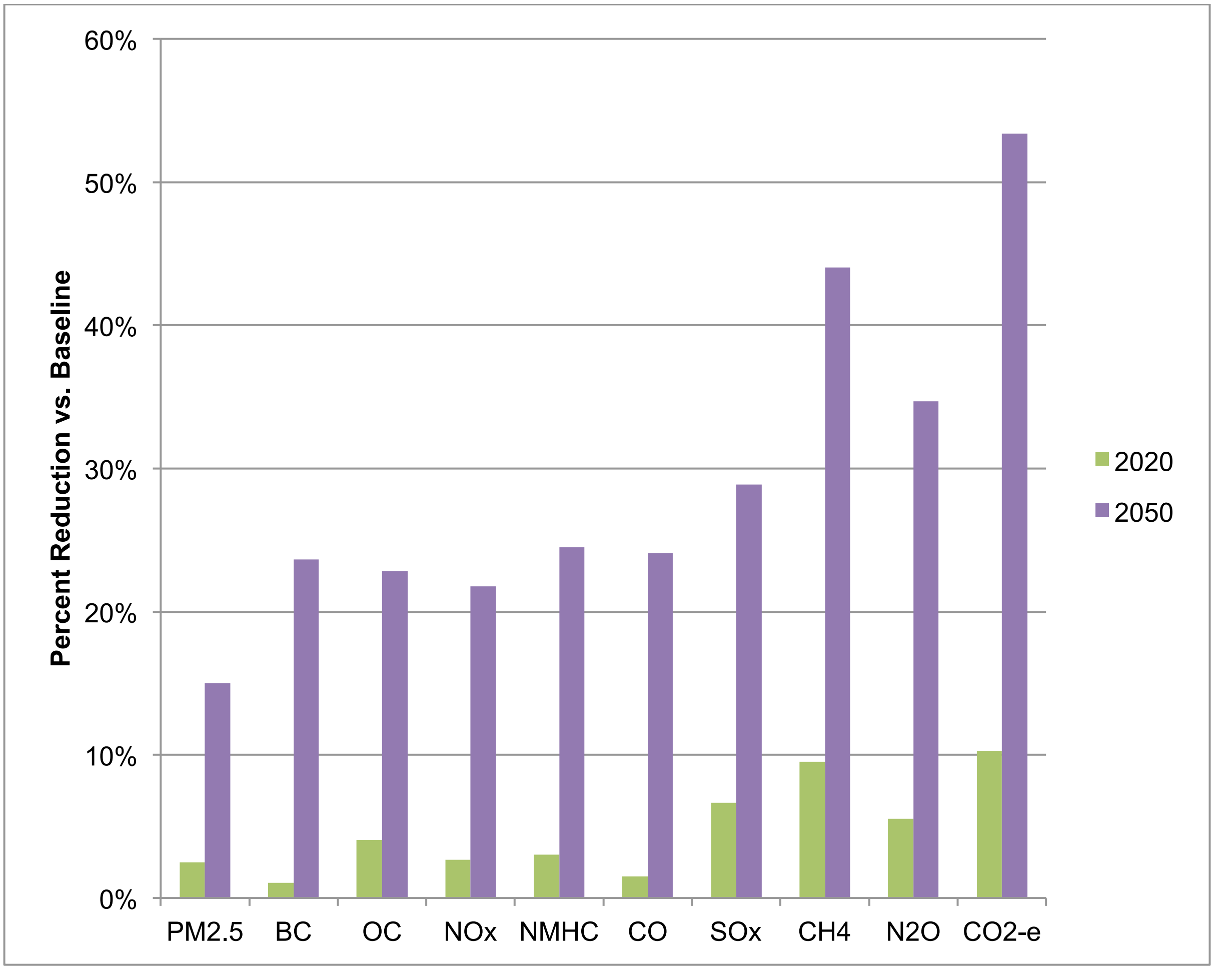

Figure 5-23: Percent reduction in annual emissions in 2020 and 2050 for the High Efficiency scenario as compared to the Baseline

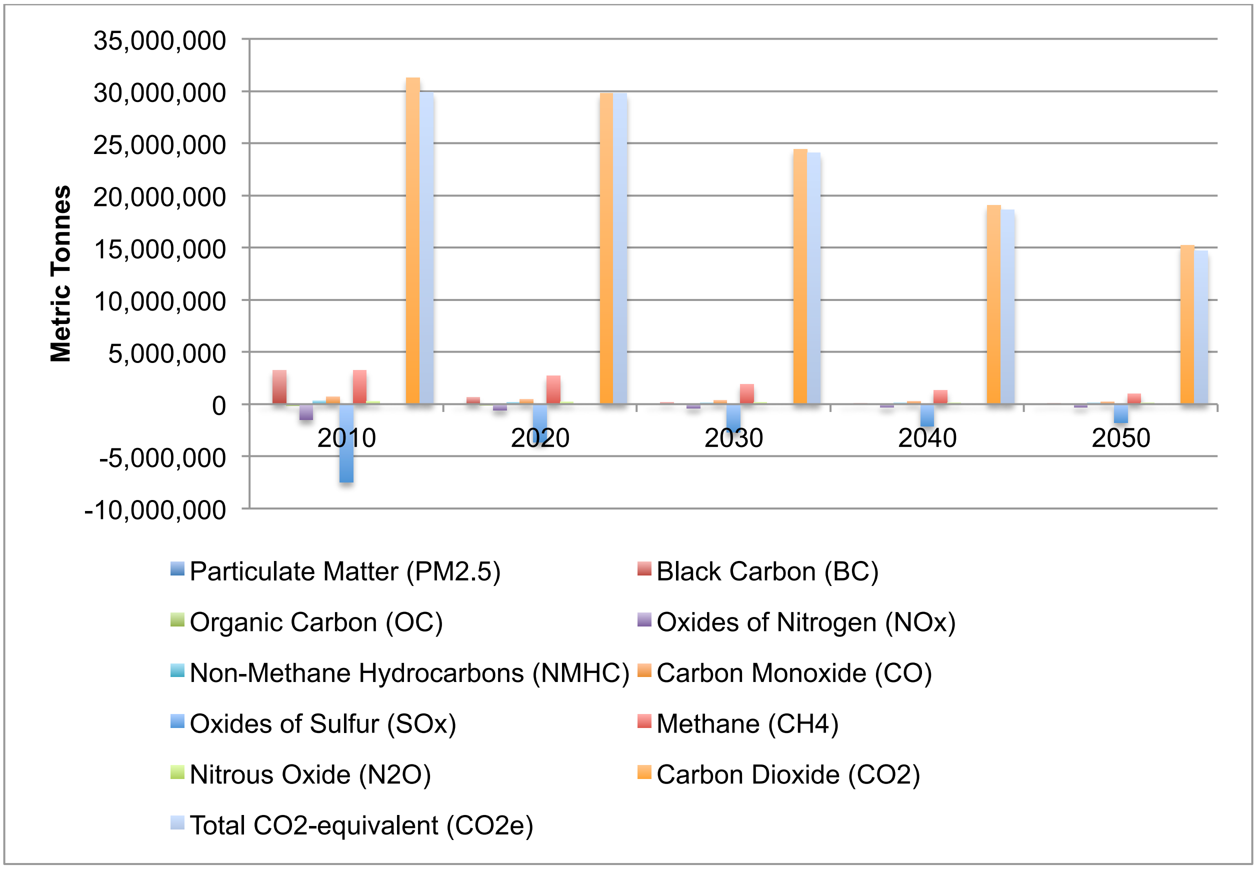

Figure 5-24: CO_2e emissions breakdown for the High Efficiency scenario

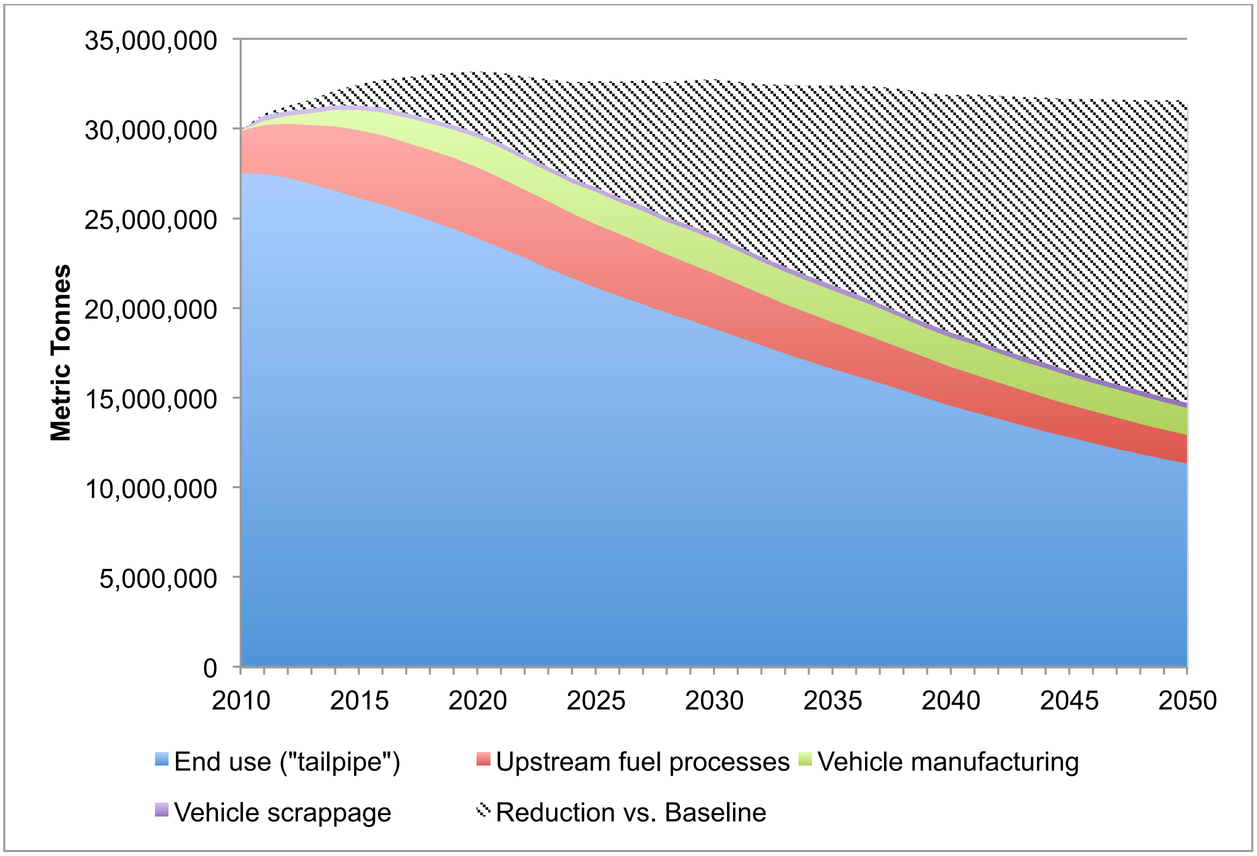

Figure 5-25: CO_2e emissions by lifecycle phase in the High Efficiency scenario

5.3.3 Fuel Use Results

The fuel use totals for the High Efficiency scenario are shown in Figure 5-26. Increased vehicle efficiency and the emergence of hybrids drive total fuel use down at an approximate rate of 1.8% per year after fuel consumption peaks in 2012. Fuel use in 2050 is approximately half that of 2010 as well as roughly half of Baseline fuel use in 2050.

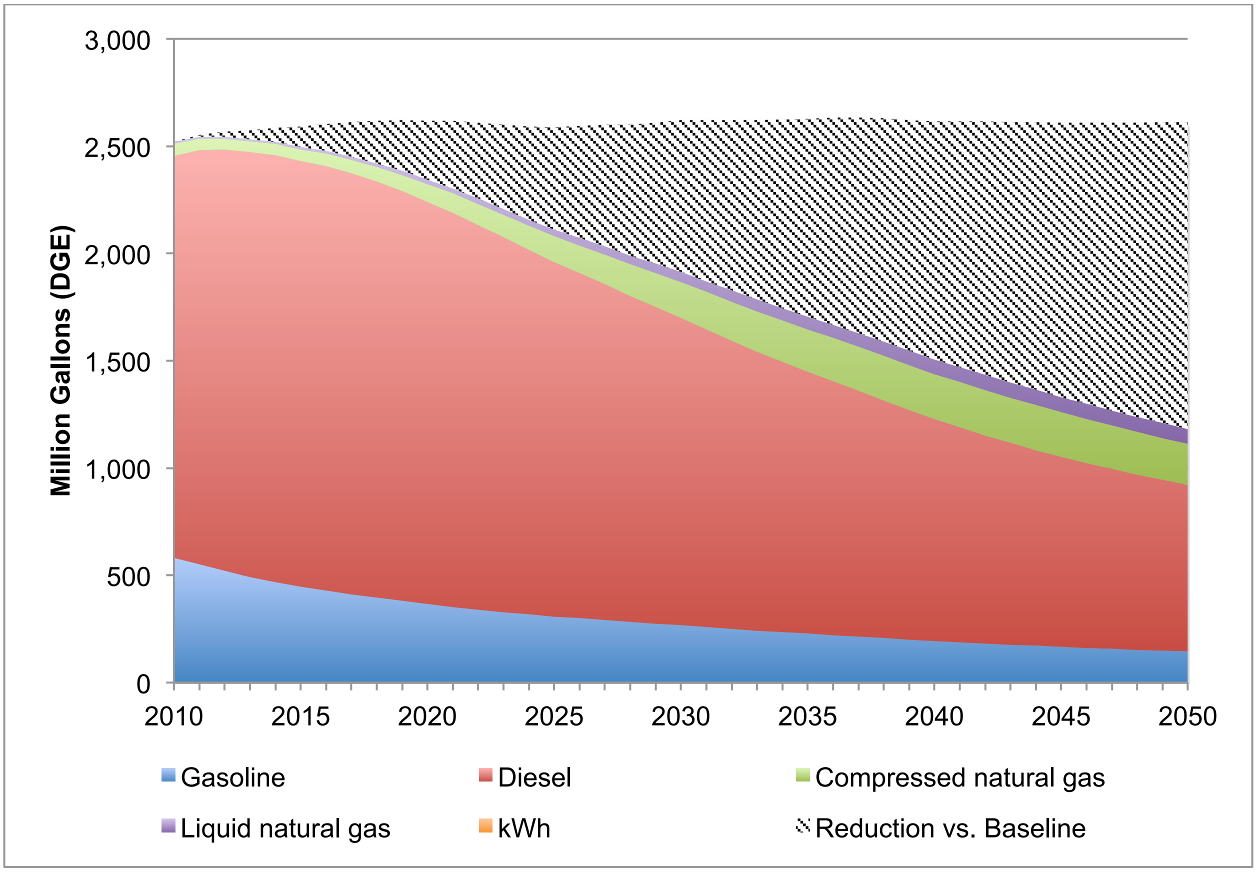

Figure 5-26: Fuel use trends of the High Efficiency scenario (million diesel gallon equivalents)

5.3.4 Cost Results

The High Efficiency scenario lifecycle cost totals are summarized in Figure 5-28 and Figure 5-29. The total costs in this scenario grow slower than in the Baseline, increasing at an average annual rate of 0.7%—from $19.2 billion in 2010 to $25.6 billion in 2050. The NPV (NPV) of the High Efficiency scenario cost stream is $628 billion, which is 6% lower than the Baseline NPV, which is $667 billion. For all six scenarios, NPV is calculated by applying a 2.1% real discount rate to each year of the annual costs. This discount rate is taken from the US Office of Management and Budget's 30-year value for "Real Treasury Interest Rates" [326]. Setting the discount rate to the long-term interest rates that governments have to pay is a method that is frequently used in societal cost-benefit analysis [327].

As with the Baseline scenario, the cost totals are dominated by vehicle retail costs, fuel costs, and maintenance and repair costs. The costs differences between the High Efficiency and Baseline scenarios over time are shown in Figure 5-30. The fuel cost savings over time grow more quickly than the increases in vehicle retail and non-fuel operating costs (which are primarily increases in insurance rates due to growing retail values). The externality cost savings of the High Efficiency scenario are a much smaller percentage compared to the fuel cost savings. In 2050, the savings due to the decreased cost of emissions damage, energy security, and noise are roughly 5% of the value of the cost savings of reduced fuel use. The relative increases in vehicle retail costs of this scenario are due to the assumed growth in per-vehicle prices (2010$) of conventional gasoline and diesel vehicles.[30] One of the critical assumptions of the High Efficiency scenario is that regulations drive fuel-saving technologies into the fleet at a higher rate than under *natural* (i.e. Baseline) circumstances. The increased costs due to fuel efficiency/GHG standards are estimated based on the costs reported in the US EPA/NHTSA heavy-duty vehicle regulation [105]. Under this regulation, the most stringent standards were adopted for high-roof tractors with sleeper cabs. Over the five-year life of the regulation, the estimated annual reduction in fuel consumption for this vehicle group is around 4% per year, and the cost increase (in inflation-adjusted dollars) is roughly 0.8% per year. This same methodology is used for the remaining seven vehicle categories, and the resulting percentages for annual cost increase and fuel consumption (FC) reduction are shown in Table 5-11. Another core assumption of the High

[30] The price floor for NG vehicles, which equals 1.0 times the price of a conventional diesel vehicle, increases as well. The same is true for hybrids, which have a price floor of 1.1.

Efficiency and other non-Baseline scenarios is that the annual fuel consumption reduction and cost increase percentages shown in Table 5-11 are constant over the entire 40-year study period to reflect the required additional technology needed to provide the annual fuel consumption reduction shown in Figure 5-15. As with the annual fuel consumption reduction percentages, the annual cost increase percentages are identical for each technology type, since the retail costs of each advanced vehicle type are based on a multiplication factor applied to conventional diesel vehicles. The purchase costs (2010$) for new vehicles compared to MY 2010 vehicles are displayed in Figure 5-27. For all of the non-Baseline scenarios, the annual cost increases in Figure 5-27 are assumed to provide the fuel-saving technologies necessary for the fuel consumption reductions over time shown in Figure 5-15. These technology potential and cost estimates are used in all five of the non-Baseline scenarios.

Table 5-11: Annual fuel purchase price increase in new vehicles for all five non-Baseline scenarios

HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
0.5%	0.25%	0.15%	0.8%	0.65%	0.25%	0.75%	0.75%

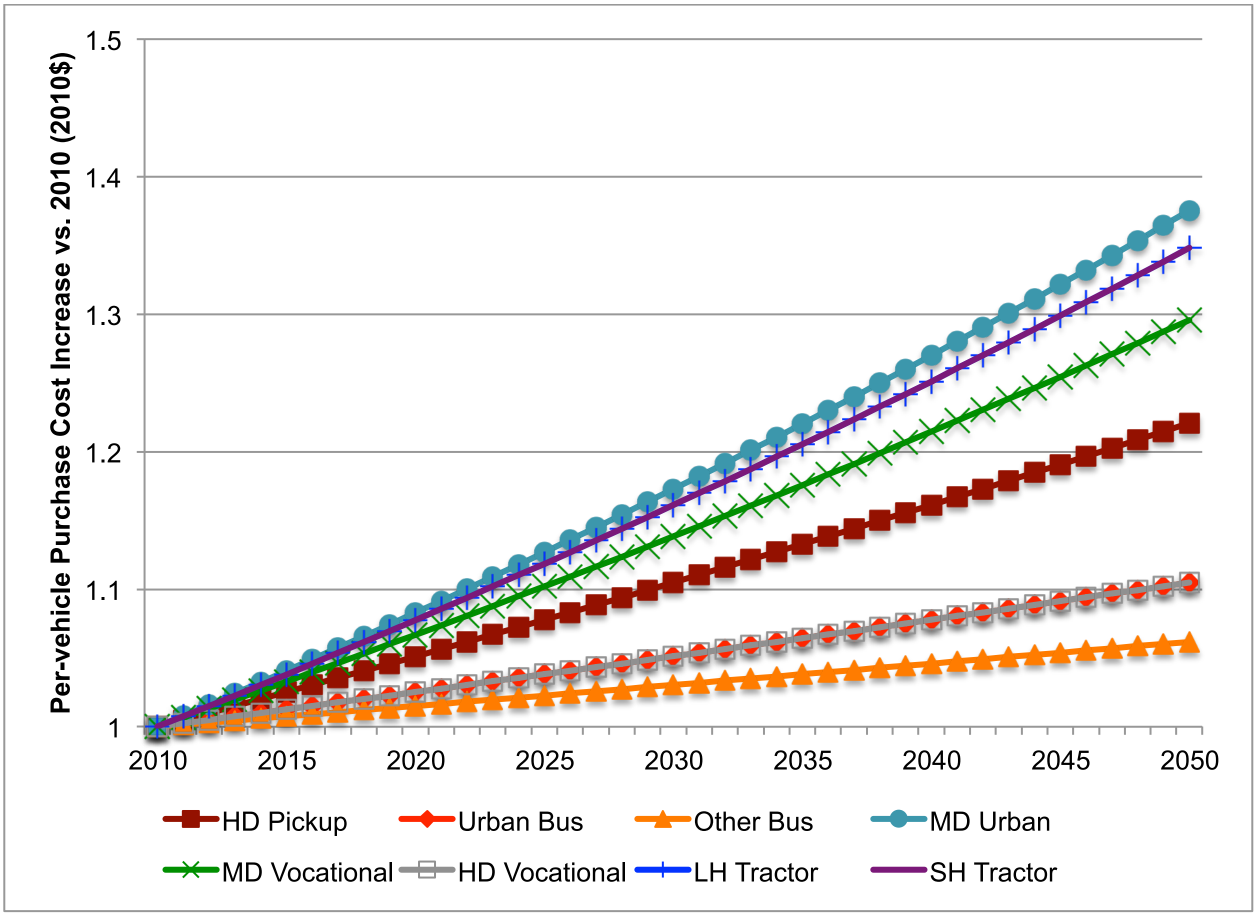

Figure 5-27: Cost increases (2010$) in new vehicles compared to 2010 vehicles for all of the non-Baseline scenarios

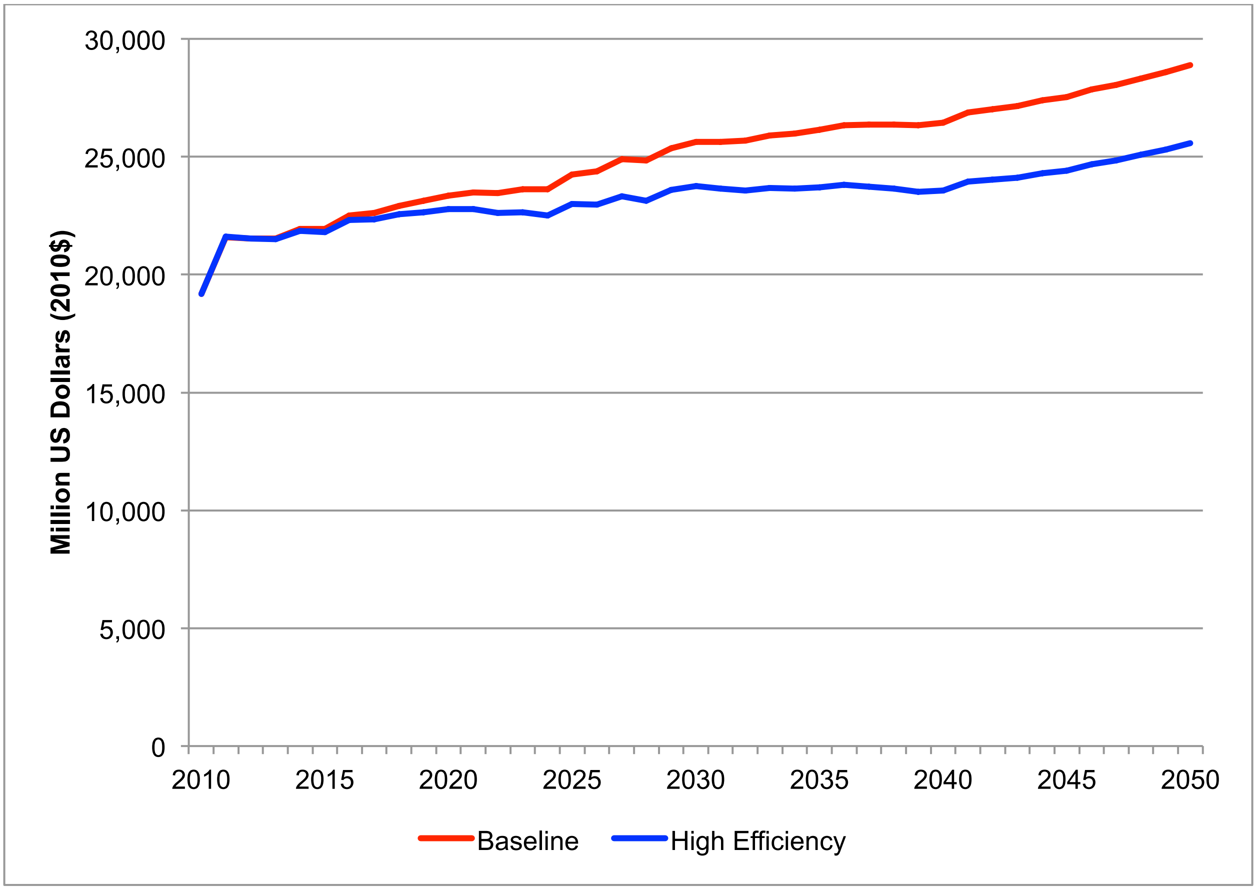

Figure 5-28: Total lifecycle costs of the High Efficiency and Baseline scenarios

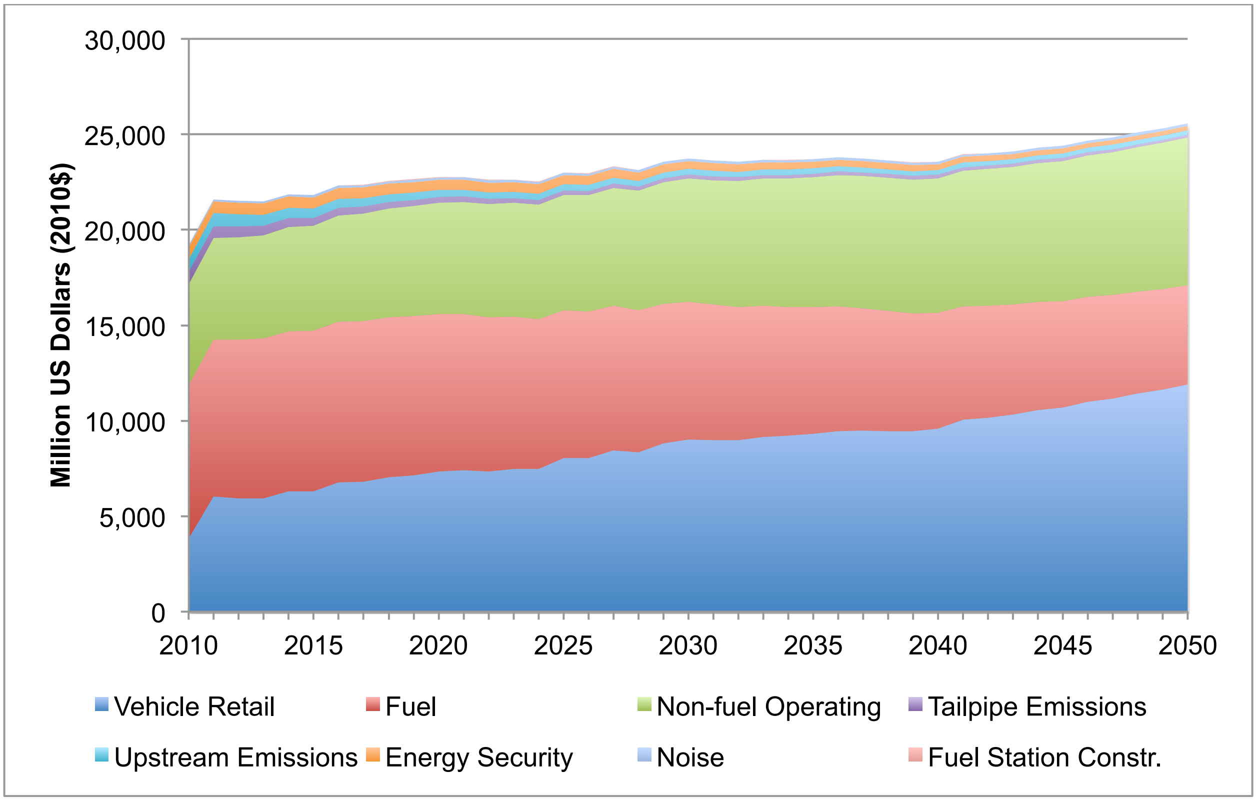

Figure 5-29: Total costs breakdown for the High Efficiency Scenario

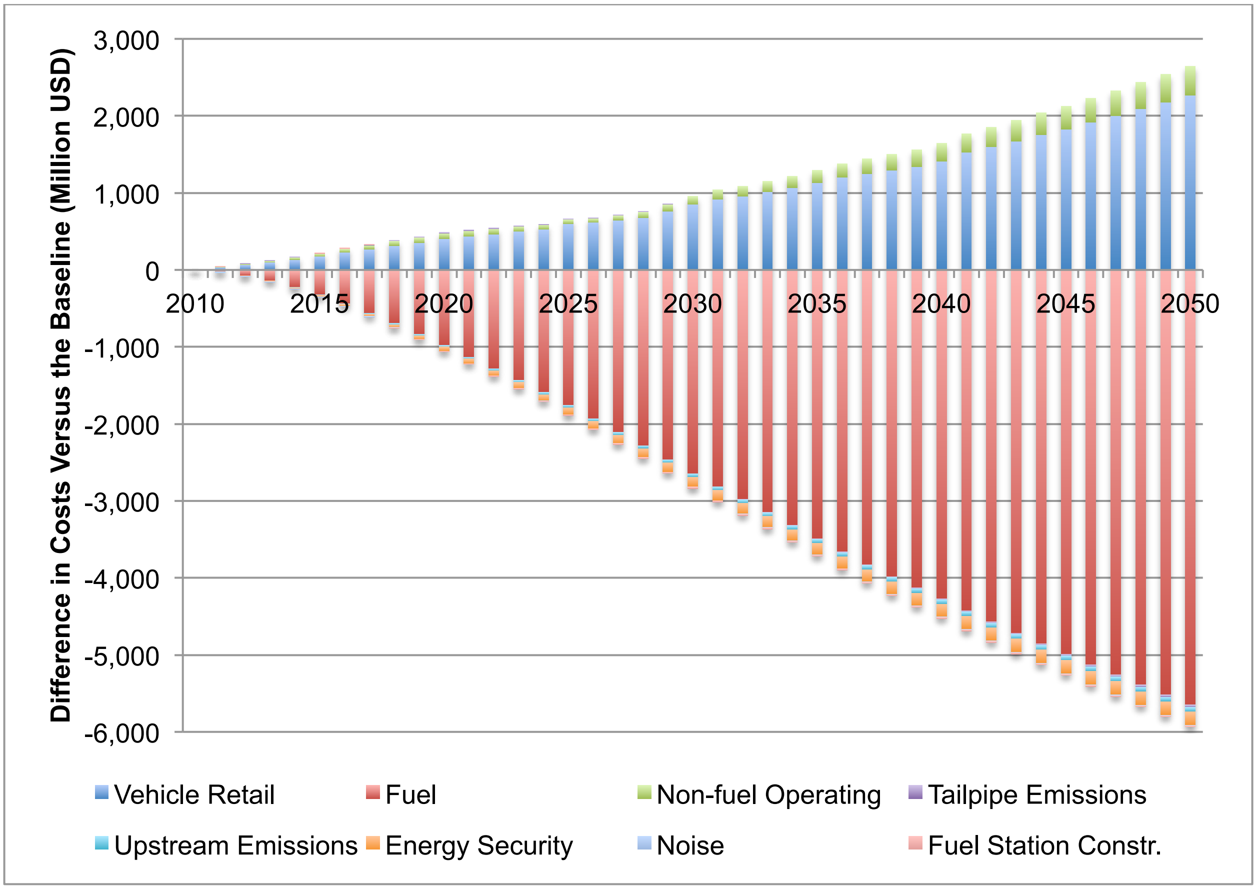

Figure 5-30: Cost differences between the High Efficiency and Baseline scenarios (positive values imply costs larger than the Baseline, negative values the inverse)

5.4 Plug-in Hybrids and Electric Vehicles (PHEVs+EVs) Scenario

In the PHEVs+EVs scenario, the HD vehicle fleet rapidly moves towards increasing levels of electrification. In categories such as transit buses and other *return-to-base* vehicles, where typical duty cycles and operating patterns are amenable to downtime grid charging, plug-in electric and full electric vehicles have a growing share of the market. Natural gas vehicle adoption diminishes to zero by the 2030-2035 timeframe, and hybrid, plug-in hybrid, and full electric vehicles comprise the entire fleet towards the end of the study period.

5.4.1 Fuel and technology evolution

The PHEVs+EVs scenario also assumes that stringent fuel efficiency/GHG regulations are in place throughout the entire study period. This scenario uses the same rate of fuel efficiency progress and conventional vehicle phase-out as the High Efficiency scenario. The per-vehicle fuel consumption rates for all new vehicle types—including plug-in hybrids and full electric vehicles—are assumed to decrease by 2-4% per year.

Relative to the Baseline and High Efficiency scenarios, the PHEVs+EVs scenario assumes that hybrids have a higher initial percentage of the advanced vehicle market starting in 2011 for the Urban Bus and HD Vocational Vehicle categories. Hybrids and NG vehicles each have 50% of the sales market in 2011, as opposed to 75% NG and 25% hybrids in the previous two scenarios. NG vehicle market share for these two vehicle groups decrease to zero by the end of Period 2, which is set at 2031 for Urban Buses and 2036 for HD Vocational Vehicles. For the other six vehicle types, hybrids are assumed to comprise the entire advanced vehicle market at the beginning of Period 1, and over time, hybrid sales give way to PHEVs and EVs. As this scenario is premised on large-scale electrification, hybrids are a vital transition technology, as advances in electric components (batteries, motors, and power electronic components) for hybrids are applicable to PHEVs and EVs as well. The market share controls for this scenario are shown in Table 5-12.

Full battery electric vehicles are not assumed to enter the LH Tractor and Other Bus segments. The large percentage of highway driving of long-haul tractors and coach buses would require very large battery packs or catenary systems, which are not considered in this study. Even assuming steady advancements in battery density out to 2050, the required battery packs would still likely be too expensive and heavy to be practical for long distance operations. However, the scenario assumes modest adoption of plug-in hybrids for these two vehicle categories—starting in 2031, sales of PHEVs grow to 20% of the market by 2050. The assumption is that PHEV battery packs that are larger than their hybrid counterparts allow for limited all-electric driving and increased fuel efficiency benefits during *blended* operation. Plug-in hybrid battery packs also provide more power for hotel loads during extended idling. A key premise of this scenario is that an increasing number of public spaces (e.g. truck stops, parking spaces, etc.) are equipped with Level 2 or higher charging infrastructure.

Table 5-12: Market share controls for the PHEVs+EVs scenario

	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
Adoption Controls								
Initial yr. of AV adoption	2020	2011	2020	2015	2015	2011	2020	2015
Pivot year 1	2030	2020	2030	2025	2025	2025	2030	2030
Pivot year 2	2040	2031	2040	2025	2025	2036	2040	2040
Conv. Vehicle Change in Market Share								
Period 1 annual change in MS (percentage)	-3%	-5%	-3%	-3%	-3%	-3%	-3%	-3%
Period 2 annual change in MS (percentage)	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%
Period 3 annual change in MS (percentage)	-15%	-15%	-15%	-15%	-15%	-15%	-15%	-15%
Natural Gas Controls								
Initial % of AV market	0%	50%	0%	0%	0%	50%	0%	0%
Period 1 annual change in MS (percentage points)	0%	-2.5%	0%	0%	0%	-2%	0%	0%
Period 2 annual change in MS (percentage points)	0%	-2.5%	0%	0%	0%	-2%	0%	0%
Period 3 annual change in MS (percentage points)	0%	0%	0%	0%	0%	0%	0%	0%
Hybrid Controls								
Initial % of AV market	100%	50%	100%	100%	100%	50%	100%	100%
Period 1 annual change in MS (percentage points)	-1%	1.5%	0%	-2%	-2%	1%	0%	-1%
Period 2 annual change in MS (percentage points)	-2%	-1%	-1%	-2%	-2%	-1%	-1%	-2%
Period 3 annual change in MS (percentage points)	-2%	-3%	-1%	-2%	-2%	-2%	-1%	-2%

	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
PHEV Controls								
Initial % of AV market	0%	0%	0%	0%	0%	0%	0%	0%
Period 1 annual change in MS (percentage points)	1%	1%	0%	1%	1%	1%	0%	1%
Period 2 annual change in MS (percentage points)	1%	2%	1%	1%	1%	2%	1%	1%
Period 3 annual change in MS (percentage points)	1%	1%	1%	1%	1%	1%	1%	1%
EV Controls								
Initial % of AV market	0%	0%	0%	0%	0%	0%	0%	0%
Period 1 annual change in MS (percentage points)	0%	0%	0%	1%	1%	0%	0%	0%
Period 2 annual change in MS (percentage points)	1%	1.5%	0%	1%	1%	1%	0%	1%
Period 3 annual change in MS (percentage points)	1%	2%	0%	1%	1%	1%	0%	1%

The new vehicle market shares for each technology type over the study period are summarized in the figures below. As with the High Efficiency scenario, advanced technology vehicles come to dominate the sales market for all eight vehicle categories. By 2050, plug-in hybrid and full electric new vehicle market shares grow to 47% and 50% respectively for Urban Buses and 49% and 24% for HD Vocational Vehicles. The two medium-duty categories have the next largest shares of grid-connected vehicles, with PHEVs and EVs each accounting for 34% of sales by 2050. For SH Tractors, plug-in hybrids enter the fleet starting in 2015 and gain one percentage point per year of the overall advanced vehicle market until 2050, when PHEVs reach 35% of the advanced vehicle sales market. For HD Pickup Trucks, plug-in hybrids enter the market starting in 2020 and also increase advanced vehicle market share at one percentage point per year until 2050, reaching 30% of sales. For both SH Tractors and HD Pickups, full electric vehicles enter the fleet in 2030 and grow to 20% of advanced vehicle sales by 2050. With LH Tractors and Other Buses, hybrids are the dominant advanced technology, with PHEVs entering the market in 2031 and increasing to 20% of advanced vehicle sales by 2050.

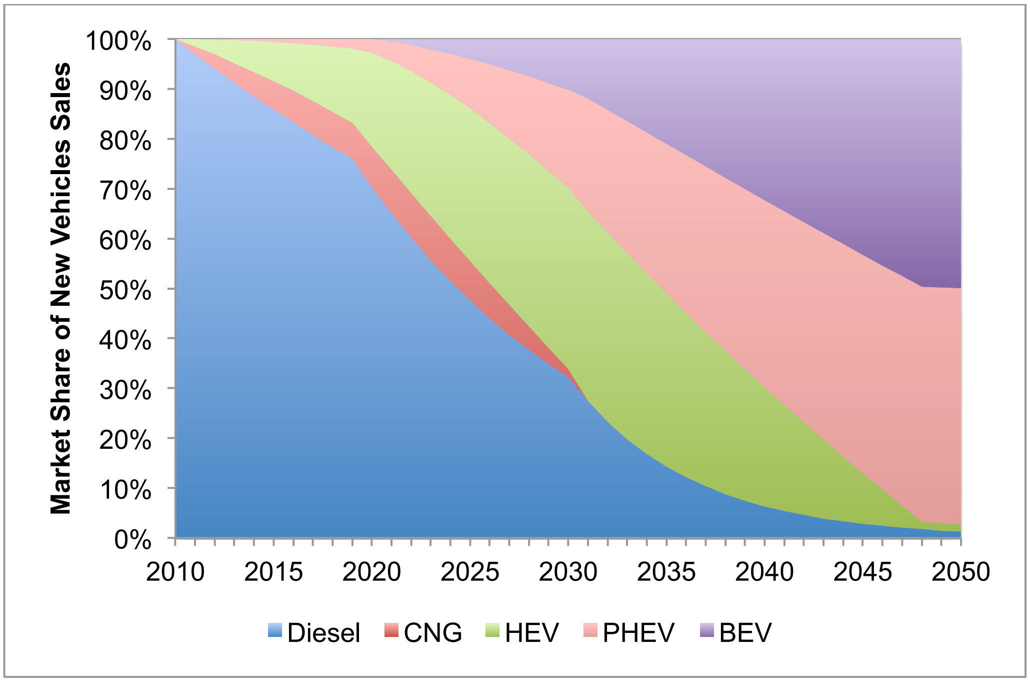

Figure 5-31: Urban Bus new vehicle market share in the PHEVs+EVs scenario

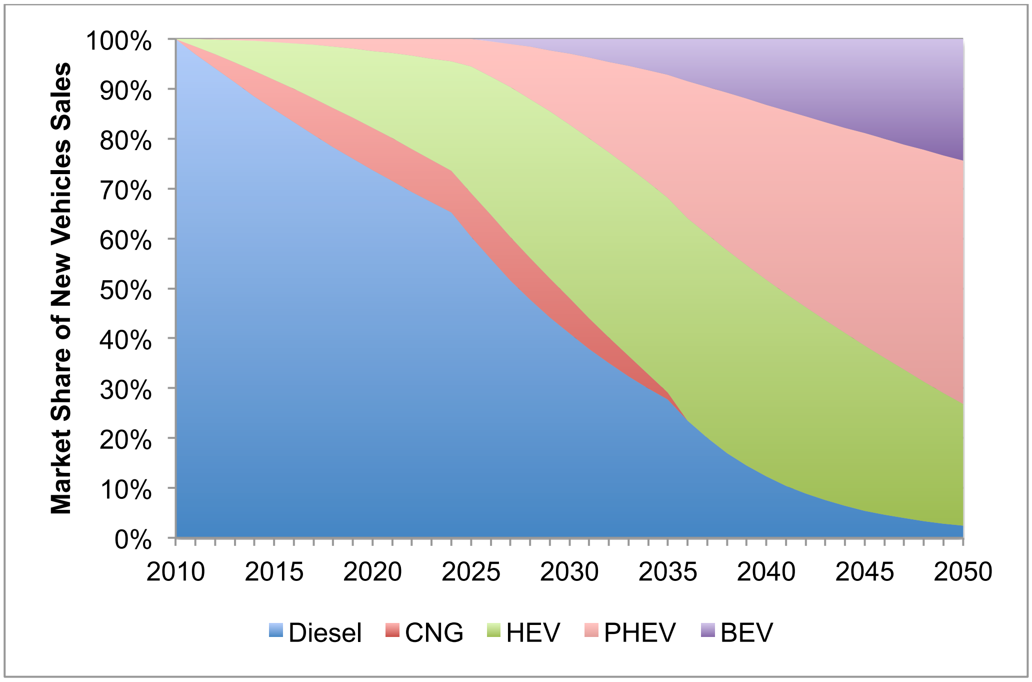

Figure 5-32: HD Vocational Vehicle new vehicle market share in the PHEVs+EVs scenario

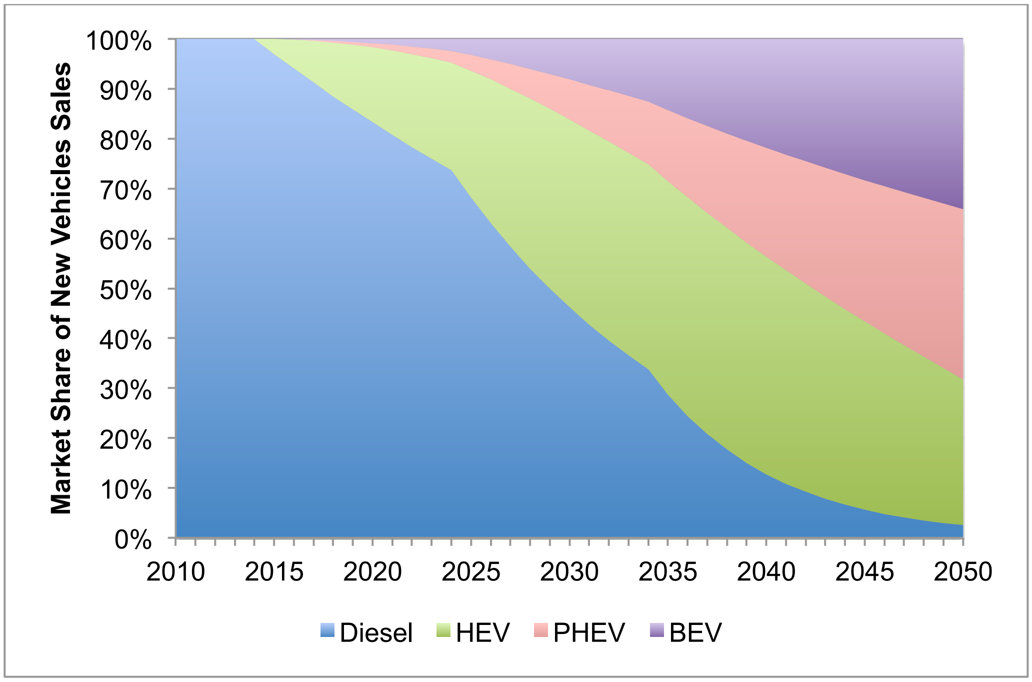

Figure 5-33: MD Urban and MD Vocational Vehicle new vehicle market share in the PHEVs+EVs scenario

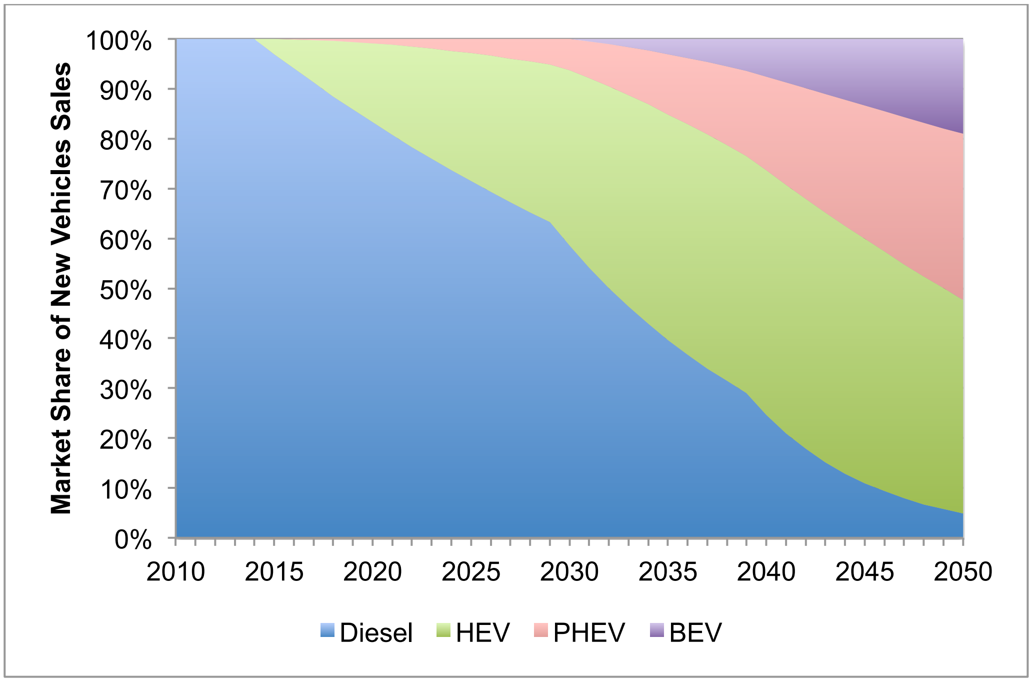

Figure 5-34: SH Tractor new vehicle market share in the PHEVs+EVs scenario

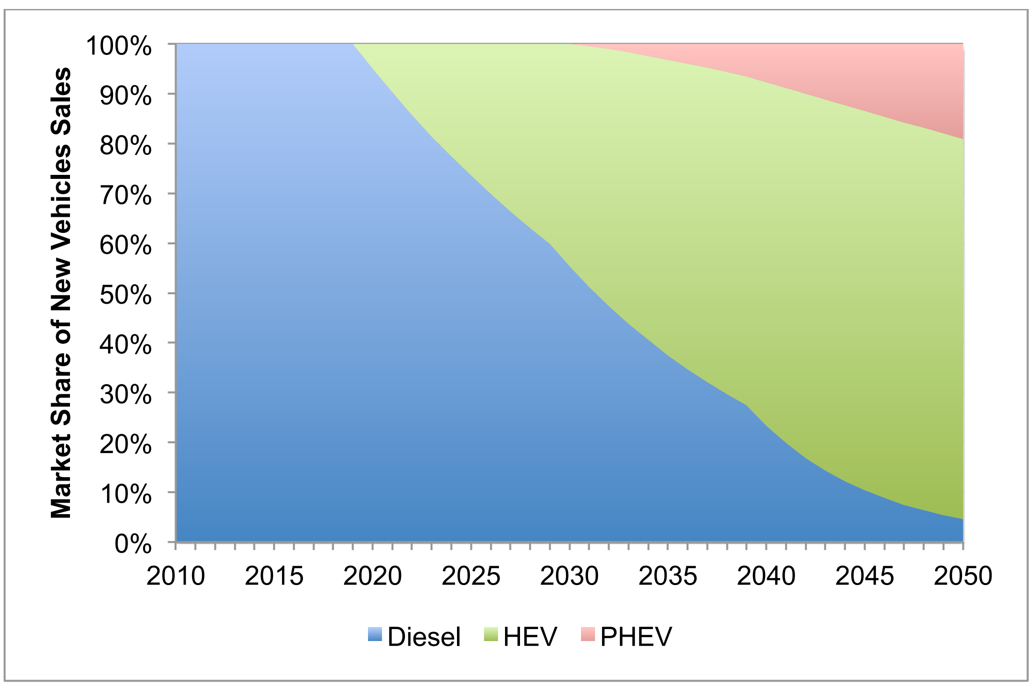

Figure 5-35: Other Bus and LH Tractor new vehicle market share in the PHEVs+EVs scenario

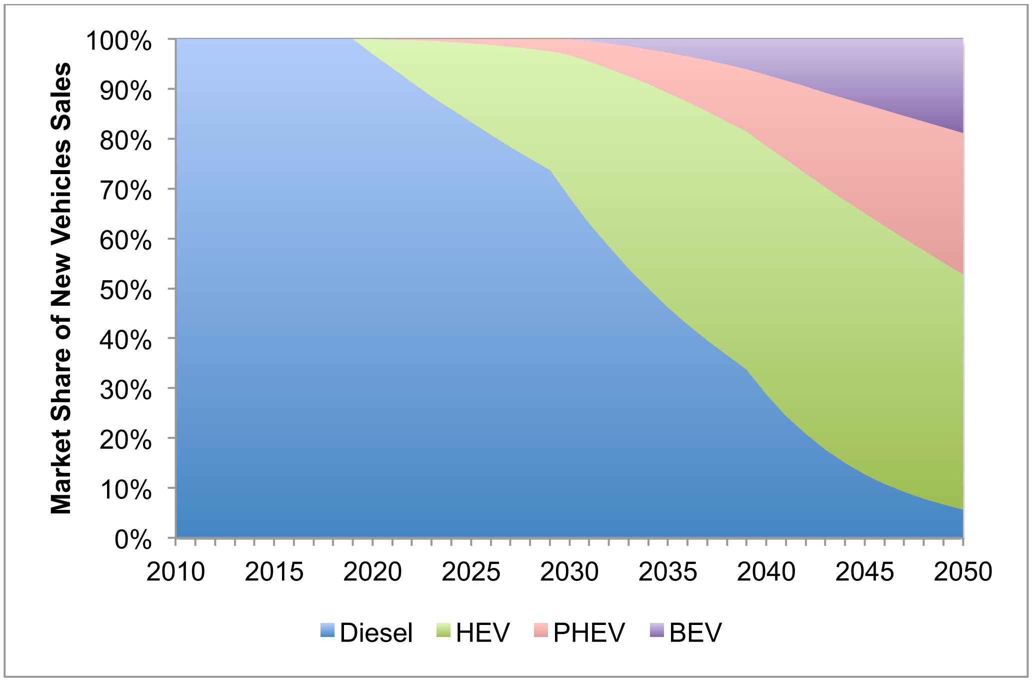

Figure 5-36: HD Pickup new vehicle market share in the PHEVs+EVs scenario

5.4.2 Emission Results

As with the previous two scenarios, the emissions levels over time for the PHEVs+EVs scenario are largely a function of fleet modernization, a decrease in per-mile emission factors of 2% per year, and declining emission rates from upstream processes. The annual emission reductions in 2020 and 2050 compared to the Baseline and High Efficiency scenarios are shown in Figure 5-37 and Figure 5-38. Compared to the High Efficiency scenario—which has identical assumptions for the rate of fleet turnover and per-mile emission factor reductions—the marginal emission reduction benefits of the higher level of electrification in the PHEVs+EVs scenario is most evident for CO, N_2O, NMHC, and NOx. The effects on PM, BC, and OC are negligible (within +/- 1%), and SOx and CH_4 emissions are both roughly 3% higher in 2050 than the High Efficiency scenario. For CO_2e emissions in 2050, the PHEVs+EVs scenario shows a 2%

reduction as compared to the High Efficiency scenario and a 46% reduction versus the Baseline. While EVs account for 13% of total VMT in 2050, they are only responsible for 4% of CO_2e emissions.

As a growing number of vehicles use energy from the electrical grid, the upstream emissions associated with electricity production becomes an increasingly important factor in the scenario emission totals. As described in Section 4.3.6.3, there are three electrical grid mix scenarios available in TOP-HDV:

1) 20-30-40-50% Renewables
2) 20-30-40-50% Renewables with High Nuclear
3) 33-50-75-100% Renewables

The emission results above and in Figure 5-37 and Figure 5-38 are based on the *20-30-40-50% Renewables* grid scenario. Figure 5-39 summarizes the emissions impacts when the other two grid mix scenarios are used in the model runs. The overall emission impacts of the *20-30-40-50% Renewables with High Nuclear* (hereto referred to as "High Nuclear") and *33-50-75-100% Renewables* (hereto referred to as "Aggressive Renewables") electricity scenarios are virtually identical. This is due to the fact that both nuclear power and the renewable energy sources modeled in TOP-HDV have estimated emission factors (i.e. grams per kWh electricity delivered) that are much lower than NG and coal-fired power plants and very close to zero (or equal to zero) in some cases. In Figure 5-39, the negative values represent scenario emission totals that are lower than with the *20-30-40-50% Renewables* electricity grid mix and vice versa for the positive values. The emission impacts of changing the electrical grid mix scenario are relatively modest, with most emissions deltas being within ± 2% of the original levels. The exceptions are NMHC, CO, and N_2O, which are roughly 3 to 4% lower in the 2030 timeframe before moving back towards the original values. For CO_2e emissions, the maximum effect is seen in 2050, when emissions are approximately 2% higher for the High Nuclear and Aggressive Renewables electricity scenarios. In the end, the choice of electrical grid power has a relatively minor effect on the emission totals because the lifecycle emissions from electric vehicles are primarily dominated by the manufacturing phase, and end-use emissions contribute a much smaller percentage of overall emissions than for other vehicle technology types.

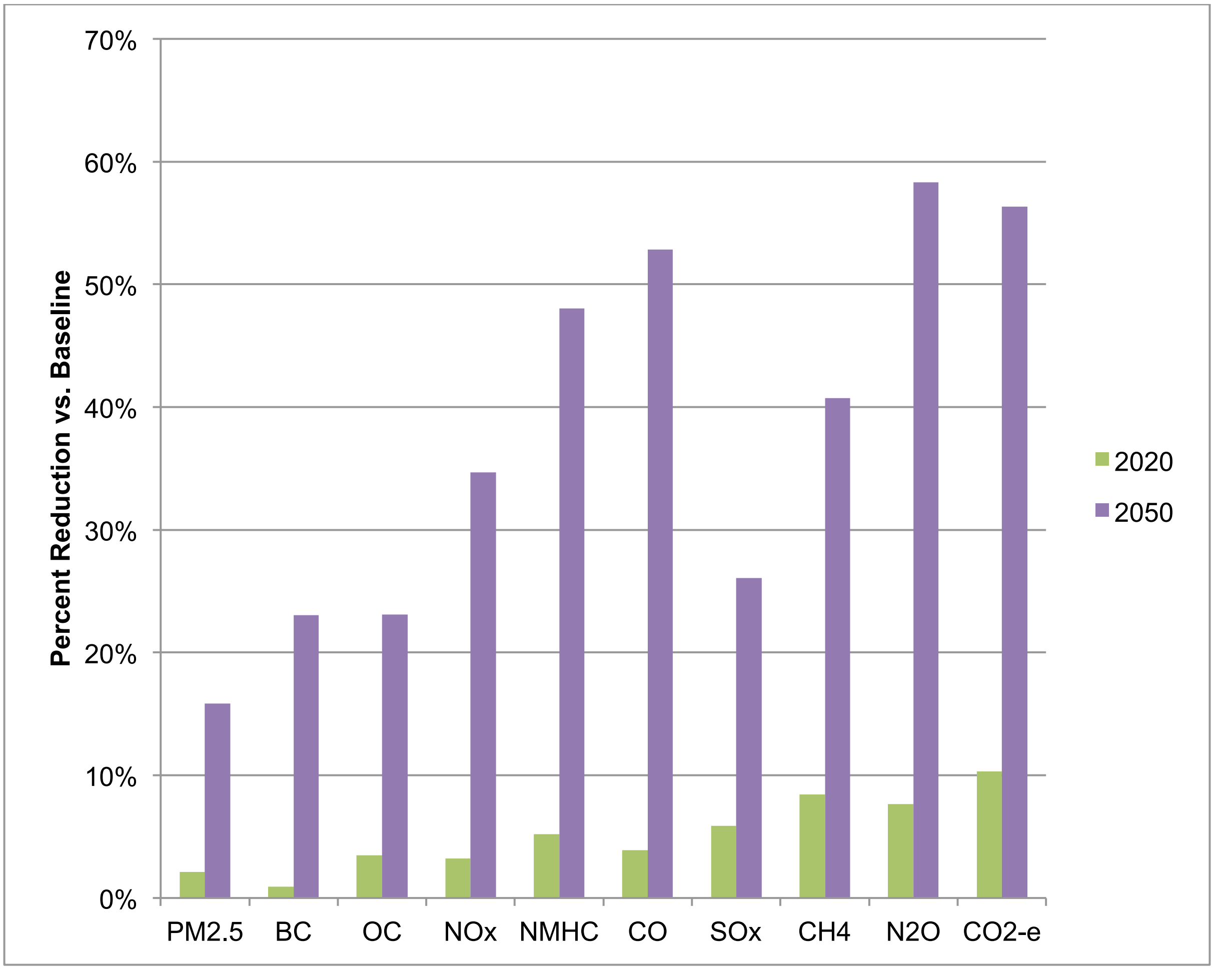

Figure 5-37: Percent reduction in annual emissions in 2020 and 2050 for the PHEVs+EVs scenario as compared to the Baseline

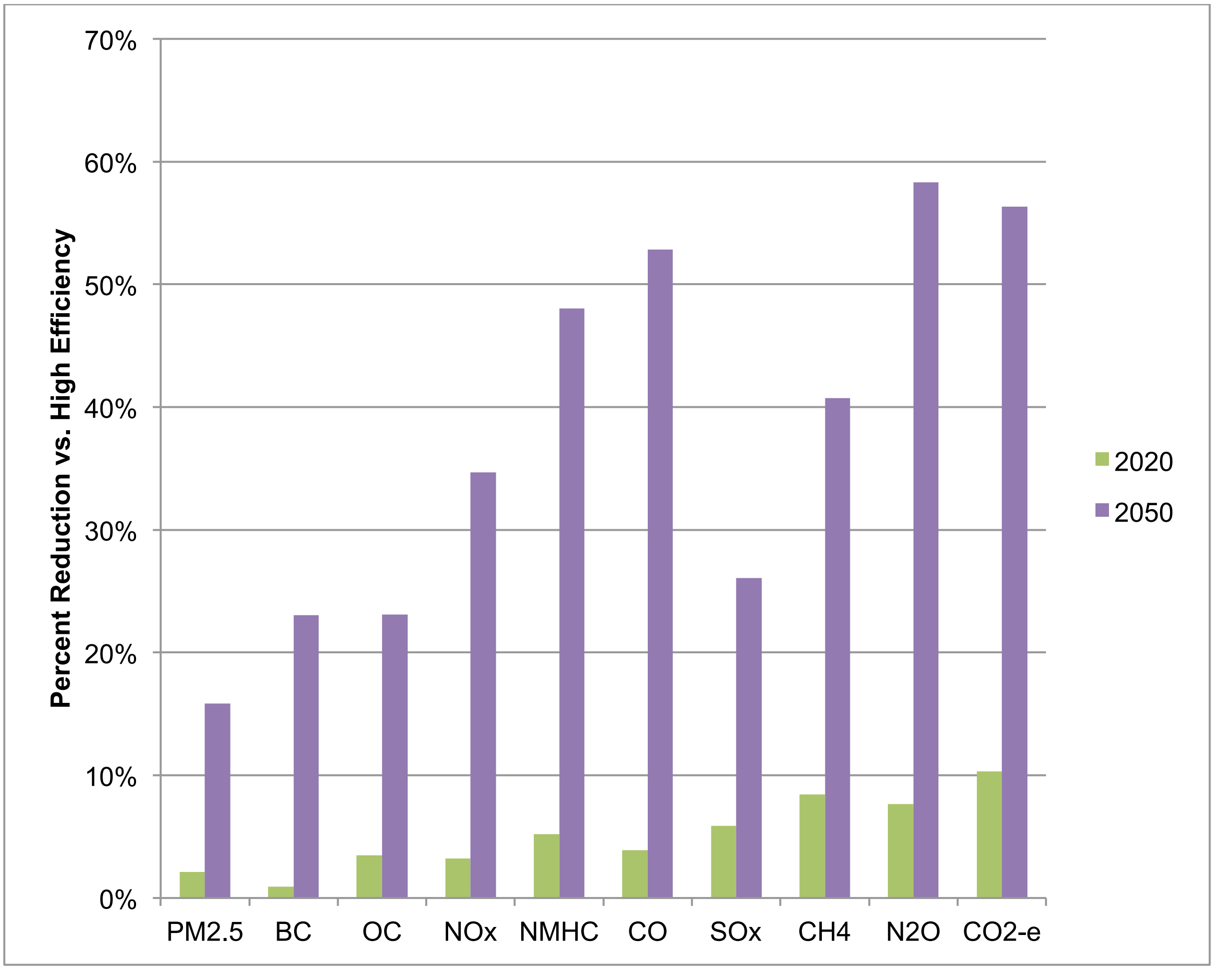

Figure 5-38: Percent reduction in annual emissions in 2020 and 2050 for the PHEVs+EVs scenario as compared to the High Efficiency scenario

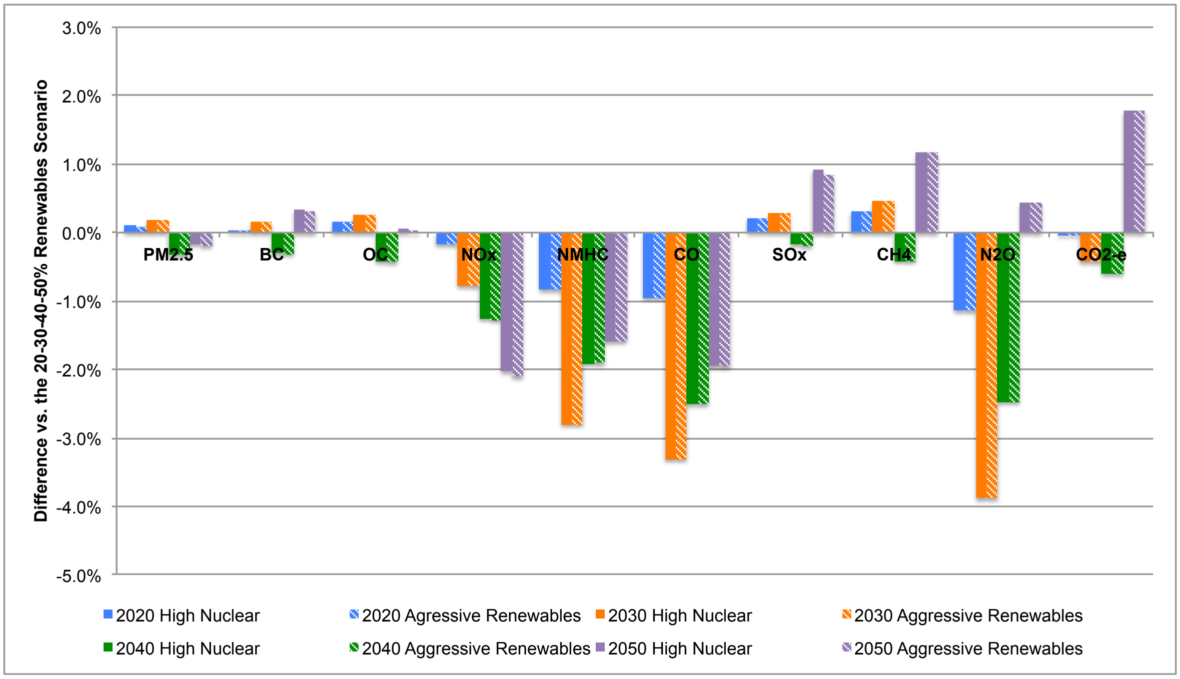

Figure 5-39: Emissions impacts of using the "High Nuclear" and "Aggressive Renewables" electricity scenarios

5.4.3 Fuel Use Results

The fuel use totals for the PHEVs+EVs scenario are shown in Figure 5-40. The fuel savings of this scenario compared to the Baseline are larger than those of the High Efficiency scenario. Also, another difference from the High Efficiency scenario is that the mix of fuels is different, as NG is largely phased out, and grid electricity use increases to 2.6 billion kWh (~ 64 million diesel equivalent gallons). In 2050, total fuel use is reduced by 67% and 41% compared to the Baseline and High Efficiency scenarios respectively.

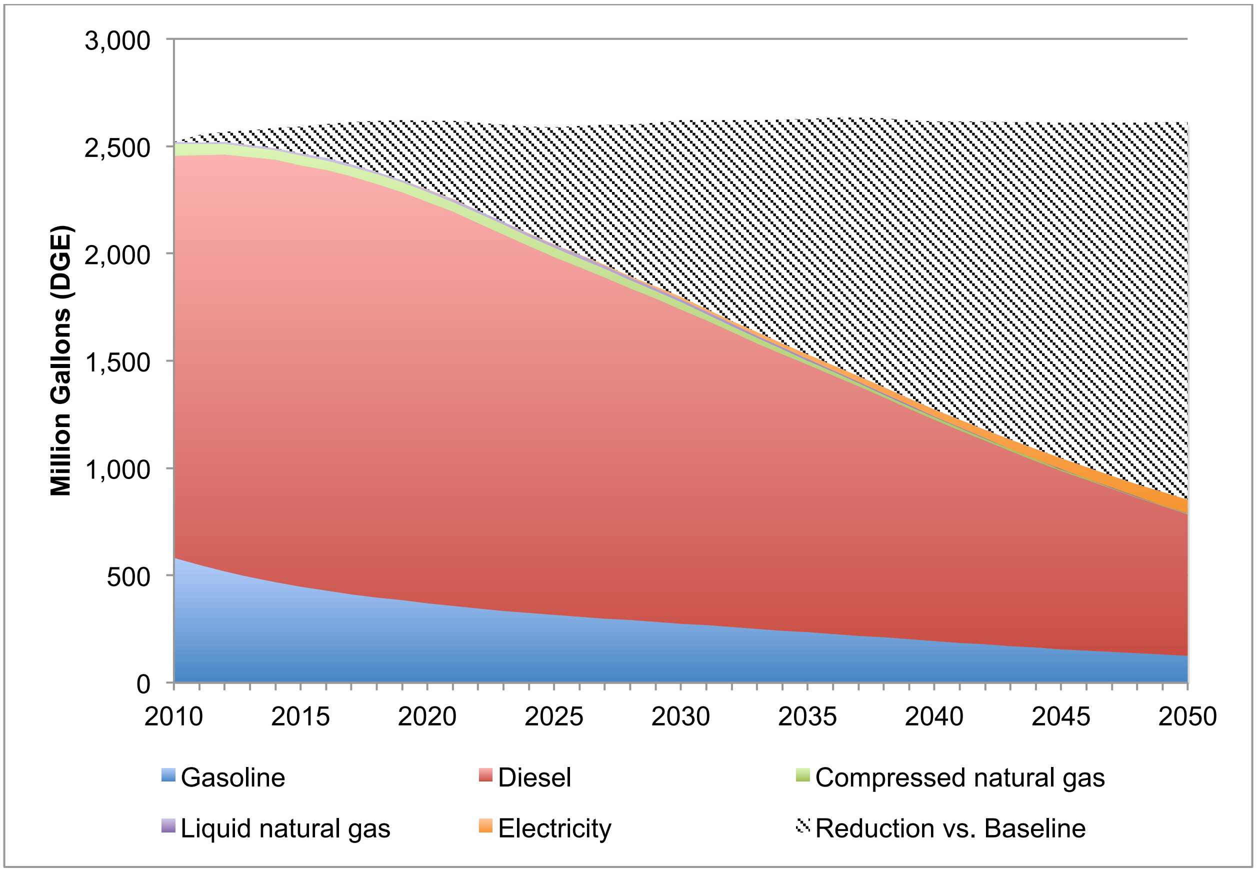

Figure 5-40: Fuel use trends of the PHEVs+EVs scenario (million diesel gallon equivalents)

5.4.4 Cost Results

The cost totals of the PHEVs+EVs and the previous two scenarios are shown in Figure 5-41. The total costs in this scenario grow slower than both the Baseline and High Efficiency scenarios and increase at an average annual growth rate of 0.6%—from $19.2 billion in 2010 to $24.3 billion in 2050. The NPV (NPV) of the PHEVs+EVs scenario cost stream is $625 billion, which is 6.3% lower than the Baseline NPV and nearly identical to the NPV of the High Efficiency scenario, which is $627 billion.

As shown in the cost breakdown summary over time, Figure 5-42, vehicle retail costs, fuel costs, and maintenance and repair costs make up the majority of the total, as in the previous two scenarios. Compared to the High Efficiency scenario, the decrease in costs in the later years of the study period is primary due to the increasing market share of PHEVs and EVs, which provide fuel cost savings compared to conventional vehicles and charge-sustaining hybrids. Generally, as the degree of electrification increases on a vehicle, the total fuel costs per unit mile (or hour) decrease.

As shown in Figure 5-43 and Figure 5-44, depending on the vehicle type, the initial purchase price premium for a PHEV ranges from 50 to 120% higher than a conventional diesel, and for EVs, this range is 150 to 280%. As cumulative production of PHEVs and EVs grows over the study period, purchase prices fall according to the rate of adoption for each individual vehicle category. For PHEVs and EVs, cost reductions generally commence in between 2025 and 2035 and reach the price floor between 2030 and 2040. Values of 1.0 and 1.2 are used as the price floor for EVs and PHEVs respectively. As described in Section 2.1.6, PHEVs are the more difficult to design than both HEVs and EVs due to the fact that, in effect, PHEVs function as both a HEV and an EV. Based on the inherent design complexities of PHEVs and the costs posed by having both an ICE and a sizeable battery pack, it is assumed that PHEVs do not achieve the same degree of cost reductions as EVs. These price floor values for PHEVs and EVs are highly uncertain, and results are generated using various ranges for these values as part of the sensitivity analysis (see Section 5.8).

The differences in costs between the PHEVs+EVs and Baseline scenarios are shown in Figure 5-45. The fuel savings benefits accelerate at a faster pace than the increased retail costs, and by 2050 the absolute value of fuel savings is larger than the increased retail costs by a factor of nearly three-to-one.

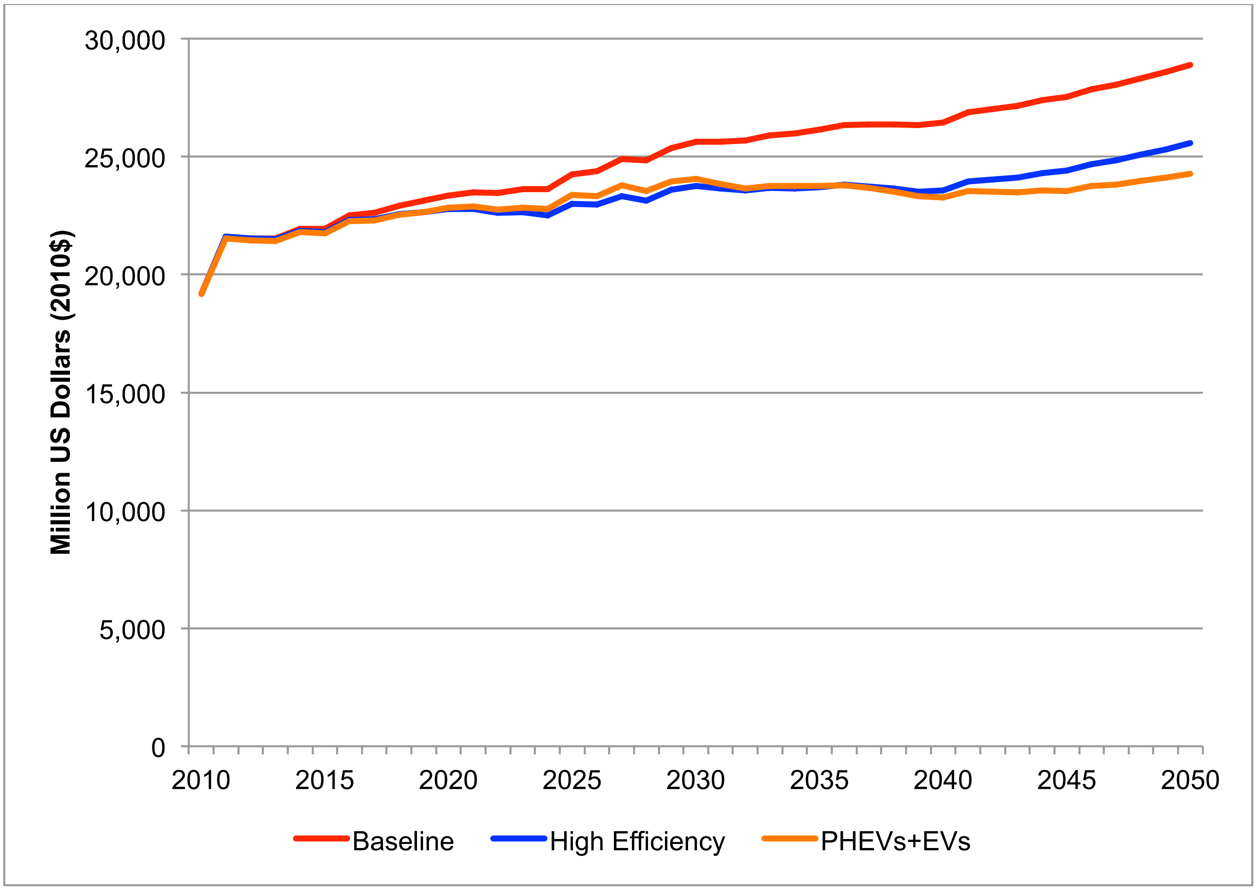

Figure 5-41: Total lifecycle costs of the PHEVs+EVs, High Efficiency, and Baseline scenarios

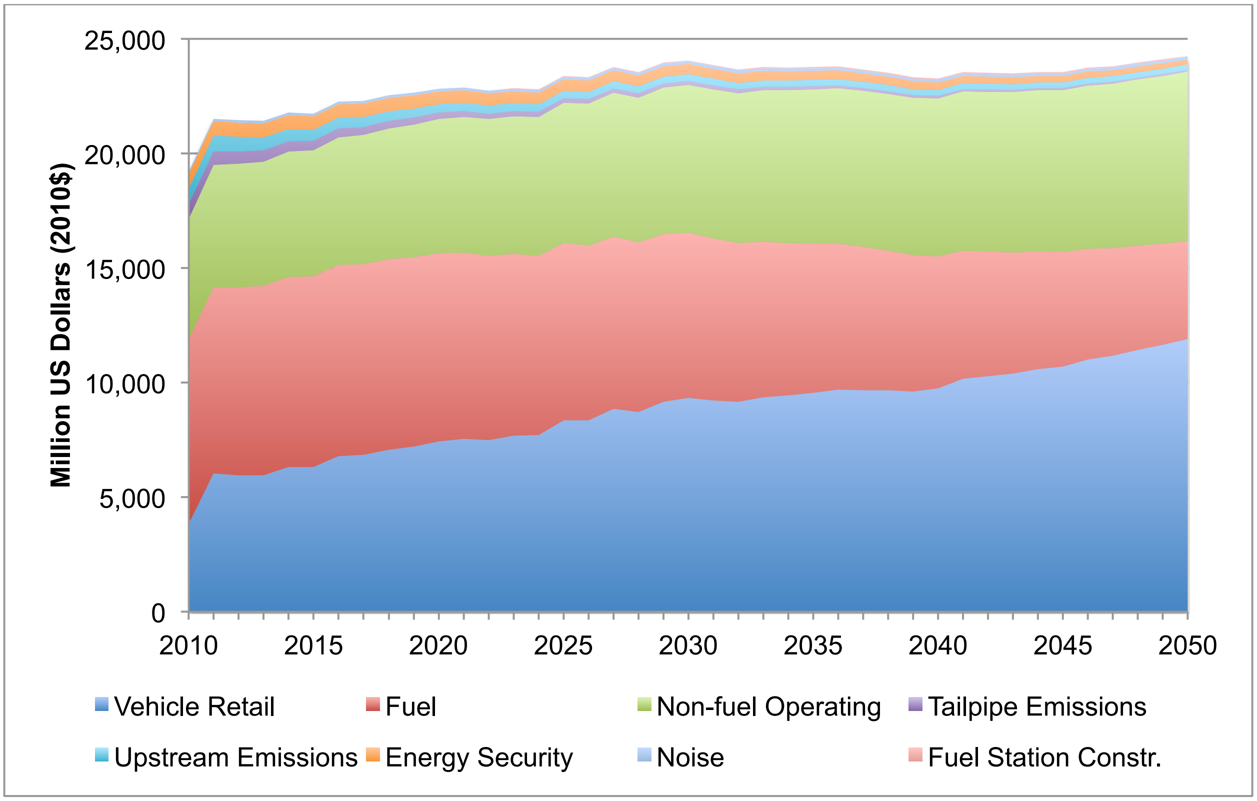

Figure 5-42: Total costs breakdown for the PHEVs+EVs scenario

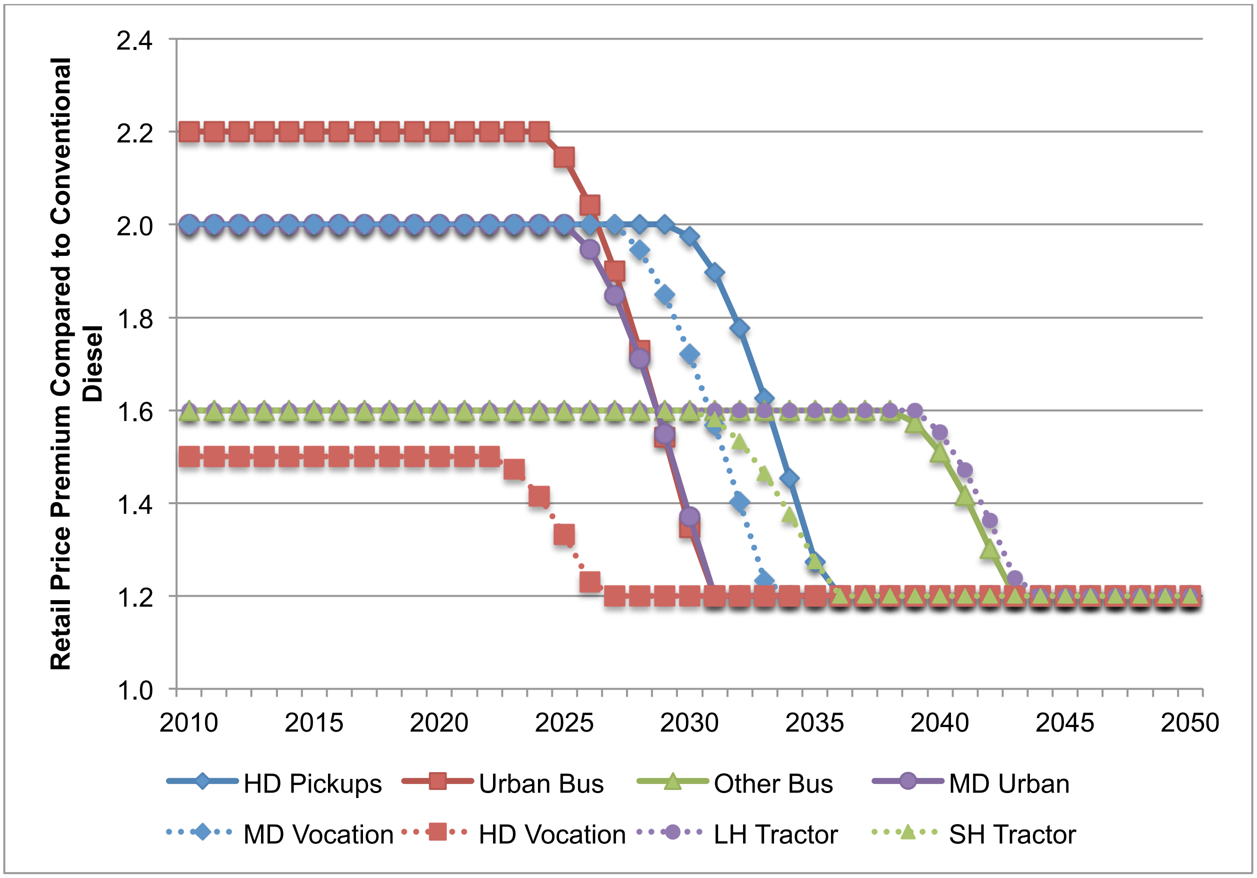

Figure 5-43: Retail price premiums for diesel plug-in hybrids in the PHEVs+EVs scenario

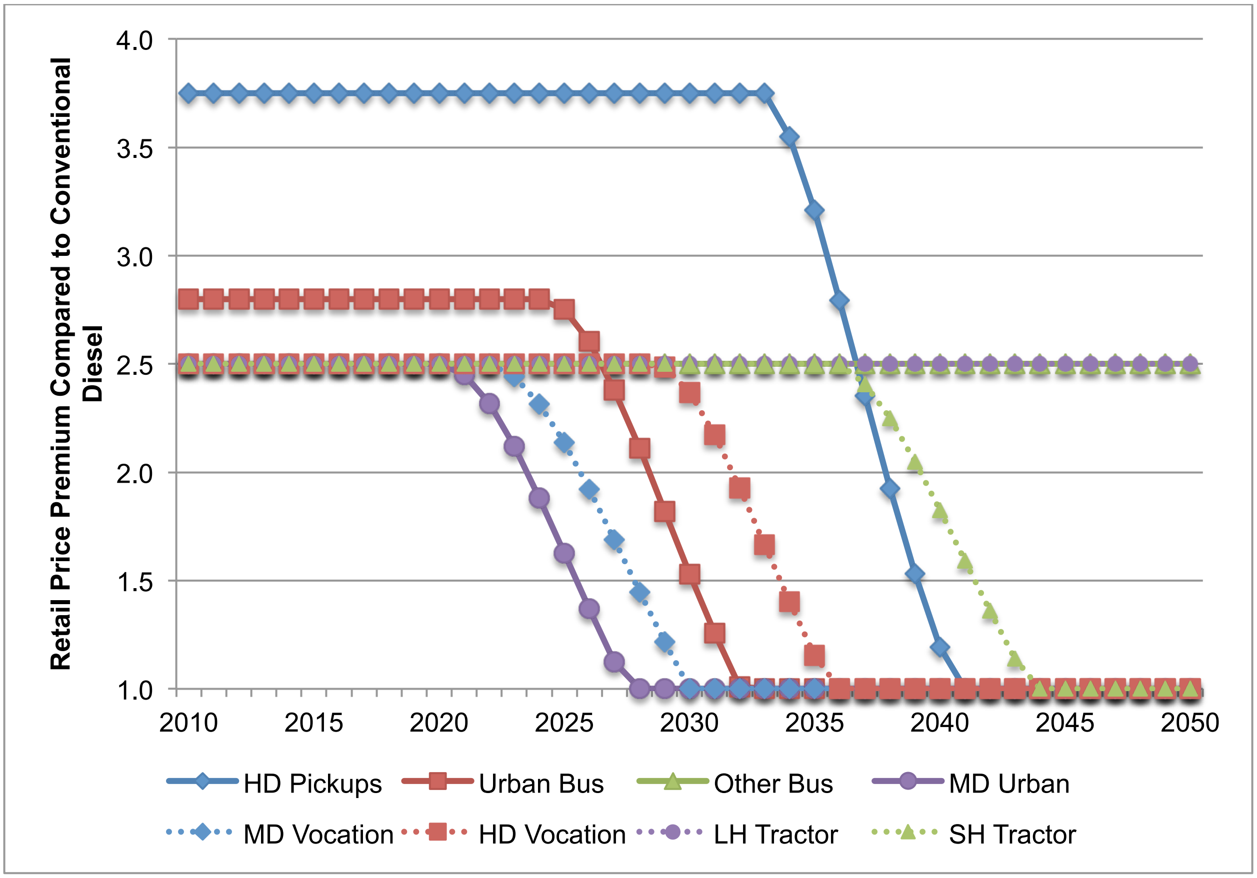

Figure 5-44: Retail price premiums for full electric vehicles in the PHEVs+EVs scenario

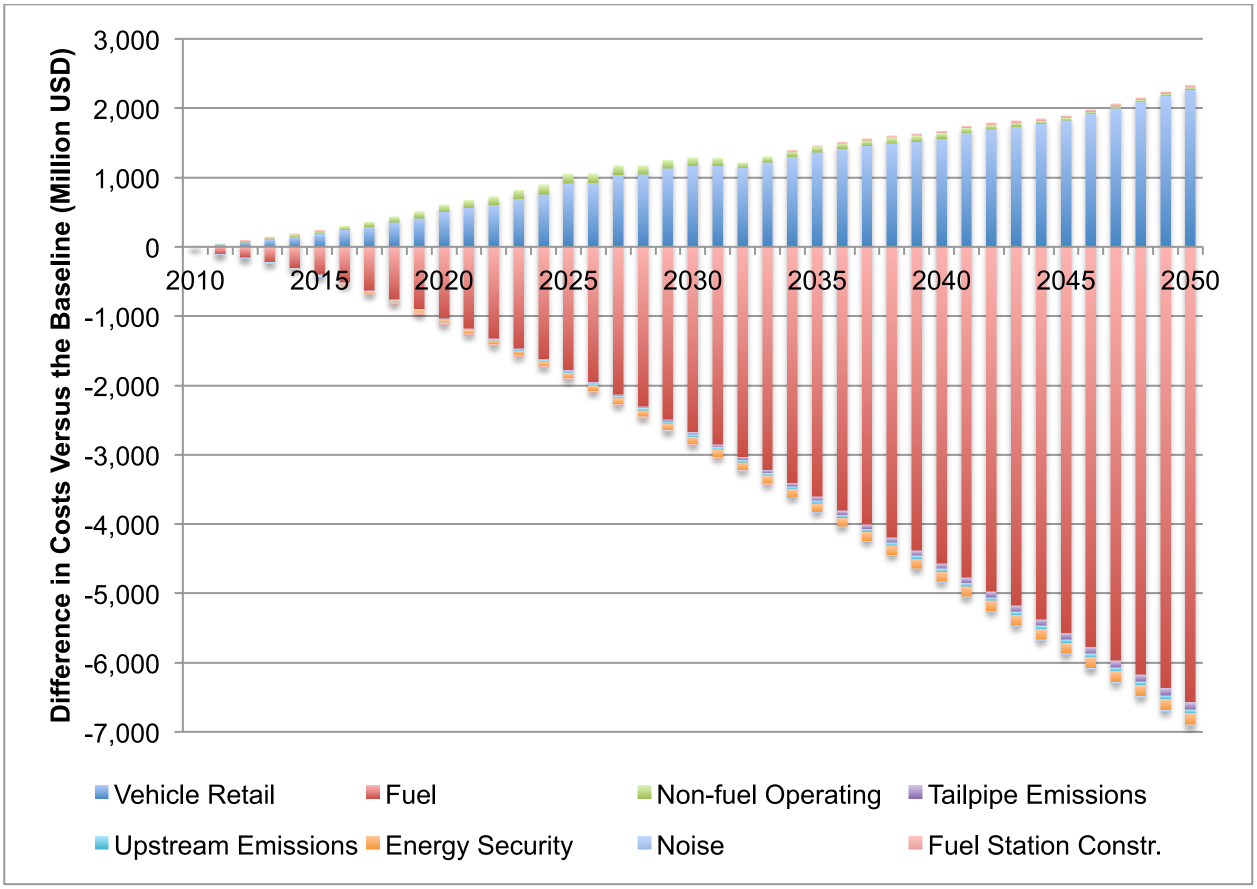

Figure 5-45: Cost differences between the PHEVs+EVs and Baseline scenarios (positive values imply costs larger than the Baseline, negative values the inverse)

5.5 Fuel Cell Vehicles (FCVs) Scenario

The FCVs scenario is a vision of the future for California HD trucks and buses in which there is a rapid acceleration of hydrogen fuel cell vehicle adoption. As before, vehicle categories such as transit buses and other urban return-to-base vehicles are the initial uptake applications for this technology. In the later years in the study period, fuel cell vehicles are widely adopted across all vehicle categories. Natural gas vehicles are fully replaced by FCVs by the 2030-2035 timeframe. Hybrids make up a substantial part of the market share in the early part of the study period but are phased out for FCVs over time.

5.5.1 Fuel and technology evolution

In the FCVs scenario, the transformation of the HD fleet is very similar to that of the PHEVs+EVs scenario, except that FCVs enter the market *en masse* instead of PHEVs and EVs. Conventional vehicles lose market share at an identical rate as in the PHEVs+EVs scenario, and NG vehicles are limited to the Urban Bus and HD Vocational Vehicle categories and are phased-out over the first half of the study period. As with the previous two scenarios, new vehicle fuel consumption is also assumed to decrease by 2-4% per year as a result of stringent vehicle fuel efficiency performance standards and other policy measures. The new vehicle market share assumptions for the FCVs scenario are summarized in Table 5-14 and depicted graphically in Figure 5-46 though Figure 5-50.

All fuel cell vehicles in this scenario are assumed to have hybridized drivetrains in order to recapture braking energy and use the fuel cell in high-efficiency regimes as much as possible. The marginal fuel savings benefits of hybridization for fuel cell vehicles are assumed to be similar to the benefits of hybridizing conventional diesel and gasoline vehicles. For all eight vehicle types, the reduction in per-mile fuel consumption of hybrid fuel cell vehicles compared to non-hybrid fuel cell vehicles is given in Table 5-13 and is based on [211] for Urban Buses and estimates for the other seven vehicle categories.

Table 5-13: Per-mile fuel consumption of hybrid FCVs as compared to non-hybrid FCVs

HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
85%	80%	90%	80%	80%	80%	95%	90%

Onboard storage of hydrogen is similar to the case of NG vehicles in that hydrogen can be carried onboard as a compressed gas or as a liquefied cryogenic fuel. For HD vehicles that require longer range capabilities, liquid hydrogen is the preferred onboard storage method. Within each of the eight vehicle categories, the assumed percentage of vehicles that carry hydrogen as a liquid fuel is identical to the percentage for NG vehicles (see Section 0). The assumed split between electric and hydraulic hybrids is the same as in the previous three scenarios.

Table 5-14: Market share controls for the FCVs scenario

	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
Adoption Controls								
Initial yr. of AV adoption	2020	2011	2020	2015	2015	2011	2020	2015
Pivot year 1	2030	2020	2030	2025	2025	2025	2030	2030
Pivot year 2	2040	2031	2040	2025	2025	2036	2040	2040
Conv. Vehicle Change in Market Share								
Period 1 annual change in MS (percentage)	-3%	-5%	-3%	-3%	-3%	-3%	-3%	-3%
Period 2 annual change in MS (percentage)	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%
Period 3 annual change in MS (percentage)	-15%	-15%	-15%	-15%	-15%	-15%	-15%	-15%
Natural Gas Controls								
Initial % of AV market	0%	50%	0%	0%	50%	50%	0%	0%
Period 1 annual change in MS (percentage points)	0%	-2.5%	0%	0%	0%	-2%	0%	0%
Period 2 annual change in MS (percentage points)	0%	-2.5%	0%	0%	0%	-2%	0%	0%
Period 3 annual change in MS (percentage points)	0%	0%	0%	0%	0%	0%	0%	0%
Hybrid Controls								
Initial % of AV market	100%	50%	100%	100%	100%	50%	100%	100%
Period 1 annual change in MS (percentage points)	-1%	1.5%	-1%	-2%	-2%	1%	-1%	-1%
Period 2 annual change in MS (percentage points)	-2%	-1%	-2%	-2%	-2%	-1%	-2%	-2%
Period 3 annual change in MS (percentage points)	-2%	-3%	-2%	-2%	-2%	-2%	-2%	-2%
FCV Controls								
Initial % of AV market	0%	0%	0%	0%	0%	0%	0%	0%

	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
Period 1 annual change in MS (percentage points)	1%	1%	1%	2%	2%	1%	1%	1%
Period 2 annual change in MS (percentage points)	2%	3.5%	2%	2%	2%	3%	2%	2%
Period 3 annual change in MS (percentage points)	2%	3%	2%	2%	2%	2%	2%	2%

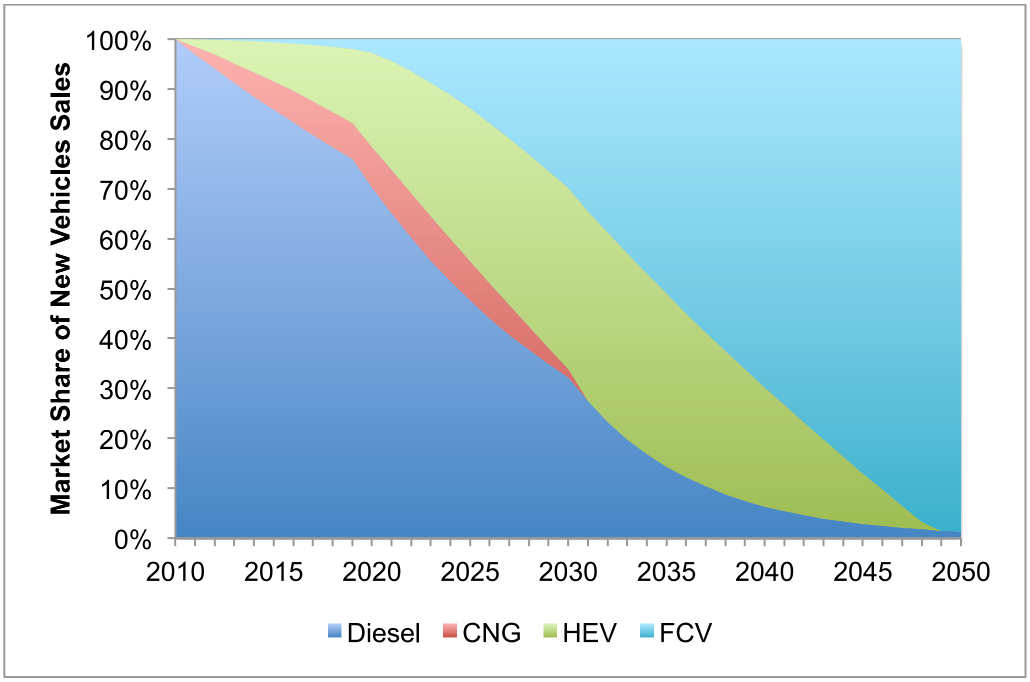

Figure 5-46: Urban Bus new vehicle market share in the FCVs scenario

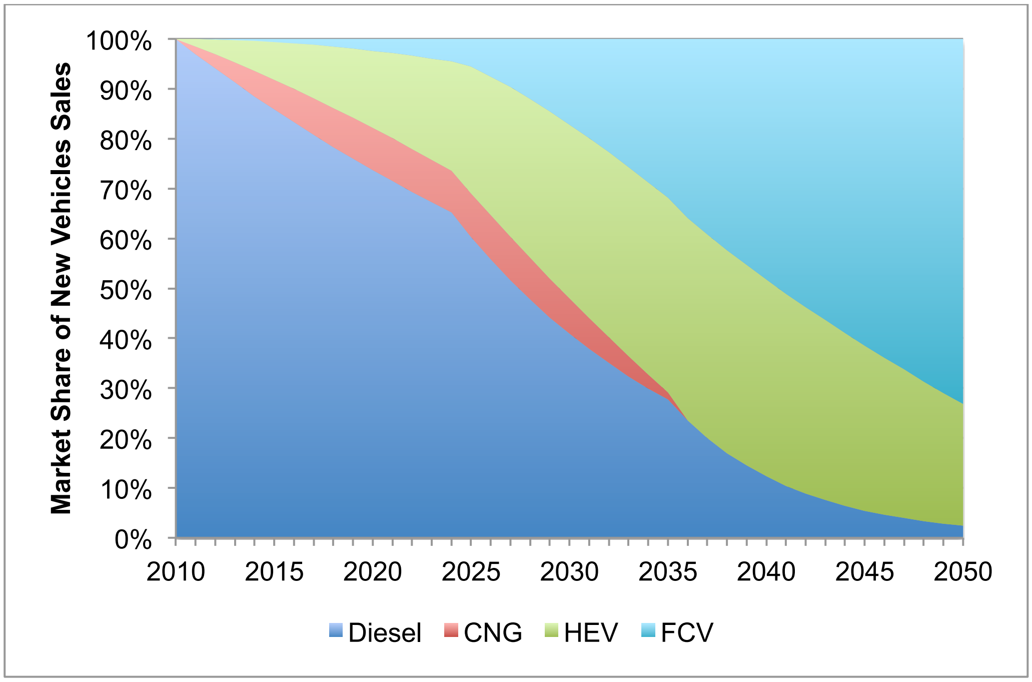

Figure 5-47: HD Vocational Vehicle new vehicle market share in the FCVs scenario

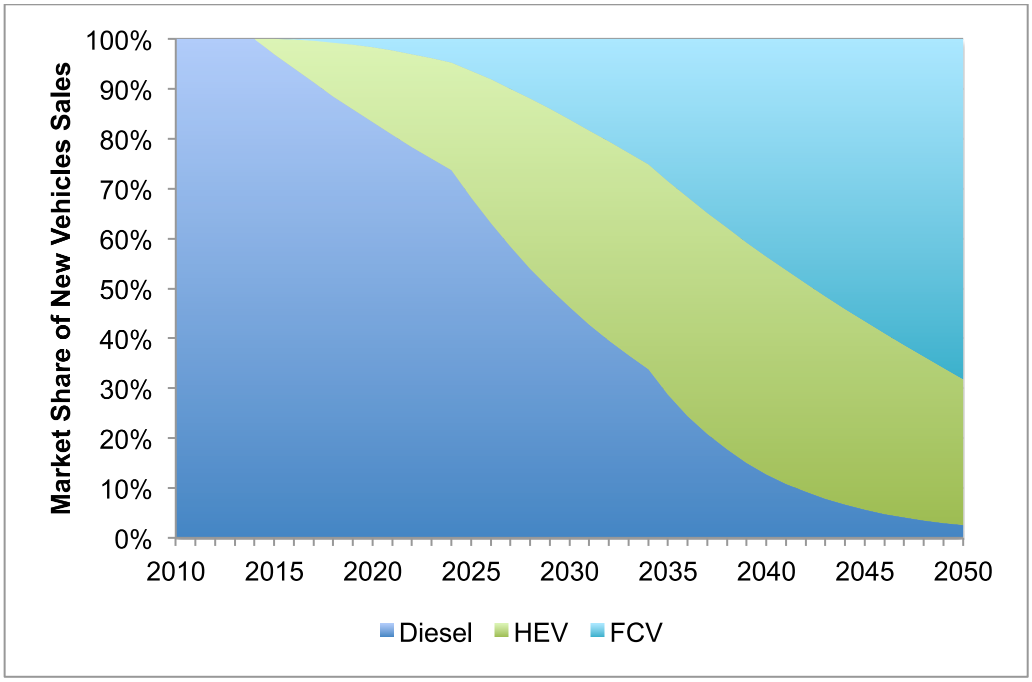

Figure 5-48: MD Urban and MD Vocational Vehicle new vehicle market share in the FCVs scenario

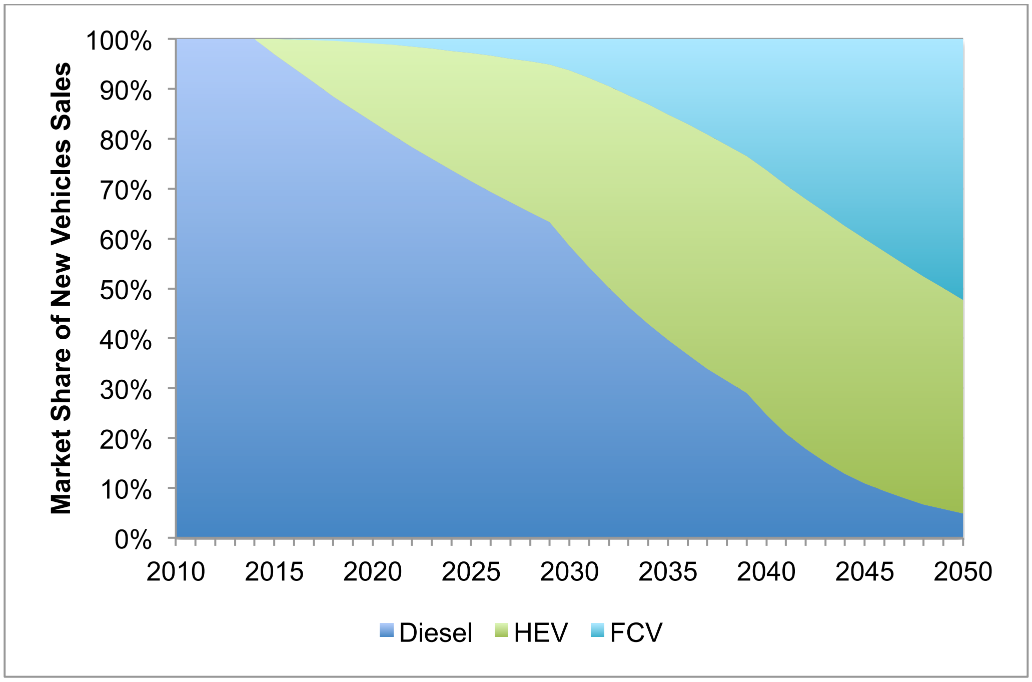

Figure 5-49: SH Tractor new vehicle market share in the FCVs scenario

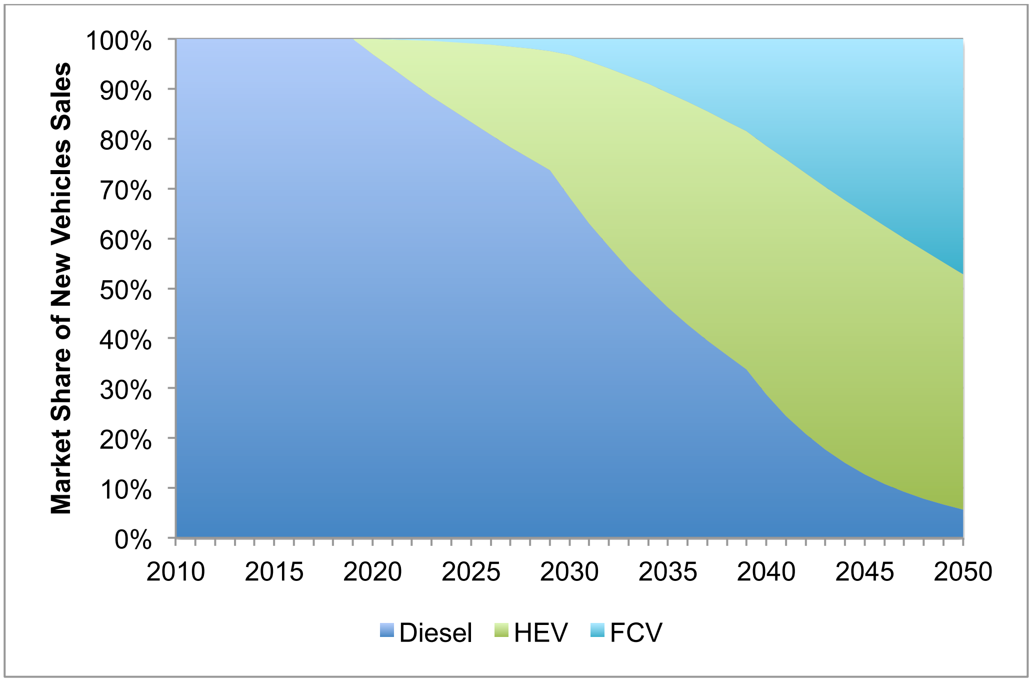

Figure 5-50: HD Pickup, Other Bus, and LH Tractor new vehicle market share in the High Efficiency scenario

5.5.2 Emission Results

As with the previous scenarios, the emissions levels over time for the FCVs scenario are driven downward as a result of gradual fleet renewal, a decrease in per-mile emission factors of 2% per year, and declining emission rates from upstream processes. In general, the emissions totals over time follow similar trends of the High Efficiency and PHEVs+EVs scenarios. The annual emission reductions in 2020 and 2050 as compared to the Baseline and High Efficiency scenarios are shown in Figure 5-51 and Figure 5-52. As compared to the High Efficiency scenario—which has identical assumptions for the rate of fleet turnover and per-mile emission factor reductions—there are emission reduction benefits in 2050 for all of the pollutant species except for SOx and CH_4, which increase by 1% and 40% respectively. This increase in SOx and

CH_4 is due to two factors: 1) relatively large fuel upstream EFs (i.e. grams of pollutant per MMBtu of fuel delivered to the end user) for hydrogen compared conventional diesel or gasoline (see Table 5-15), and 2) fuel upstream emissions representing a large percentage of total emissions for both SOx and CH_4. The lifecycle emissions breakdowns for these two pollutants in Figure 5-53 and Figure 5-54 reveal that a marginal increase in fuel upstream emissions is much more impactful to total emissions for CH_4 compared to SOx. In 2050, emissions due to fuel production and distribution represent 86% and 52% of total CH_4 and SOx emissions respectively.

Even as FCVs capture an increasing share of the market, Figure 5-56 and Figure 5-57 show that conventional vehicles and hybrids make up a large percentage of total CO_2e emissions. In 2050, vehicle tailpipe emissions—that is, emissions from non-FCVs—represent just over half of total CO_2e emissions. Accounting for all four lifecycle phases (emission from vehicle operations, fuel upstream processes, manufacturing, and scrappage), conventional vehicles and hybrids are responsible for nearly three-quarters of CO_2e emissions. In 2050, fuel cell vehicles account for 41% of total VMT and 23% of lifecycle CO_2e emissions.

As with electricity, hydrogen is an energy carrier that can be produced from a variety of different feedstocks and by using a number of different methods. The four feedstock and delivered fuel (i.e. gaseous or liquefied fuel) combinations for hydrogen that can be modeled in TOP-HDV are listed in the left-hand column of Table 5-15. The conventional method for producing hydrogen from NG is to reform the methane using steam at high temperatures, which ultimately produces both carbon dioxide and hydrogen. Water is the other hydrogen feedstock option that is available in the model. Water can be transformed into hydrogen and oxygen by passing an electrical current through the water in a process called electrolysis.

The results shown in Figure 5-51 and Figure 5-52 represent a future in which hydrogen production shifts entirely from steam methane reformation to water electrolysis according to the *High Electrolysis* scenario in Table 5-16. Assuming that steam methane reformation is the sole method of producing hydrogen over the study period (*Steam Methane Reformation* scenario) changes emissions significantly. As shown in Figure 5-55, the choice of NG as a feedstock for hydrogen results in increased emissions for all pollutants except CH_4. This is wholly a function of the fuel upstream EF for electrolysis being larger than that of steam methane reformation in the case of CH_4 (see Table 5-15).

Table 5-15: Ratio of hydrogen upstream EFs to conventional diesel upstream EFs

Hydrogen Pathway	CH4				SOx			
	2020	2030	2040	2050	2020	2030	2040	2050
NG to CH_2	2.0	2.0	1.9	1.9	1.6	1.8	2.5	2.3
Water to CH_2	2.6	2.8	3.1	3.4	1.0	1.1	1.3	1.2
NG to LH_2	2.2	2.1	2.2	2.2	4.0	4.8	6.7	6.3
Water to LH_2	2.8	3.0	3.4	3.7	3.4	3.9	4.4	4.2

Table 5-16: Two feedstock scenarios for hydrogen production

H_2 Production Scenario	2010-2020		2021-2030		2031-2040		2041-2050	
	NG	H_2O	NG	H_2O	NG	H_2O	NG	H_2O
High Electrolysis	100%	0%	67%	33%	33%	67%	0%	100%
Steam Methane Reformation	100%	0%	100%	0%	100%	0%	100%	0%

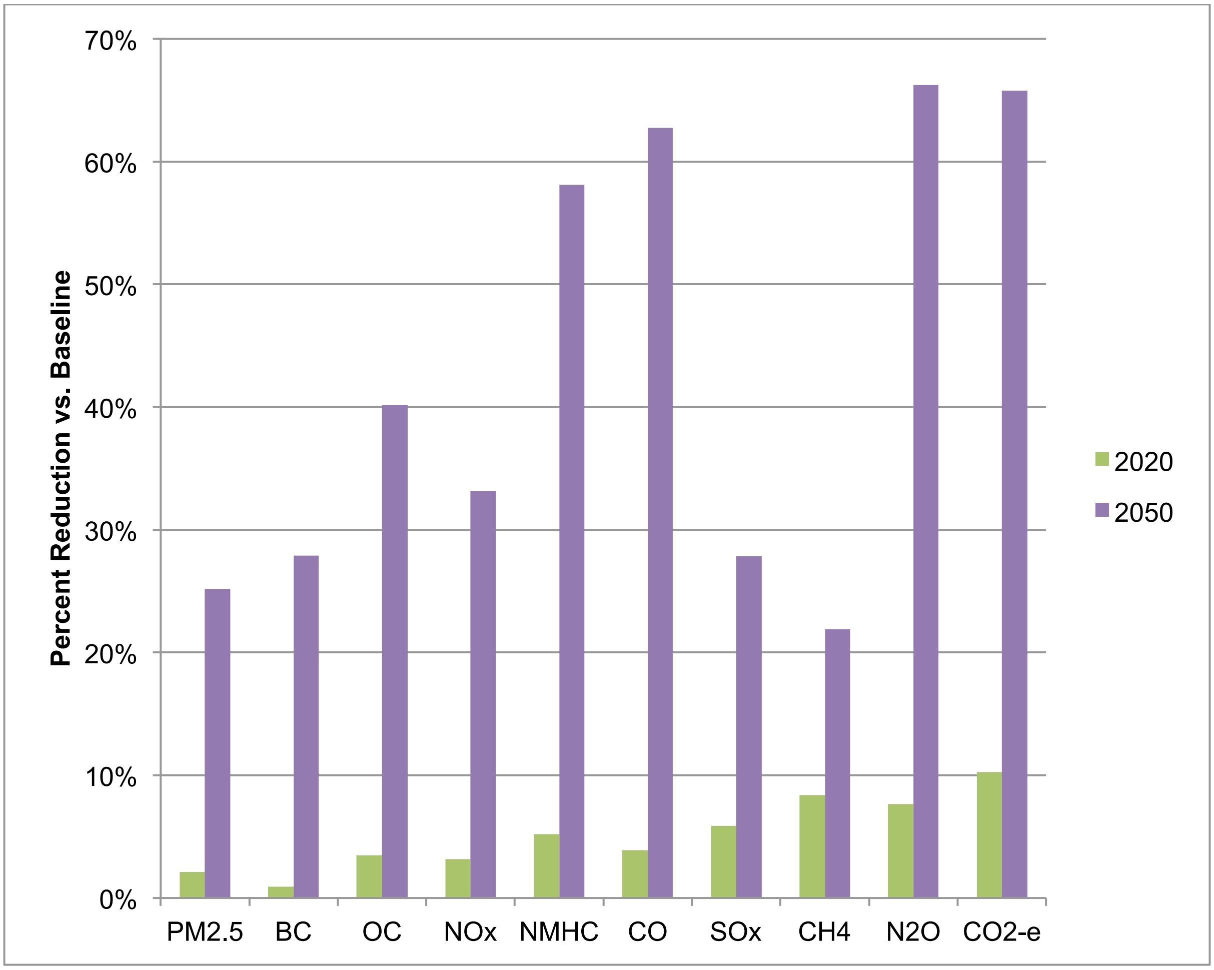

Figure 5-51: Percent reduction in annual emissions in 2020 and 2050 for the FCVs scenario as compared to the Baseline

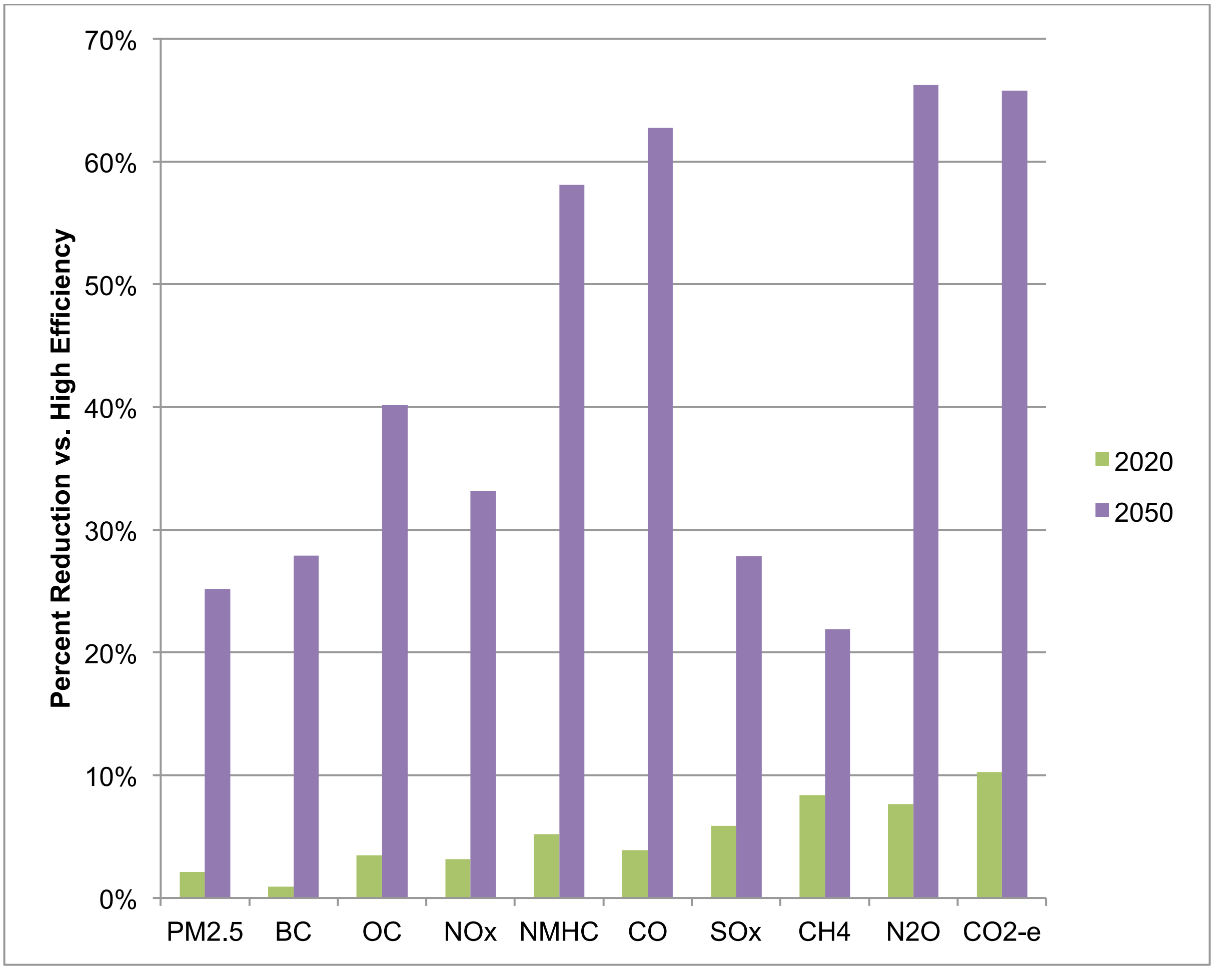

Figure 5-52: Percent reduction in annual emissions in 2020 and 2050 for the FCVs scenario as compared to the High Efficiency scenario

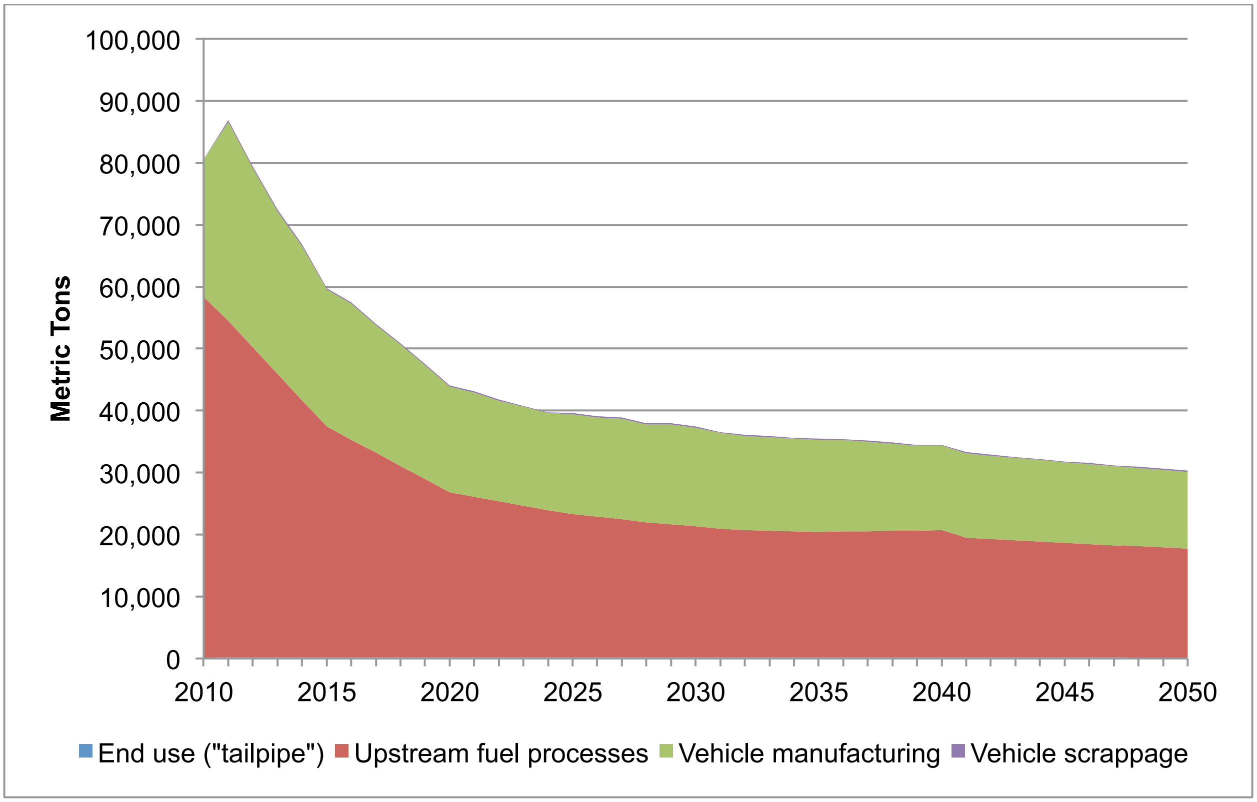

Figure 5-53: CH_4 emissions by lifecycle phase in the FCVs scenario

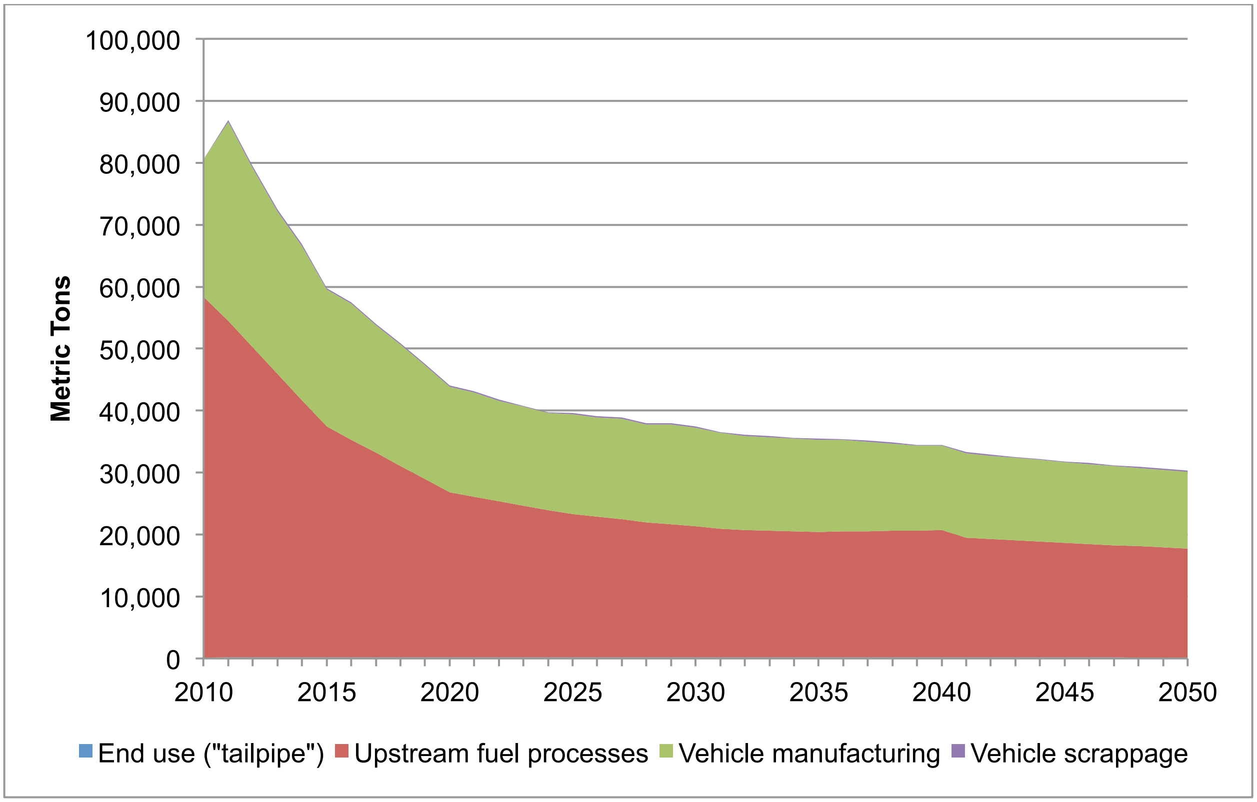

Figure 5-54: SOx emissions by lifecycle phase in the FCVs scenario

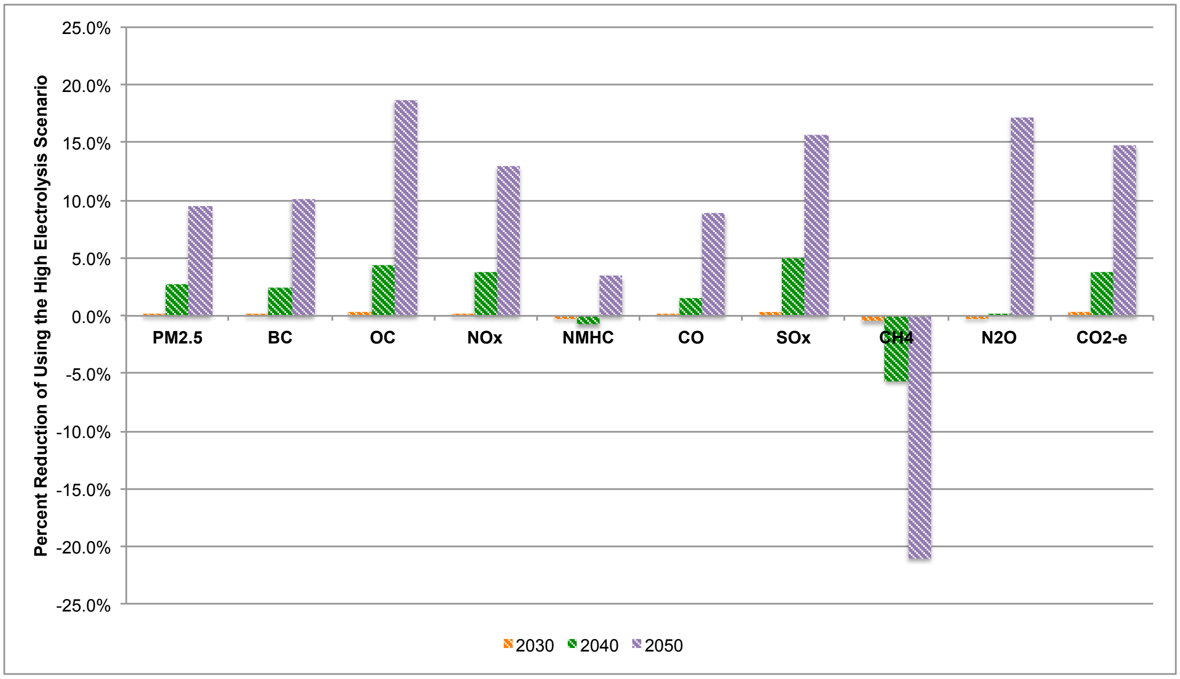

Figure 5-55: Percent reduction in emissions from using the *High Electrolysis* hydrogen production scenario

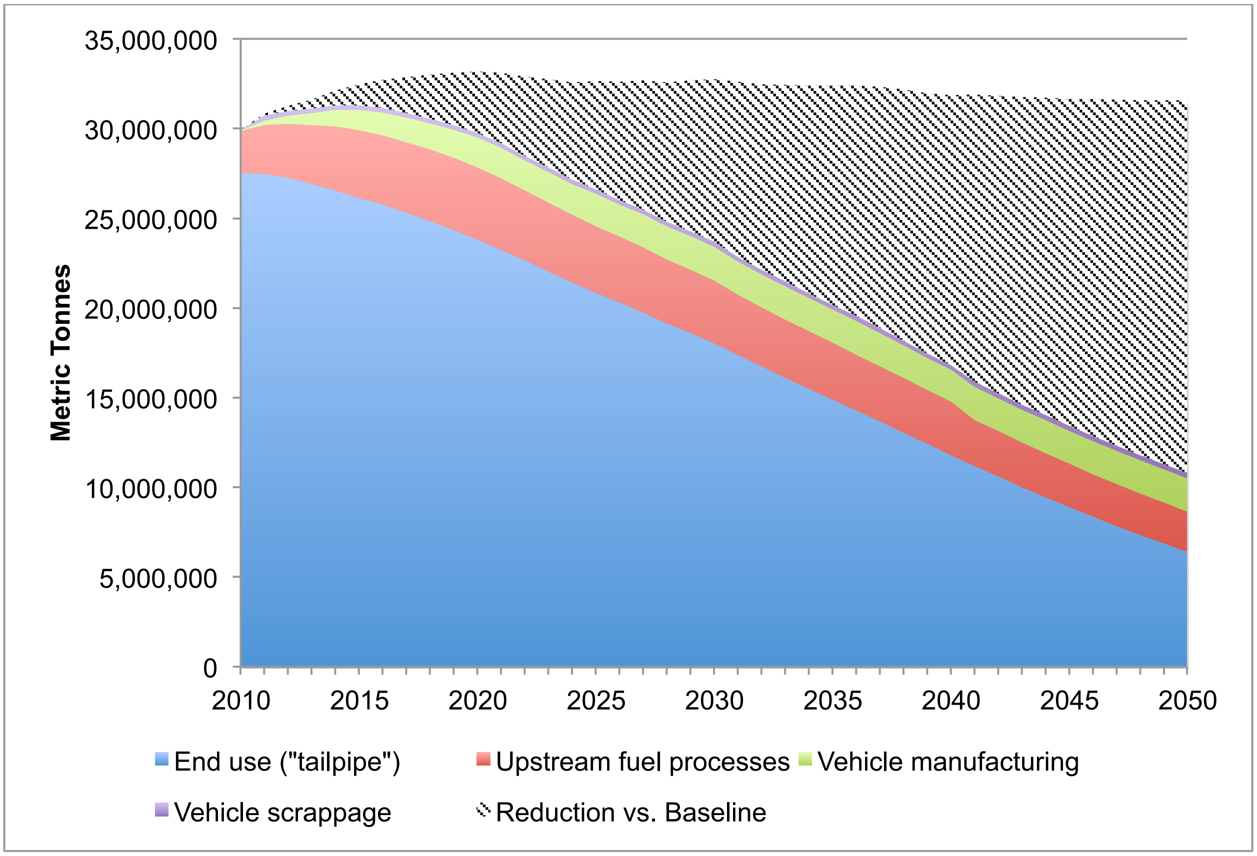

Figure 5-56: CO_2e emissions by lifecycle phase in the FCVs scenario

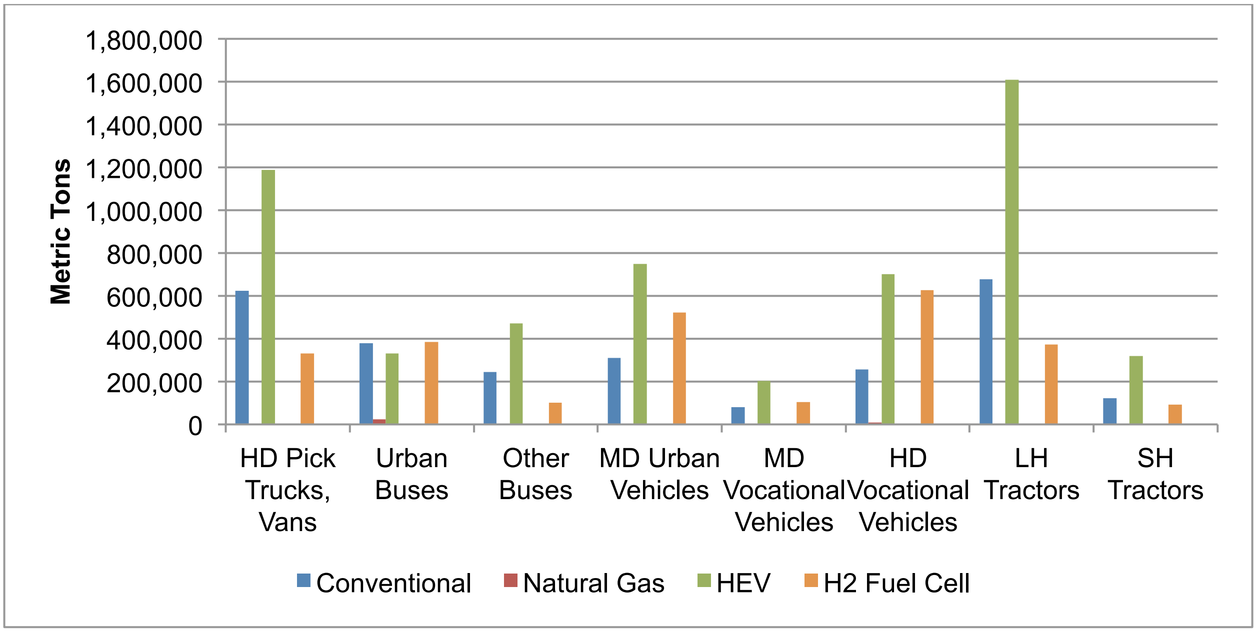

Figure 5-57: CO_2e emissions by vehicle technology type in 2050 in the FCVs scenario

5.5.3 Fuel Use Results

The diesel gallon equivalent fuel use totals for the FCVs scenario are shown in Figure 5-58. In 2050, the total fuel use is 68%, 29%, and 1% less than the Baseline, High Efficiency, and PHEVs+EVs scenarios respectively. Compared to the High Efficiency scenario (which has identical phase-out rates of conventional vehicles), the sizeable decrease in fuel use is primarily due to the rapid replacement of hybrids with fuel cell vehicles in the post-2025 timeframe. By 2050, the total hydrogen consumed is 266 million kilograms, which equates to approximately 200 million diesel equivalent gallons.

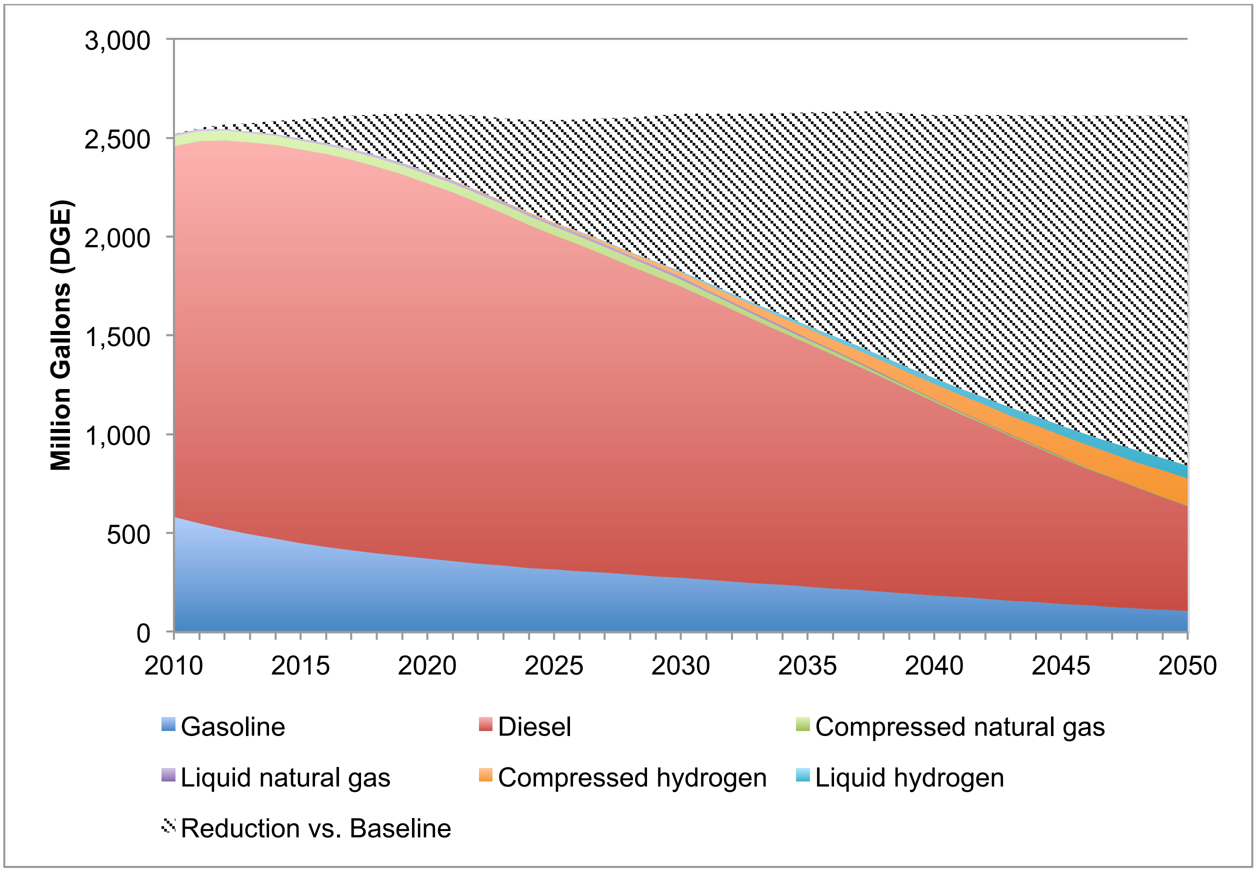

Figure 5-58: Fuel use trends of the FCVs scenario (million diesel gallon equivalents)

5.5.4 Cost Results

The cost totals of the FCVs as well as the Baseline and High Efficiency scenarios are shown in Figure 5-59. The total costs (in 2010$) in the FCVs scenario grow at an annual rate of 1.1% in the first 20 years of the study period. After this period of growth, costs decrease gradually at an average annual reduction of 0.3%. The NPV (NPV) of the FCVs scenario cost stream is $618 billion, which is 7% lower than the Baseline scenario and roughly 1% lower than both the High Efficiency and PHEVs+EVs scenarios.

As shown in the cost breakdown summary over time, Figure 5-60, vehicle retail costs, fuel costs, and non-fuel operating costs make up the majority of the total, as with the previous three scenarios. Compared to the previous scenarios, the gradual swell in retail costs during the first half of the study period is a function of the accelerated adoption of fuel cell vehicles, which are initially more expensive on a per-vehicle basis, both in terms of purchase prices and operational costs. With the exception of the transit bus market, fuel cell technology is very nascent in the heavy-duty vehicle sector. The incremental purchase price of fuel cell trucks are estimated based on the price deltas from the fuel cell bus market [253] and an assumption that learning in the transit bus market transfers to other vehicle categories and make it such that fuel cell systems represent a smaller incremental cost in initial product offerings. As shown in Figure 5-61, the initial purchase price premium for a FCV is estimated to be three or four times the price of a conventional diesel for the non-Urban Bus vehicle categories and 5.5 times for Urban Buses.

As cumulative production of fuel cell vehicles increases steadily, per-vehicle purchases prices of the four return-to-base vehicle categories (i.e. Urban Buses, HD Vocational, MD Urban, and MD Vocational) begin to decrease around 2020, and the remaining four vehicle types begin to experience learning curve-related cost reductions between 2025 and 2030. A value of 1.0 (i.e. price parity with diesels) is used as the price floor for fuel cell vehicles based on a NAS report for the passenger vehicle sector that estimates that the long-term costs of fuel cell vehicles could become less expensive than conventional vehicles under a high volume scenario [78]. Perhaps more so than any technology modeled in TOP-HDV, the purchase costs, operational costs, and the price floor of fuel cell HD vehicles are highly uncertain. All of these parameters are varied as part of the sensitivity analysis (see Section 5.8). As shown in Figure 5-61, assuming a price floor factor of 1.0, the reduction in purchase price premiums is substantial for all eight vehicle types—on the order of a factor of three or four reduction. As fuel cell vehicles increase in market share, the increased experience with these vehicles drives down operations costs as well. Across all of the vehicle categories, fuel cell vehicles are assumed to initially have maintenance and repair costs that are 50% higher than a conventional diesel vehicle based on incremental maintenance costs reported by transit bus agencies that have operated fuel cell buses [211]. Since maintenance and repair costs are linked to the rate of change of purchase prices in the model, non-fuel operating costs decrease significantly—as with purchase prices, a factor of three or four reduction is achieved. This level of reduction drives operations costs to much lower levels than that of conventional vehicles. Compared to internal combustion engines, there are considerably less moving parts in fuel cell systems, and it is conceivable that with roughly 30+ years of in-use experience, maintenance costs for these vehicles can be roughly half that of vehicles with internal combustion engines.

The differences in costs between the FCVs and Baseline scenarios are shown in Figure 5-62. The growth in fuel savings overtakes the additional purchase costs around 2020, and from then on the fuel savings accelerate such that by 2050 the reduced fuel costs are nearly four times the size of the incremental retail costs. Operating costs are slightly higher than the Baseline in the first half of the study period, and learning effects drive down these costs over the last 20 years. By 2050, reductions in operating costs represent 12% of the overall savings of the FCVs scenario. Based on California Energy Commission projections out to 2030 [313], the retail cost (in 2010$) of hydrogen from all four pathways is assumed to be constant over the entire study period. Versus the Baseline, the cost reduction benefits from all four externalities—tailpipe and upstream emissions, energy security, and noise—grow gradually over time.

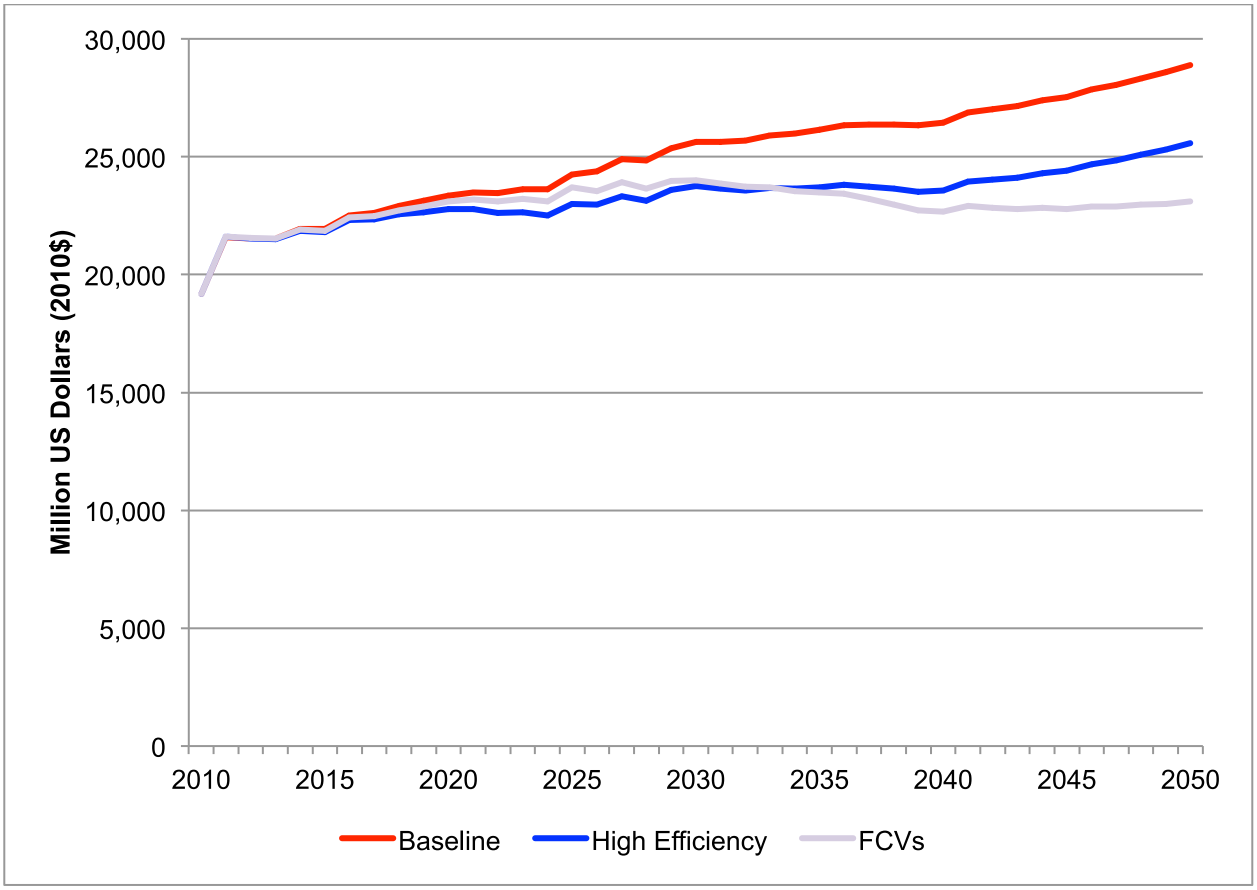

Figure 5-59: Total lifecycle costs of the FCVs, High Efficiency, and Baseline scenarios

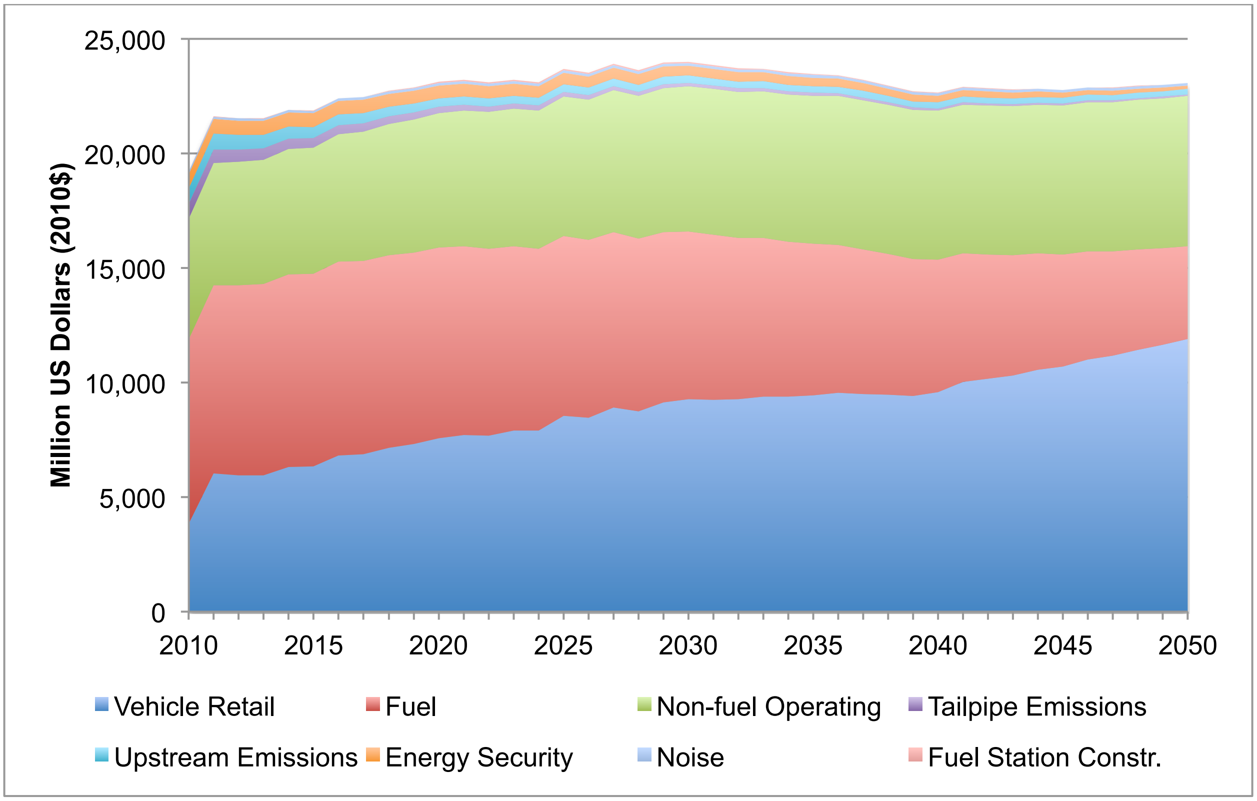

Figure 5-60: Total costs breakdown for the FCVs scenario

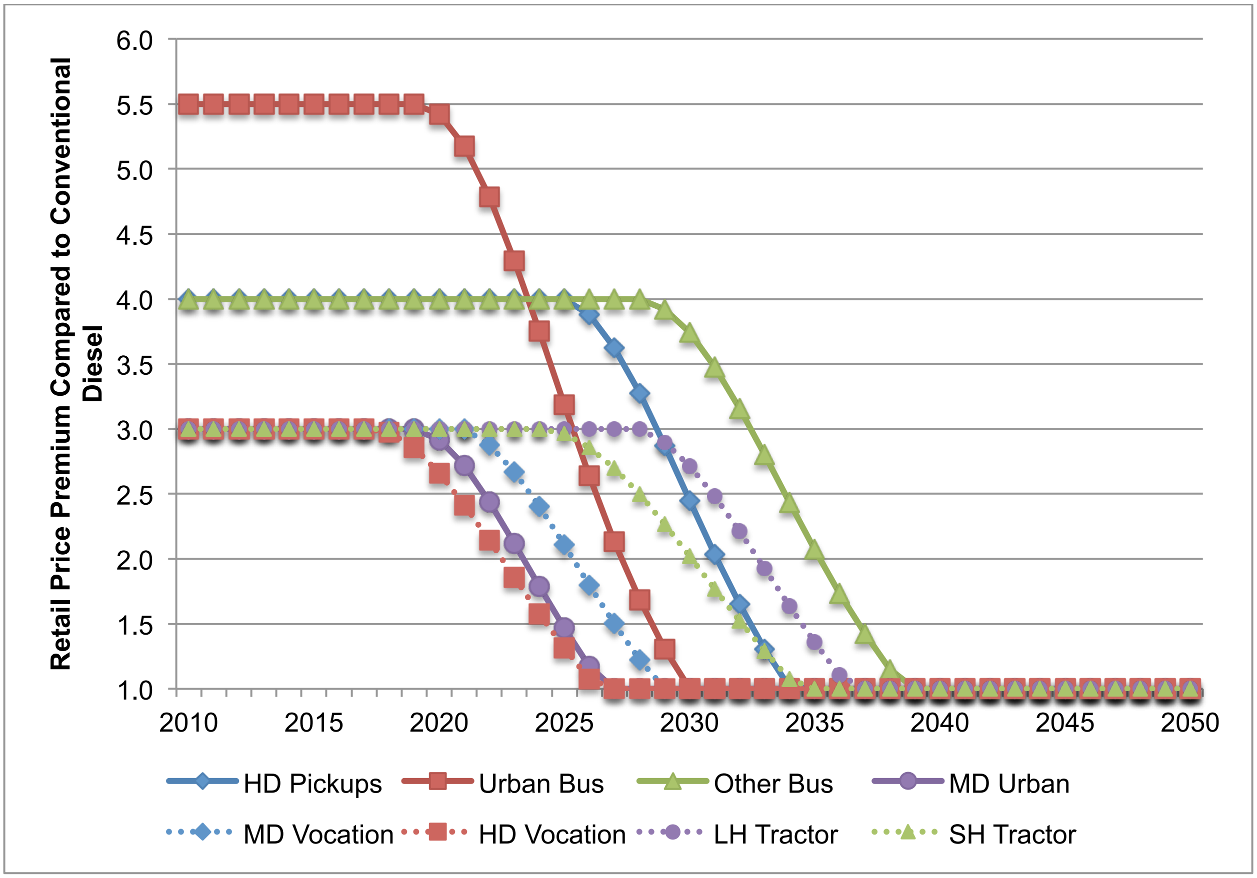

Figure 5-61: Retail price premiums for fuel cell vehicles in the FCVs scenario

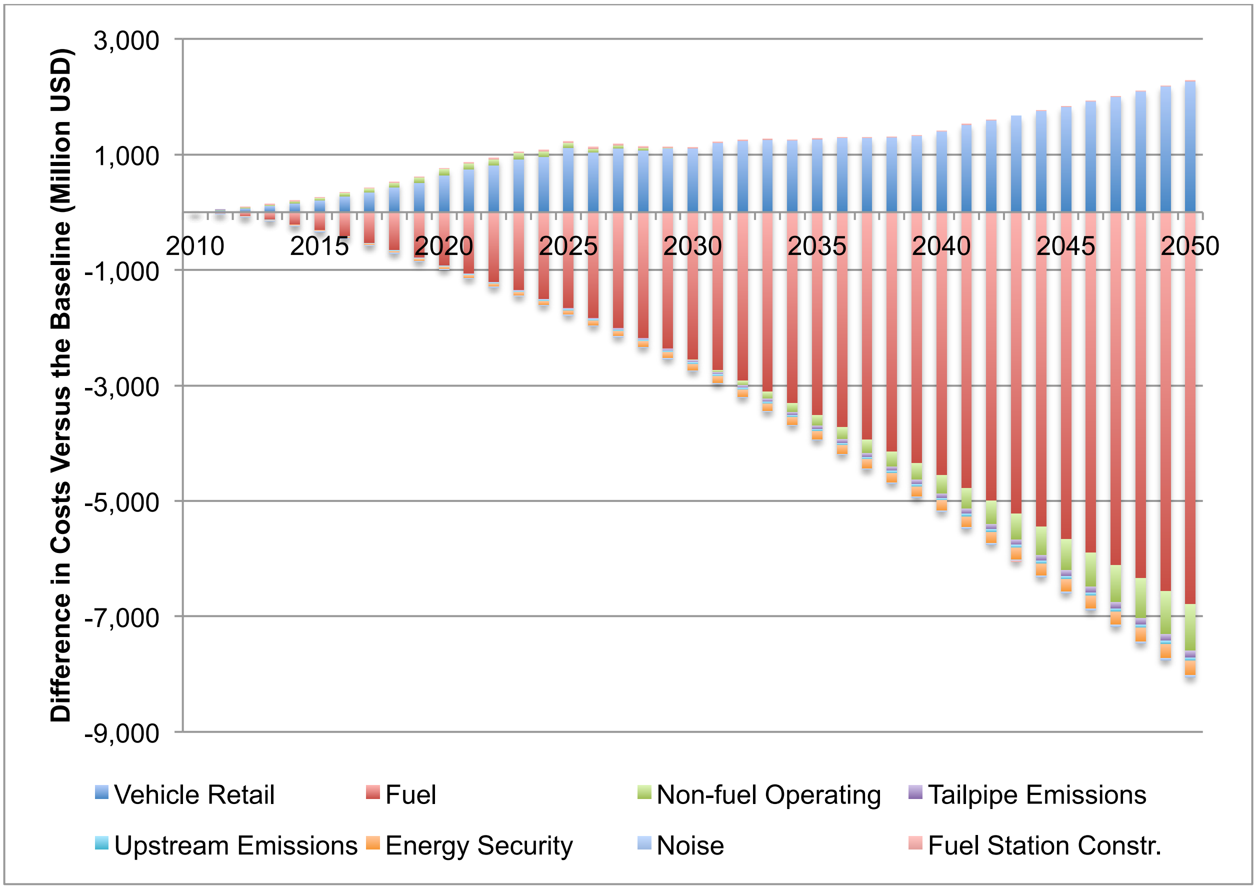

Figure 5-62: Cost differences between the FCVs and Baseline scenarios (positive values imply costs larger than the Baseline, negative values the inverse)

5.6 Alternative Fuels Scenario

In the Alternative Fuels scenario, the fuel supply for the California HD fleet becomes increasingly diversified in terms of source feedstocks. A key assumption is that the supply of lower-carbon *drop-in* fuels such as renewable diesel and Fischer-Tropsch (FT) diesel as well as non-fossil-based NG grow in market share and displace large percentages of conventional diesel across all of the HD vehicle categories. For the case of NG in which new fueling infrastructure is required to support additional demand, vehicle categories such as transit buses and other urban return-to-base vehicles are assumed to be the initial market for this technology, and in the later years in the study period, NG vehicles are widely adopted across all vehicle categories. For diesel substitutes, because conventional vehicles can utilize fuels such as renewable diesel and FT diesel without any substantive changes to engine and aftertreatment technology, a guiding premise of this scenario is that each drop-in fuel makes up an identical percentage of the fuels market in each of the eight vehicle categories. As with the Baseline and High Efficiency scenarios, conventional diesel and gasoline, NG, and hybrid vehicles are the only technology types modeled in this scenario.

5.6.1 Fuel and technology evolution

The phase-out of conventional diesel and gasoline vehicles occurs at the same rate as the previous three non-Baseline scenarios and is shown in Table 5-18 along with the market share assumptions for NG and hybrid vehicles. A critical assumption of this scenario is that NG vehicles hold a substantial portion of the advanced vehicle market starting in the *Initial Year of Advanced Vehicle* adoption, and NG vehicles come to dominate the sales market over time. Initially, sales of NG Urban Buses, MD Urban, and HD Vocational vehicles outnumber hybrids by a factor of three-to-one. For the remaining five vehicle categories, the advanced vehicle market is initially split evenly between NG and hybrid vehicles. Also shown in Table 5-18 is the assumption that NG vehicles increase their advanced vehicle market share at a rate of one percentage point per year for all eight of the vehicle categories. The resulting market share trends are shown in Figure 5-63 through Figure 5-65.

Aside from the growing prominence of NG vehicles over time, the other key feature of the Alternative Fuels scenario is that an increasing quantity of both diesel and NG are supplied by lower-carbon feedstocks. As described in Section 4.3.6.3, in order to simplify the user inputs and functionality, each feedstock's percentage contribution to each *finished fuel* is modeled as a constant for each of the four 10-year periods. The feedstock breakdown for diesel and NG over time is summarized in Table 5-17.

In developing the set of feedstock options for this scenario, a guiding principle was to only select feedstock-to-fuel pathways that provide substantial well-to-tank (WTT) carbon reductions compared to conventional fossil-based fuels. As such, three non-fossil feedstocks are modeled for diesel and two non-fossil feedstocks are modeled for NG (see Table 5-17). For diesel substitutes, two notable omissions are renewable diesel (i.e. *not* monoalkyl esters) and biodiesel (i.e. fatty acid methyl ester) derived from soy crops. In recent years the overall environmental and economic impacts of energy crops such as corn and soy have come into question, as these renewable fuel sources are often associated with indirect land-use change emissions and food supply disruptions. In the final rulemaking of California's Low Carbon Fuel Standard (LCFS) [100], the ARB estimates that soy-based renewable diesel and biodiesel each have WTT CO_2-equivalent emissions that are roughly 10% less than conventional diesel, after accounting for land-use impacts, and the estimated land-use emissions associated with these two fuel pathways represent roughly 75% of their overall WTT CO_2-equivalent emissions.

In order to maximize the feasible carbon reductions of this scenario, soy-based diesel is avoided, and, instead, biomass from municipal and forestry wastes is assumed to be the source of all of the non-petroleum diesel consumed. In Table 5-17, the percentages for the final 10 years of the study period for the three lower-carbon diesel fuels are based on the analyses done by Parker et al. [328] and Leighty [329] to assess the available biomass resources in California. The first waste stream feedstock, municipal solid waste (MSW), can be transformed into diesel fuel via the FT process. Using Parker et al.'s assessment of biomass available in California and the western states, Leighty estimates that in 2050, biomass from MSW can make up 16-21% of the total biofuel supply in California. Based on Leighty's "Middle Scenario" biofuel supply curves for California in 2050 (see Leighty (2010) Figure 10), MSW can supply roughly 80-100 million gallons of FT diesel. Using the conservative end of this range, that quantity of FT diesel is approximately 25% of the total 320 million gallons of diesel that are consumed in 2050 in the Alternative Fuels scenario. Forestry residues are also a large potential resource for biomass in California. Leighty estimates that 2 to 3% of the total biofuel supply in 2050 can be supplied by forestry biomass. Leighty's "Middle Scenario" supply curve puts the total biofuel available in 2050 at about 6 billion gallons of gasoline equivalents (gge). Assuming 2% of this total is derived from forestry biomass, this results in 120 million gge. The author assumes that renewable biofuel supplies will be split between passenger vehicles and the HD fleet based on the current fuel use totals of the two modes and that the percent usage of each mode will be constant over time. On an energy equivalent basis, HD vehicles use approximately 20% of the fuel consumed by on-road transportation [313]. Multiplying this percentage by 120 million gge results in 24 million gge, which is roughly 21 million dge. This contribution from forestry biomass is 7% of the total diesel demand in 2050 in this scenario. Diesel substitutes can also be produced from edible and inedible tallow, lard and choice white grease feedstocks, which are byproducts of the meat processing and slaughter industries. Leighty estimates that these byproducts can supply 1 to 2% of the total biofuel supply in California in 2050. Taking 1% as a conservative estimate, tallow's contribution would be half that of forestry biomass, or approximately 10.5 million dge, which is 3% of the total 320 million gallons of diesel needed in 2050.

There are also a number of renewable, lower-carbon pathways of producing NG. For the sake of modeling simplicity, only two waste stream-based feedstocks are included in this analysis: landfill gas and biogas from dairy farms. These two feedstocks have the lowest CO_2-equivalent intensity of any NG pathway that was considered for California's LCFS (see Table 7 in [100]). The California Energy Commission estimates that between 59 and 78 billion cubic feet (bcf) of methane is currently available for extraction from landfills in California. The California Department of Finance projects that the state's population will increase by 37% between 2010 and 2050 [330]. Assuming that the amount of methane available from landfills increases proportionally to population growth and the composition of landfill waste remains relatively constant, a conservative estimate of 59 bcf of landfill gas (LFG) currently available yields the following results for diesel gallon equivalents in 2050:

59 bcf * 1.37 = 81 bcf ≈ 608 million dge

According to the CEC, HD vehicles consume 80 to 90% of transportation NG in California [313]. Assuming that the HD fleet continues to dominate the use of NG out into the future, LFG could supply approximately 45% of the ~1,070 dge total NG demand of the Alternative Fuels scenario:

608 million dge * 80% / 1,070 dge = 45%

For dairy farm biogas, Krich et al. [283] estimate that there are currently roughly 14 bcf/year of methane that could be technically recovered from dairy cow manure in California. Assuming that demand for dairy products—and thus, the available manure-based biogas—increases in proportion to state population, this feedstock source could supply approximately 10% of the total NG consumed in 2050 in this scenario:

14 bcf * 1.37 = 19 bcf → (19 bcf / 81 bcf) * 45% ≈ 10%

Table 5-17: Percentage breakdowns for diesel and NG feedstocks in the Alternative Fuels scenario

	2010-2020	2021-2030	2031-2040	2041-2050
Diesel Feedstocks				
Crude oil	98.75%	93%	80%	65%
Municipal solid waste (FT diesel)	1%	5%	15%	25%
Forest biomass (FT diesel)	0.2%	1.5%	3.5%	7%
Tallow (renewable diesel)	0.05%	0.5%	1.5%	3%
TOTAL	100%	100%	100%	100%
Natural Gas Feedstocks				
Fossil NG	99%	90%	70%	45%
Landfill gas	0.75%	9%	25%	45%
Dairy farm biogas	0.25%	1%	5%	10%
TOTAL	100%	100%	100%	100%

Table 5-18: Market share controls for the Alternative Fuels scenario

	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
Adoption Controls								
Initial yr. of AV adoption	2020	2011	2020	2015	2015	2011	2020	2015
Pivot year 1	2030	2020	2030	2025	2025	2025	2030	2030
Pivot year 2	2040	2030	2040	2025	2025	2035	2040	2040
Conv. Vehicle Change in Market Share								
Period 1 annual change in MS (percentage)	-3%	-5%	-3%	-3%	-3%	-3%	-3%	-3%
Period 2 annual change in MS (percentage)	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%	-7.5%
Period 3 annual change in MS (percentage)	-15%	-15%	-15%	-15%	-15%	-15%	-15%	-15%
Natural Gas Controls								
Initial % of AV market	50%	75%	50%	75%	50%	75%	50%	50%
Period 1 annual change in MS (percentage points)	1%	1%	1%	1%	1%	1%	1%	1%
Period 2 annual change in MS (percentage points)	1%	1%	1%	1%	1%	1%	1%	1%
Period 3 annual change in MS (percentage points)	1%	1%	1%	1%	1%	1%	1%	1%
Hybrid Controls								
Initial % of AV market	50%	25%	50%	25%	50%	25%	50%	50%
Period 1 annual change in MS (percentage points)	-1%	-1%	-1%	-1%	-1%	-1%	-1%	-1%

	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
Period 2 annual change in MS (percentage points)	-1%	-1%	-1%	-1%	-1%	-1%	-1%	-1%
Period 3 annual change in MS (percentage points)	-1%	-1%	-1%	-1%	-1%	-1%	-1%	-1%

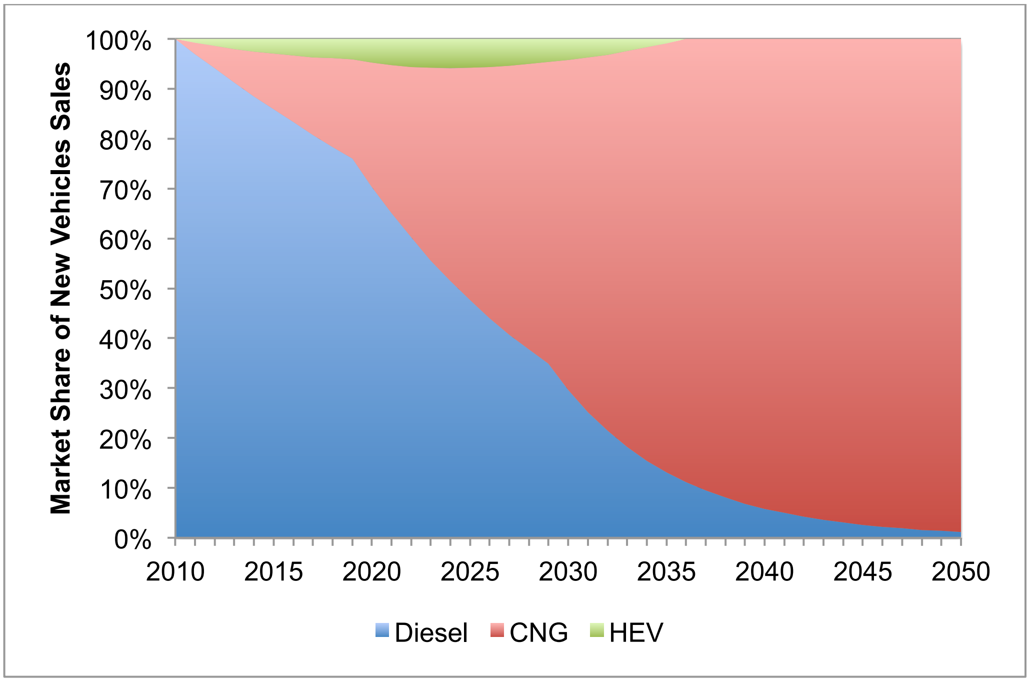

Figure 5-63: Urban Bus, MD Urban, and HD Vocational Vehicle new vehicle market share in the Alternative Fuels scenario

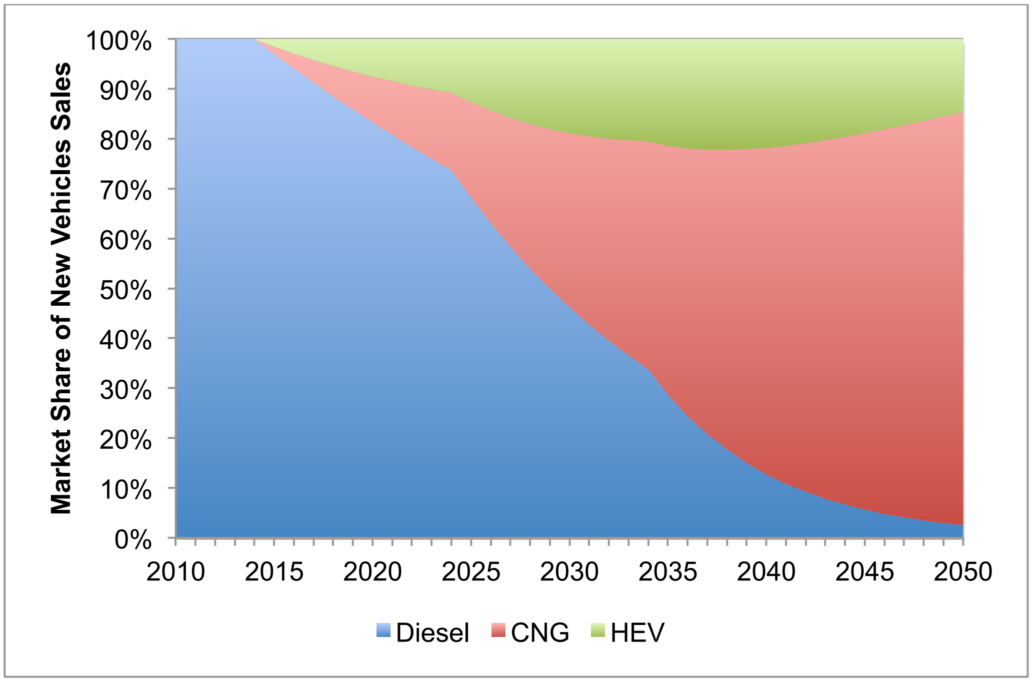

Figure 5-64: MD Vocational Vehicle and SH Tractor new vehicle market share in the Alternative Fuels scenario

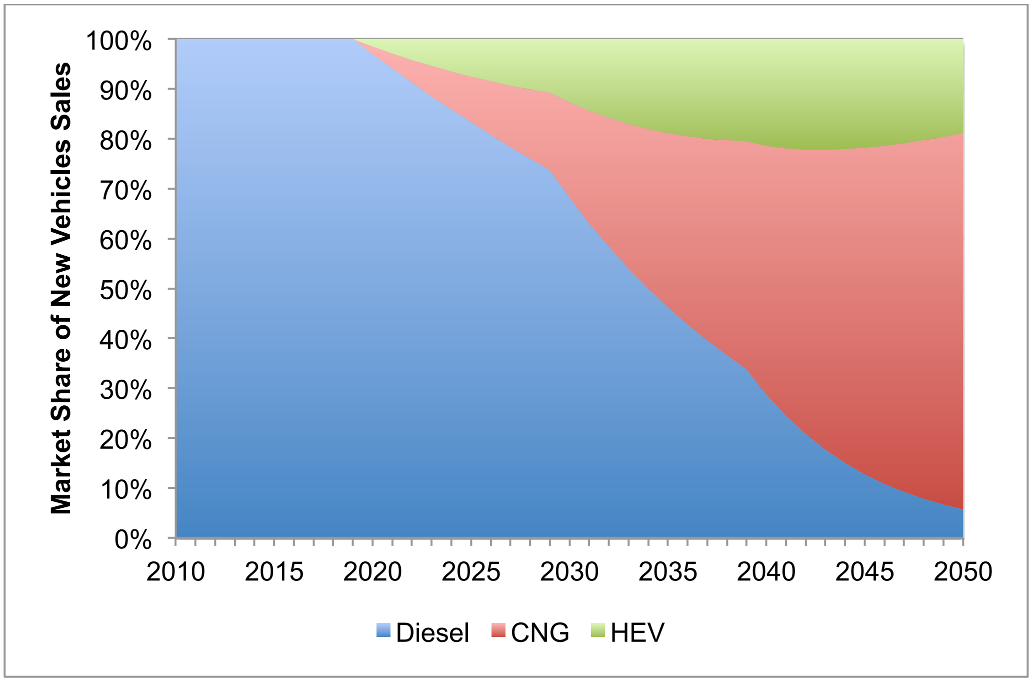

Figure 5-65: HD Pickup, Other Bus, and LH Tractor new vehicle market share in the Alternative Fuels scenario

5.6.2 Emission Results

For certain criteria pollutant species, the emissions results of this scenario diverge significantly from the previous scenarios. This is evidenced in Figure 5-66 and Figure 5-67, where emissions of NOx, NMHC, CO, and N_2O increase as compared to the baseline. These trends are primarily a function of the grams/mile emission factors for NG vehicles, which are significantly higher than diesel vehicles and hybrids for these four species.

The CO_2-equivalent emissions results are shown in Figure 5-68. In 2050, the CO_2e emission total of the Alternative Fuels scenario is 47% and 5% lower than the Baseline and High Efficiency scenarios respectively. For the four lifecycle phases, the CO_2e emissions comparison of these three scenarios is summarized in Table 5-19. The emission reduction impacts of the

Alternative Fuels scenario are most evident for upstream fuels processing. Large-scale adoption of low-carbon diesel and NG result in upstream emissions that are 83% and 68% lower than the Baseline and High Efficiency scenarios respectively. The vehicle manufacturing totals are approximately 10% higher for the Alternative Fuels scenario as compared to the other two scenarios, which is based on the additional energy and emissions associated with manufacturing high-pressure NG fuel tanks. Because the diesel and NG substitutes are estimated to have identical carbon-content to their fossil counterparts (in combustion), tailpipe emissions of the High Efficiency and Alternative Fuels scenarios are roughly comparable. As discussed in Section 0, a modeling simplification is that vehicle decommissioning-related emissions are identical between the various technology types, and, as such, scrappage emissions are the same in each of the six scenarios.

Table 5-19: CO_2e emissions of the Baseline, High Efficiency, and Alternative Fuels scenario by lifecycle phase

Lifecycle Phase	Emissions Totals in 2050 (metric tons)			Difference vs. Alt Fuels	
	Baseline	High Efficiency	Alternative Fuels	Baseline	High Efficiency
Tailpipe	24,676,883	12,396,792	12,320,950	+50.1%	+0.6%
Upstream fuels	3,343,562	1,806,682	571,468	+82.9%	+68.4%
Vehicle manufacturing	3,248,381	3,169,167	3,602,894	-9.8%	-12.0%
Scrappage	296,316	296,316	296,316	0%	0%
Total	31,565,591	17,668,957	16,791,628	+46.8%	+5.0%

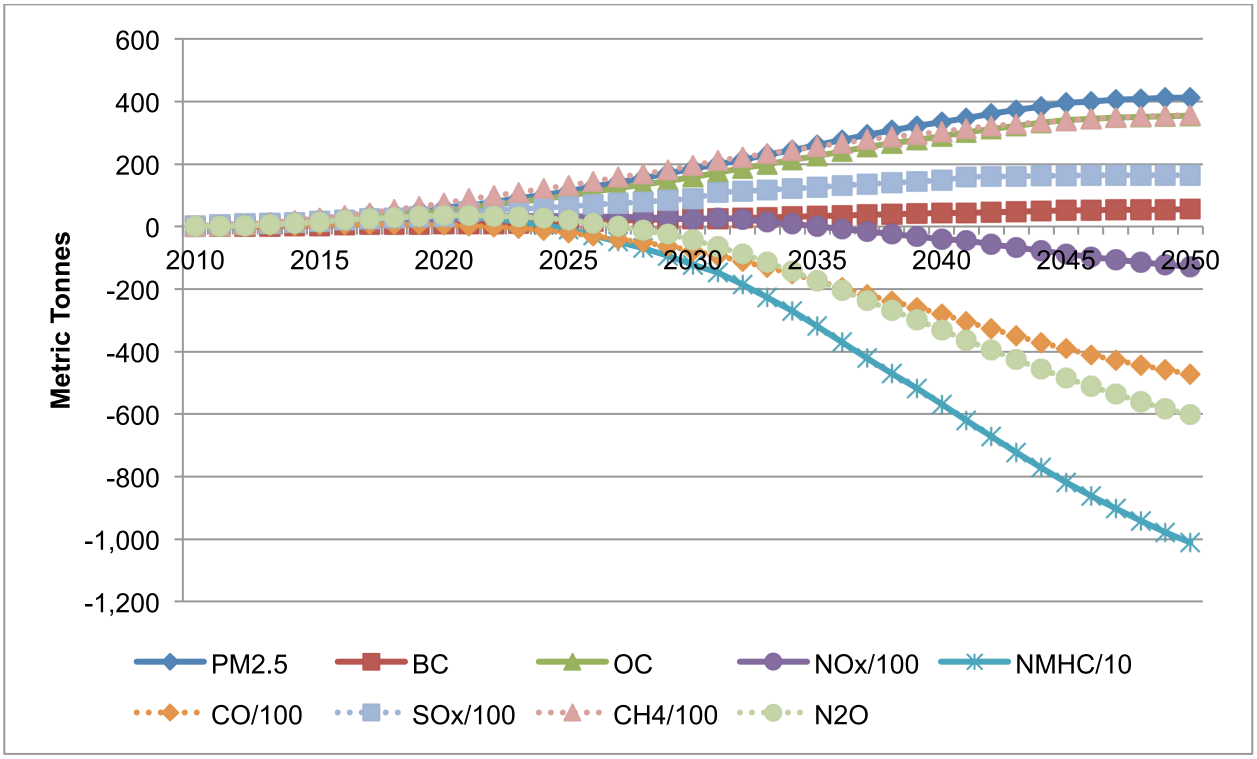

Figure 5-66: Emissions reductions of the Alternative Fuels scenario as compared to the Baseline

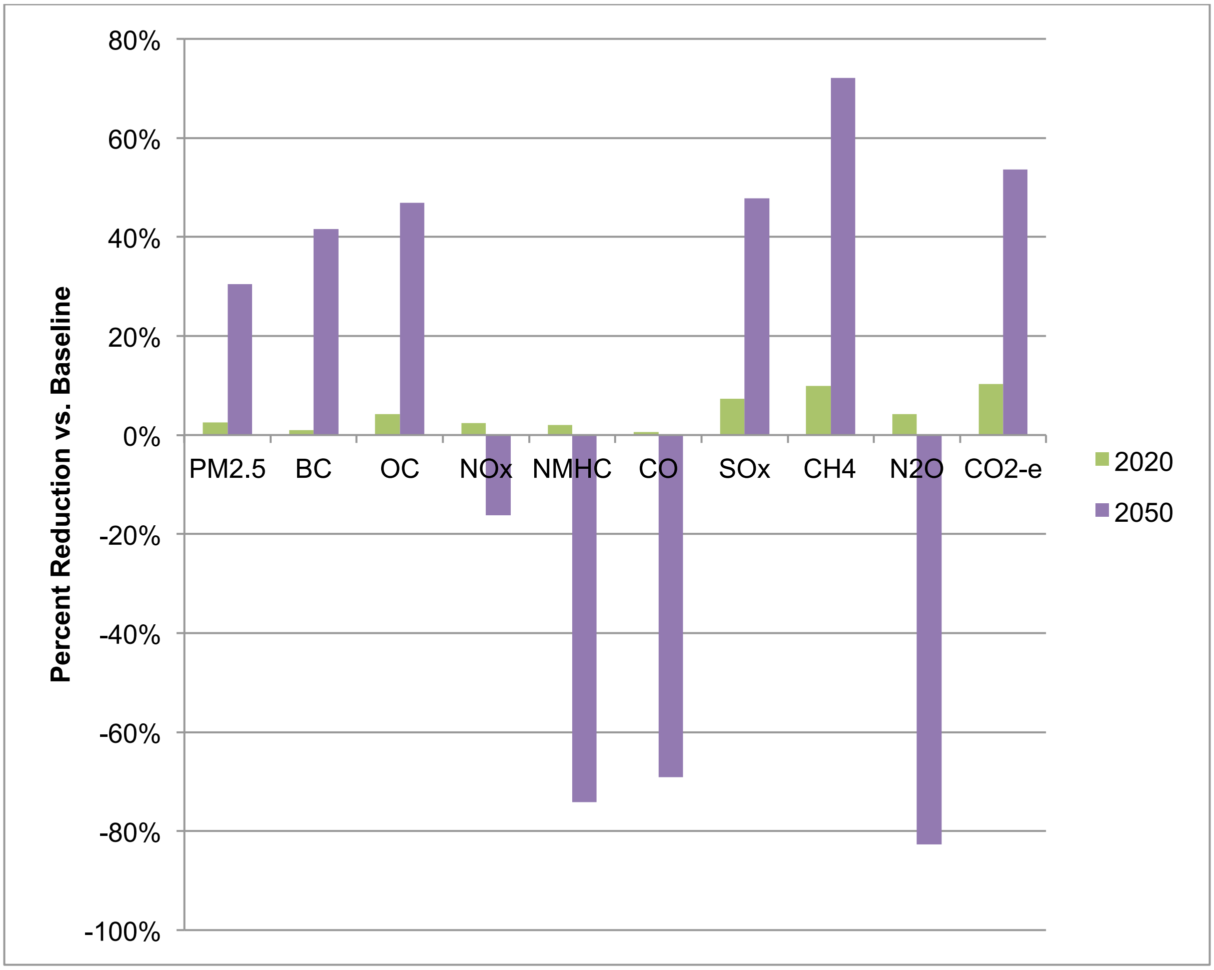

Figure 5-67: Percent reduction in annual emissions in 2020 and 2050 for the Alternative Fuels scenario as compared to the Baseline

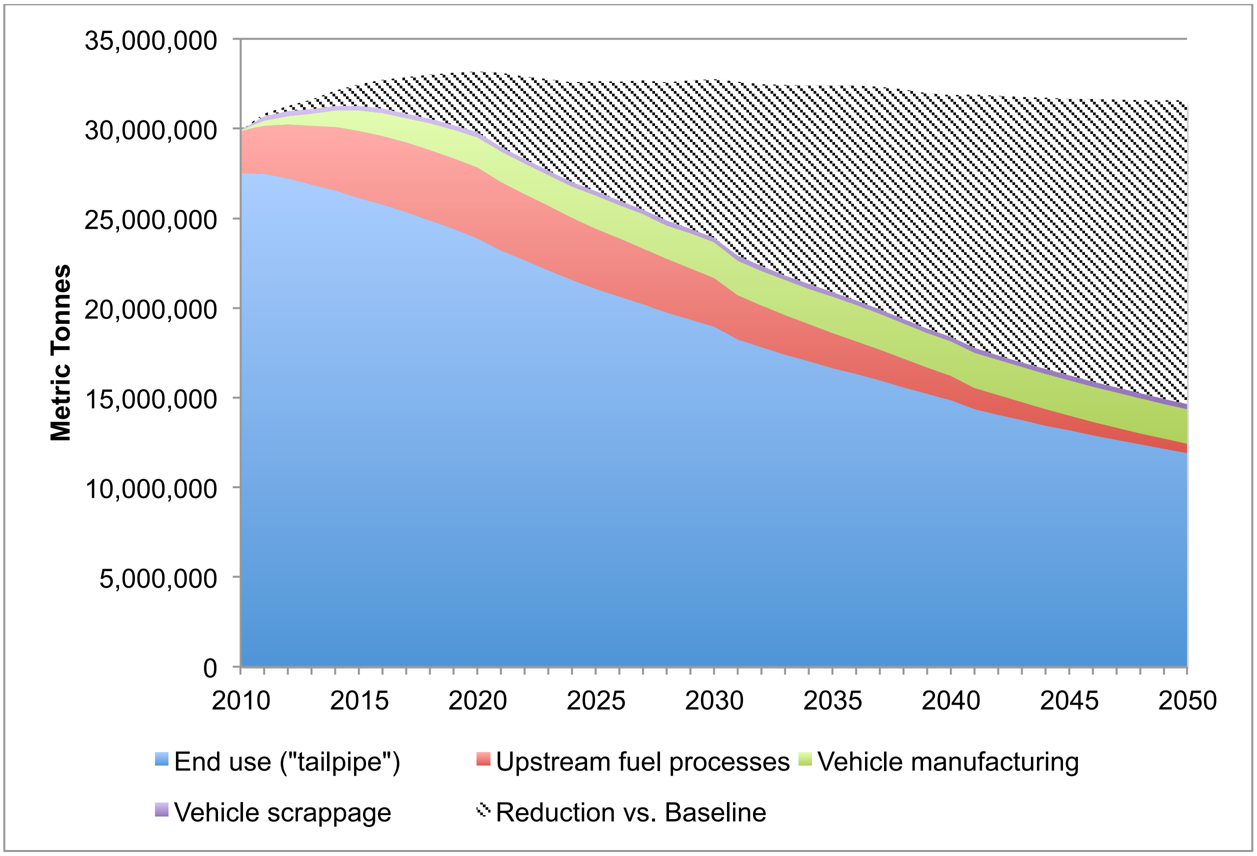

Figure 5-68: CO_2e emissions by lifecycle phase in the Alternative Fuels scenario

5.6.3 Fuel Use Results

The diesel gallon equivalent fuel use totals for the Alternative Fuels scenario are shown in Figure 5-69. In 2050, total NG consumption is larger than that of diesel (both conventional and low-carbon diesel) by ratio of roughly 3-to-1. Total fuel use in 2050 is 45% lower than the Baseline and 13% higher than the High Efficiency scenario. Fuel consumption of the Alternative Fuels scenario is higher than the High Efficiency scenario because the Alternative Fuels scenario has a much larger percentage of NG vehicles in the fleet as compared to hybrids. Hybrids have per-vehicle fuel use rates that are between 5 and 20% less than conventional diesel vehicles and

15 to 30% less than NG vehicles. An assumption of the model is that NG vehicles are not hybridized, based on the fact that, as of this writing, there are no NG hybrid vehicles being sold commercially in the HD sector (primarily due to the incremental costs of both the NG and hybrid systems), and no manufacturers have made announcements that NG hybrids will be introduced in the near-term. However, as battery costs and driveline components decrease in costs over life due to learning effects, it is likely that manufacturers will begin to offer hybridized NG vehicles. In this case, the fuel use totals in the later years of the study period would be lower, based on the rate that NG hybrids are substituted for conventional NG vehicles.

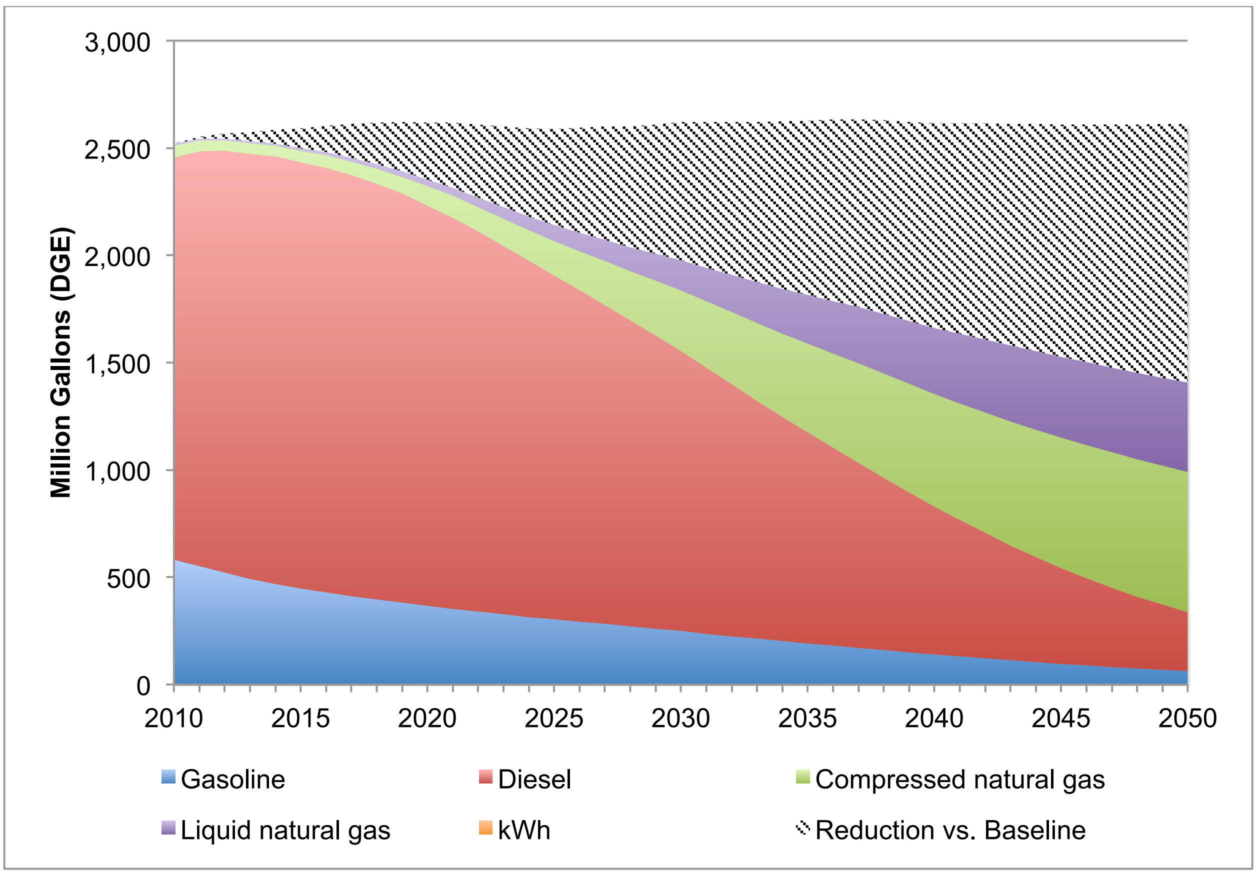

Figure 5-69: Fuel use trends of the Alternative Fuels scenario (million diesel gallon equivalents)

5.6.4 Cost Results

As shown in Figure 5-70, the cost totals of the Alternative Fuels scenario are approximately equal to the High Efficiency scenario in the first half of the study. Between 2030 and 2050, the fuel cost benefits of the increased percentage of NG used by the HD fleet drives the total costs of the Alternative Fuels scenario lower than the High Efficiency scenario. The NPV of the Alternative Fuels scenario cost stream is $619 billion, which is 7% lower than the Baseline NPV and 1% lower than the High Efficiency NPV. Out to 2050, the largest savings compared to the High Efficiency scenario are seen in fuel costs. As illustrated in Figure 5-71, fuel's contribution to total costs decreases significantly from 2010 to 2050. Also, as with the other scenarios, retail, fuel, and maintenance expenses make up the large majority of total costs over the entire study period. Costs due to emissions damage, energy security, noise, and refueling station construction decrease from 11% of total costs in 2010 to 3% in 2050.

As in the previous scenarios, California Energy Commission transportation fuel forecasts are used for conventional diesel and NG future costs, whose per-gallon retail prices are estimated to rise at 1.2% and 0.4% per year respectively. Identical annual price escalation rates are assumed for liquid and compressed NG.

There are much higher levels of uncertainty for non-conventional fuel costs, given the scarce (or non-existent) commercial availability of fuels that are derived from waste streams. The 2010 retail prices for MSW and forestry biomass-based FT diesel as well as renewable diesel from tallow are estimated at $2.20, $2.35, and $2.78 per gallon respectively based on the US EPA's cost projections for the Renewable Fuels Standard (RFS2), which were performed by the National Renewable Energy Laboratory (NREL) [331]. Though the NREL cost projections were made for the year 2022, they estimated that costs in 2010 would likely be similar. To obtain customer pump prices, the total fuel costs from the EPA feedstock and conversation cost estimates are marked up at 15% to reflect retailer operating costs and profit margin [313].[31] As with non-petroleum diesel sources, biomethane conversion for use as a transport fuel is a nascent industry, and the price estimates used for this scenario are based on limited real-world project data. The prices for landfill gas in 2010 are based on the total project costs and the annual output of the Altamont, CA LFG-to-LNG plant that supplies fuel to the refuse trucks that service the site [282]. For dairy biogas, Table 8-8 from Krich et al. (*Estimated Inputs, Outputs and Associated Costs for Large Dairy Digester, Generator, and Liquefied Biomethane Facility*) serves as the sole cost data point. As with FT and renewable diesel, 15% is assumed as a mark-up for non-fossil NG due to limited availability of real-world data. Due to the virtual absence of FT diesel, renewable diesel, or biomethane markets to date, there is almost no information available on cost projections. To reflect this uncertainty, three plausible price (2010$) change scenarios are utilized in the project. The cost results below reflect an assumed annual rate of change of 0%. As part of the sensitivity analysis, two additional cases—an increase of 1% per year and a decrease of 1% per year—are modeled.

Figure 5-72 tracks the change over time in vehicle purchase and maintenance costs of NG vehicles versus conventional diesels for the Alternative Fuels scenario. For 2010, the relative cost differences between NG and diesel vehicles are much more ambiguous for per-mile maintenance costs in comparison to purchase costs. Based on the uncertainty of whether NG vehicles provide a benefit or disbenefit in terms of maintenance costs (see Table 4-22), a cost

[31] The mark-up value of 15% is based on an approximation of the combined totals of “Other Operating Costs” and “Return Over Operating Costs” in Figure 5-23 (*US Biodiesel Operating Margins (April 2007 to July 2011*) of the CEC’s 2011 Transportation Energy report. The margins for FT diesel are assumed to be identical to that of soy-based biodiesel.

ratio of 1.0 (i.e. cost parity between NG and diesel vehicles) was chosen. As a result of using this 1.0 multiplier in 2010, the per-mile maintenance costs for NG vehicles decrease to levels below diesels over time, based on the fact that the rate of change of maintenance costs is directly tied to the rate of change in purchase costs. In the case of SH Tractors, LH Tractors, and MD Vehicles, per-mile maintenance costs of NG vehicles drop to 33% and 27% less than diesels as the purchase price ratio falls to its minimum as cumulative production volume increases over time (as in previous scenarios, a 1.0 value is used for the price floor). This fixed relationship between purchase price and maintenance costs is a shortcoming of the model and perhaps results in total maintenance costs for the Alternative Fuels scenario that are too optimistic in the case of NG vehicles. To capture a more conservative outlook, a higher maintenance cost ratio for NG vehicles in 2010 (1.3) is modeled in the sensitivity analysis (see Section 5.8).

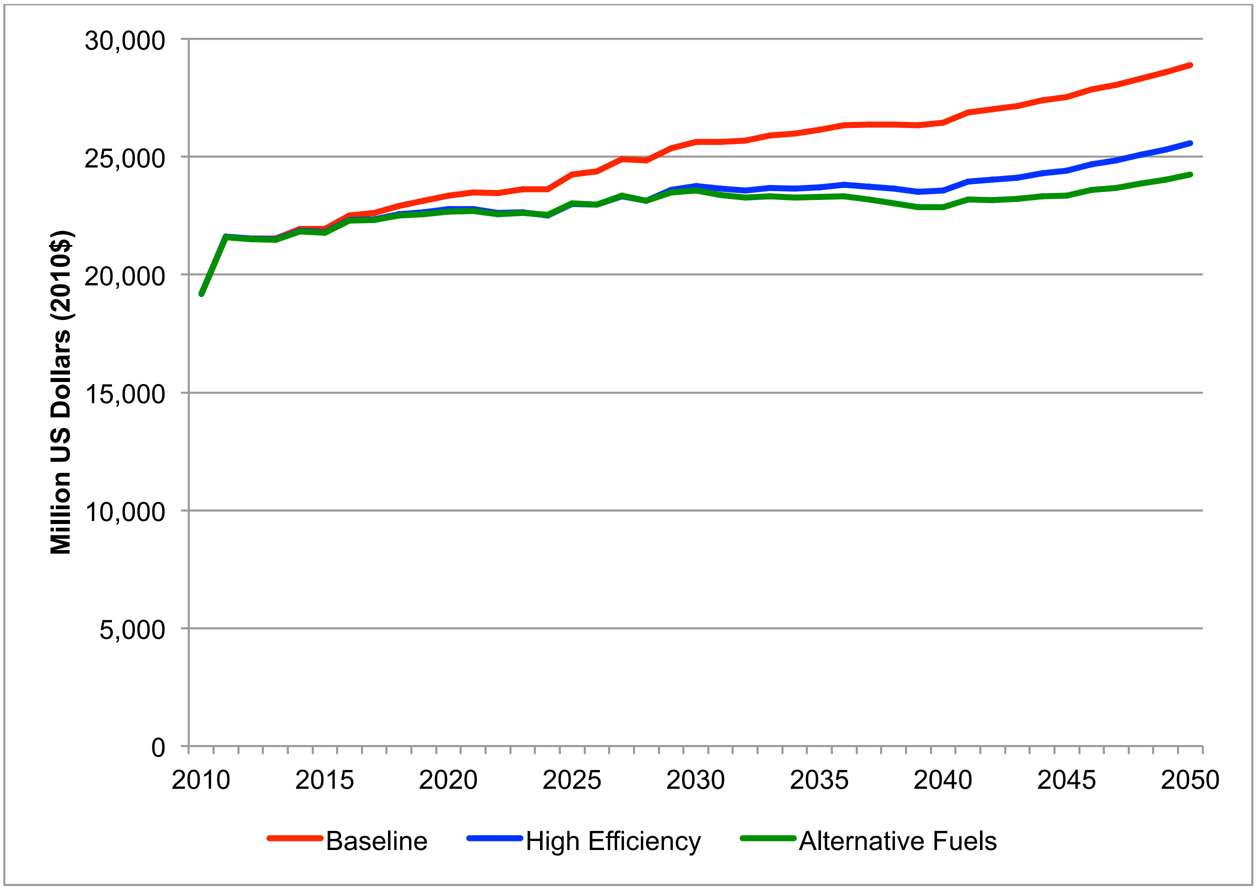

Figure 5-70: Total lifecycle costs of the Alternative Fuels, High Efficiency, and Baseline scenarios

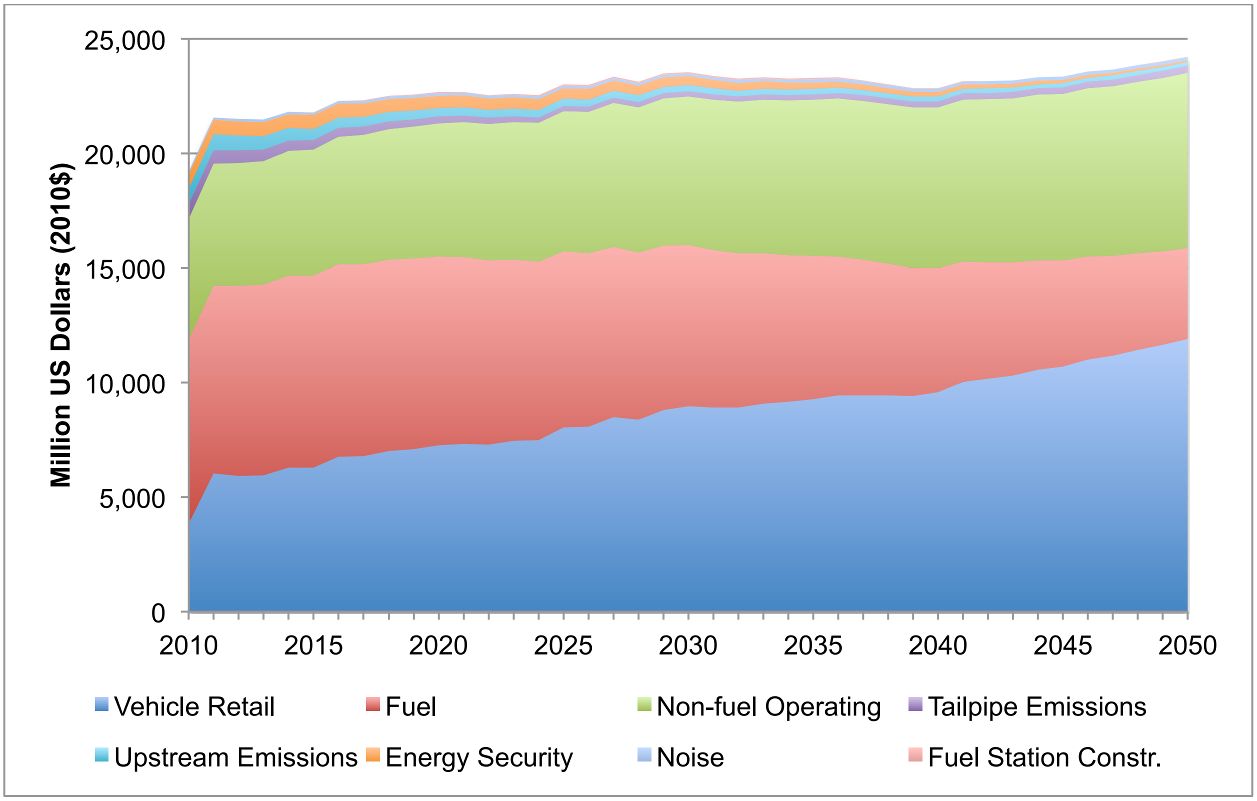

Figure 5-71: Total costs breakdown for the Alternative Fuels scenario

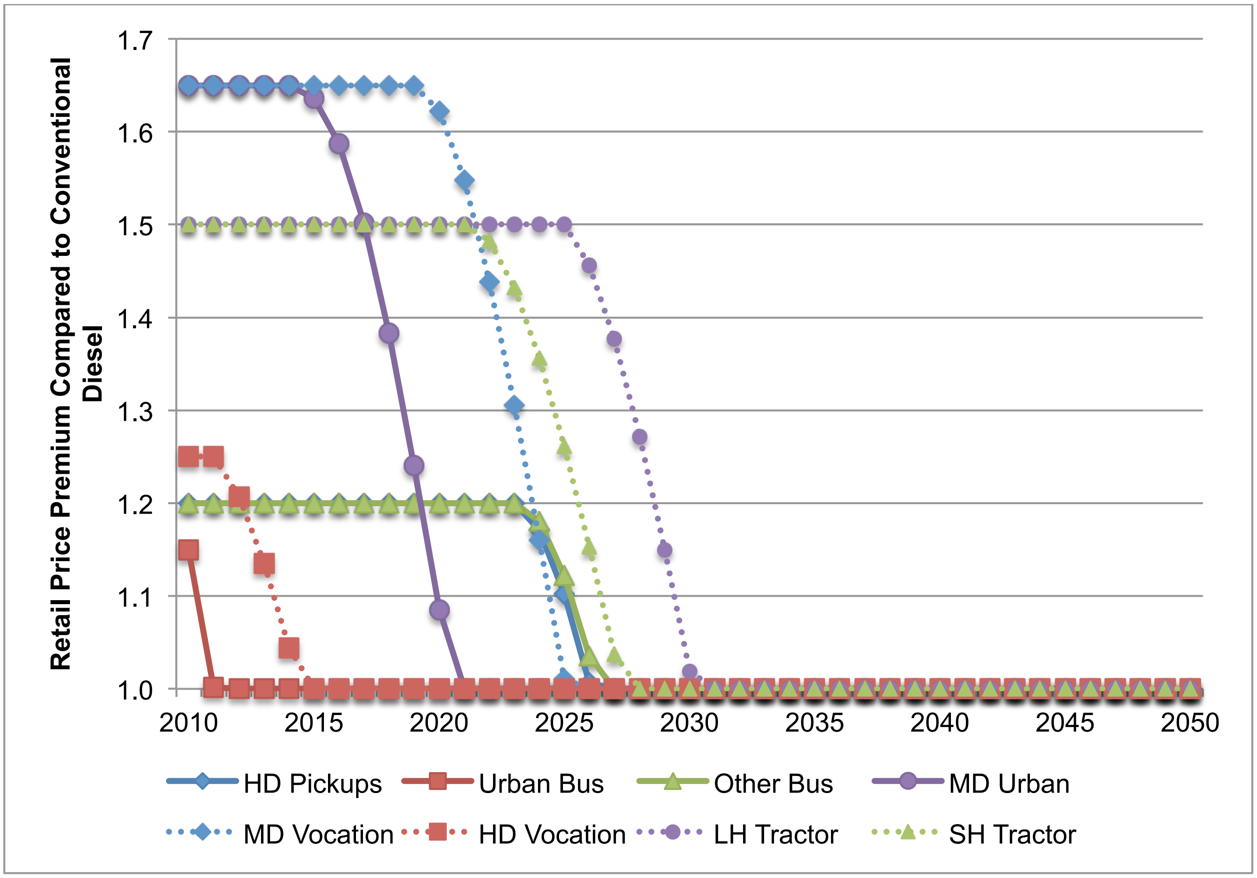

Figure 5-72: Retail price premiums for NG vehicles in the Alternative Fuels scenario

5.7 80% Reduction in CO_2-equivalent Emissions by 2050 (80in50) Scenario

An amalgamation of the previous three scenarios, the 80in50 scenario assumes a rapid uptake of electric and hydrogen fuel cell vehicles as well as the widespread adoption of lower-carbon fuel and energy pathways. The key difference of the 80in50 scenario is that these vehicle and fuel market transformations occur at an accelerated rate in order to reduce the total CO_2e emissions from the HD fleet in 2050 by 80% compared to estimated 1990 emission levels. Looking at the entire HD fleet, all six technology types are modeled in this scenario—conventional, NG, hybrid, plug-in hybrid, full electric, and hydrogen fuel cell vehicles.

5.7.1 Fuel and technology evolution

The defining characteristics of the 80in50 scenario are the aggressive phase-out of conventional vehicles and the rapid adoption of a variety of advanced fuels and technologies. Table 5-20 and Figure 5-73 through Figure 5-76 summarize the market assumptions for each of the eight vehicle categories. Compared to the previous scenarios, the pivot years are roughly five years earlier for most of the vehicle categories, and the annual reduction in conventional vehicle market share is 5%, 15%, and 25% for Periods 1, 2, and 3 respectively (as compared to 3%, 7.5%, and 15% in the previous four scenarios). As a result of this accelerated phase-out, conventional vehicles are virtually gone from the new vehicle market by the later years of the study period, with conventional vehicles only representing about 1% or less of total sales by 2040 or later.

As before, the Urban Bus and HD Vocational Vehicle fleets are the vehicle types where advanced technologies first enter the HD fleet. For these two vehicle categories, the initial advanced vehicle market is split evenly between NG and hybrid vehicles. Looking at the cumulative market share trends in Figure 5-73, NG, hybrid, and plug-in hybrid vehicle sales grow to just over 10% each in the 2020 timeframe before falling to zero over the next 10 years. Penetration of electric and fuel cell vehicles is gradual in the early years, followed by a relatively swift capture of the market in the 2020s such that by roughly 2030 the entire advanced vehicle market is comprised of EVs and FCVs. By 2040, virtually all vehicles sold are either of these two zero tailpipe emissions technologies.

For the two medium-duty vehicle categories, the market evolution is similar to Urban Buses and HD Vocational Vehicles. The key differences are that all three pivot years are assumed to occur four years later, and, initially, the entire advanced vehicle market is controlled by hybrids (this is true of the other four vehicle categories as well). This preference for hybrids over NG vehicles is driven by the preference for the superior fuel efficiency and CO_2 emissions performance of hybrids. The technology evolution assumptions for HD Pickups are similar, with the key difference being that EVs and FCVs do not begin to enter the fleet until after 2025.

The late adopter fleets are the last vehicle groups to adopt zero emission technology. As discussed in Section 5.4.1, due to physical limitations presented by current and projected battery energy densities, it is assumed that full battery electric coach buses (i.e. Other Bus) and tractors are not practical for large-scale adoption during the study period.[32] For these three vehicle types, hydrogen fuel cell vehicles are the zero emissions technology of choice and carry onboard hydrogen in liquid form in order to maximize the range capabilities. FCVs enter the fleets in 2025, and by 2035, represent 100% of the advanced vehicle market. This ten-year phase-in of FCVs into these fleets is a very aggressive assumption and would represent an unprecedented penetration of a vehicle technology option. As discussed more in Chapter 6, such a rapid market transformation would presumably have to be motivated by strong regulatory action. This is likely true for the other five vehicle categories as well, where the entire sales market moves from nearly 100% conventional diesel and gasoline to practically 100% EV and FCV over the course of 20-25 years.

[32] As discussed in the Chapter 2, catenary systems are currently being demonstrated in which tractor trucks are able to operate in all-electric mode when attached to the overhead catenary wires. However, looking out to 2050, it is the author's judgment that these catenary systems are only feasible for limited stretches of roadway, and, if these systems are constructed for use on public highways, they will only represent a very small percentage of total heavy-duty vehicle VMT in California.

For fuels, the 80in50 scenario has identical feedstock diversification assumptions for diesel and NG as the Alternative Fuels scenario (see Table 5-17). Also, hydrogen production is assumed to transition from 100% methane steam reformation to 100% water electrolysis over the study period according to the schedule laid out in the *High Electrolysis* scenario of Table 5-16. The lowest carbon pathway is assumed for electricity as well, and by 2050, all electric power is generated from renewable resources per the *Aggressive Renewables* grid scenario in which the renewable contribution is 33%, 50%, 75%, and 100% in 2020, 2030, 2040, and 2050 respectively.

Table 5-20: Market share trends of the 80in50 scenario

	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
Adoption Controls								
Initial yr. of AV adoption	2015	2011	2015	2015	2015	2011	2015	2015
Pivot year 1	2025	2021	2025	2025	2025	2021	2025	2025
Pivot year 2	2035	2031	2035	2025	2025	2031	2035	2035
Conv. Vehicle Change in Market Share								
Period 1 annual change in MS (percentage)	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%
Period 2 annual change in MS (percentage)	-15%	-15%	-15%	-15%	-15%	-15%	-15%	-15%
Period 3 annual change in MS (percentage)	-25%	-25%	-25%	-25%	-25%	-25%	-25%	-25%
Natural Gas Controls								
Initial % of AV market	0%	50%	0%	0%	0%	50%	0%	0%
Period 1 annual change in MS (percentage points)	0%	-2.5%	0%	0%	0%	-2.5%	0%	0%
Period 2 annual change in MS (percentage points)	0%	-2.5%	0%	0%	0%	-2.5%	0%	0%
Period 3 annual change in MS (percentage points)	0%	0%	0%	0%	0%	0%	0%	0%
Hybrid Controls								
Initial % of AV market	100%	50%	100%	100%	100%	50%	100%	100%
Period 1 annual change in MS (percentage points)	-5%	-2.5%	0%	-5%	-5%	-2.5%	0%	0%
Period 2 annual change in MS (percentage points)	-5%	-2.5%	-10%	-5%	-5%	-2.5%	-10%	-10%
Period 3 annual change in MS (percentage points)	0%	0%	0%	0%	0%	0%	0%	0%

	HD Pickup	Urban Bus	Other Bus	MD Urban	MD Vocation	HD Vocation	LH Tractor	SH Tractor
PHEV Controls								
Initial % of AV market	0%	0%	0%	0%	0%	0%	0%	0%
Period 1 annual change in MS (percentage points)	5%	2%	0%	2%	2%	2%	0%	0%
Period 2 annual change in MS (percentage points)	-5%	-2%	0%	-2%	-2%	-2%	0%	0%
Period 3 annual change in MS (percentage points)	0%	0%	0%	0%	0%	0%	0%	0%
EV Controls								
Initial % of AV market	0%	0%	0%	0%	0%	0%	0%	0%
Period 1 annual change in MS (percentage points)	0%	2%	0%	2%	2%	2%	0%	0%
Period 2 annual change in MS (percentage points)	5%	4%	0%	4%	4%	4%	0%	0%
Period 3 annual change in MS (percentage points)	0%	0%	0%	0%	0%	0%	0%	0%
FCV Controls								
Initial % of AV market	0%	0%	0%	0%	0%	0%	0%	0%
Period 1 annual change in MS (percentage points)	0%	1%	0%	1%	1%	1%	0%	0%
Period 2 annual change in MS (percentage points)	5%	3%	10%	3%	3%	3%	10%	10%
Period 3 annual change in MS (percentage points)	0%	0%	0%	0%	0%	0%	0%	0%

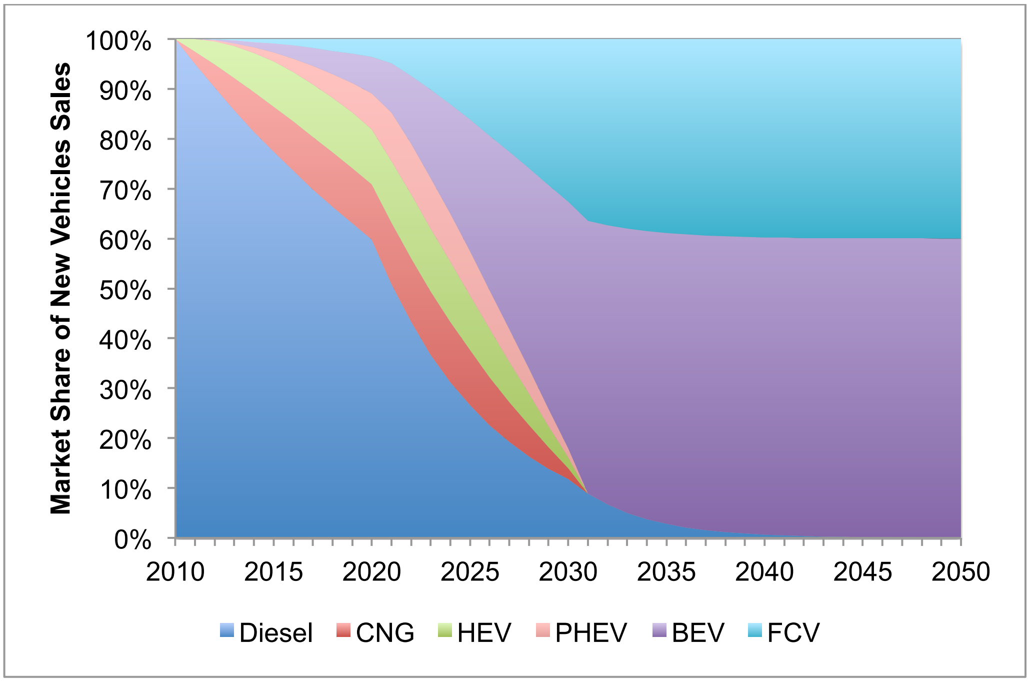

Figure 5-73: Urban Bus and HD Vocational Vehicle new vehicle market share in the 80in50 scenario

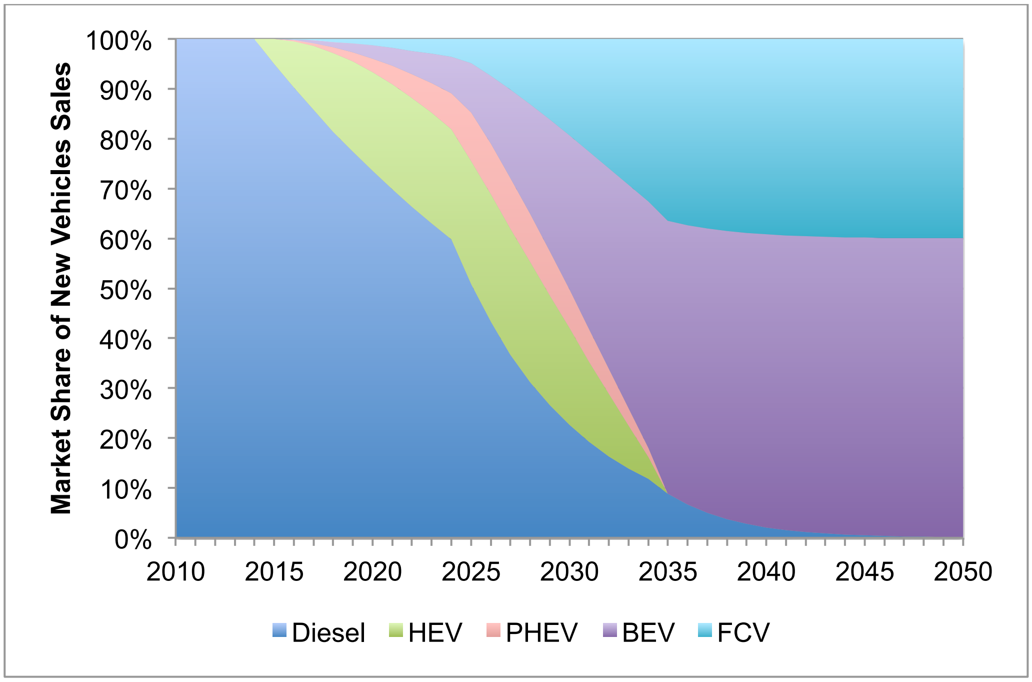

Figure 5-74: MD Urban and MD Vocational Vehicle new vehicle market share in the 80in50 scenario

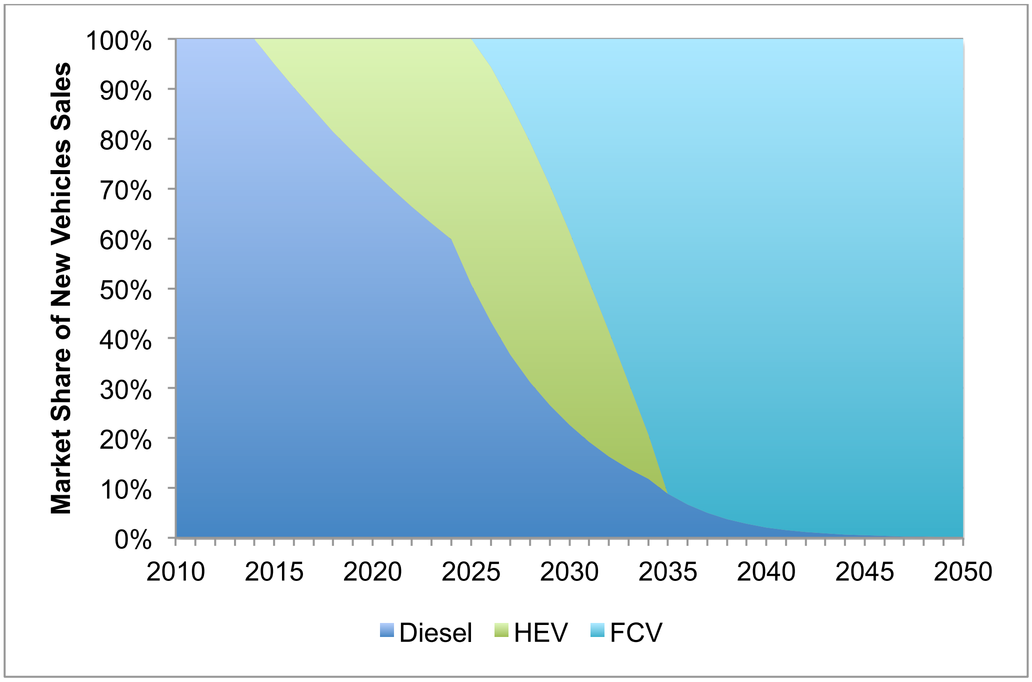

Figure 5-75: Other Bus, LH Tractor, and SH Tractor new vehicle market share in the 80in50 scenario

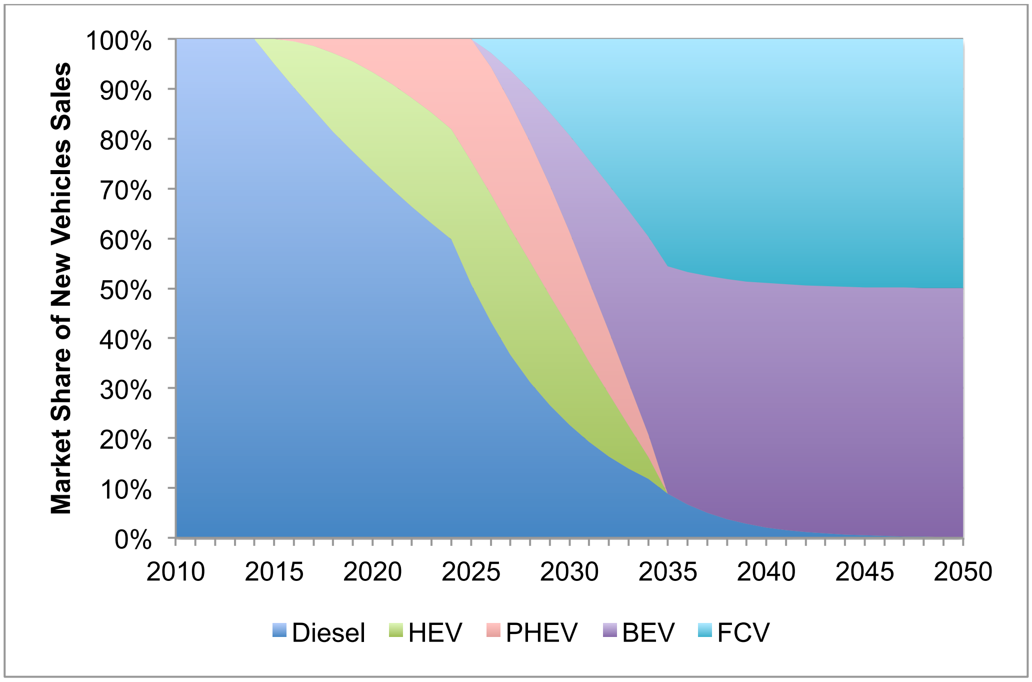

Figure 5-76: HD Pickup new vehicle market share in the Alternative Fuels scenario

5.7.2 Emission Results

The surge in uptake of zero tailpipe emission vehicles in the 2020 to 2040 timeframe coupled with the transition to low-carbon fuels and electricity results in the emissions outcome that is summarized in Figure 5-77, Figure 5-78, and Figure 5-79. Across the various pollutant species, the reductions as compared to the Baseline are modest in the first 10 years of the study period but become fairly substantial by the final decade, as emissions are displaced to upstream processes, and upstream processes are increasingly powered by low-carbon renewable resources. For CO_2-equivalent emissions, this trend is shown in Figure 5-78—in 2010, tailpipe emissions represent 92% of total emissions, but by 2050 this value is reduced considerably to 15%.

In 2050, lifecycle CO_2e emissions are 5 million metric tonnes, which is 84% less than the Baseline and 80% less than the estimated emission levels in 1990. For HD vehicles, the 1990

CO_2e emissions are estimates using official inventory values from the ARB. The 2020 target value of 25 million metric tonnes is derived using the following formula:

TOP-HDV 1990 CO2e emissions = [TOP-HDV 2010 emissions] *

[ARB 1990 emissions] / [ARB 2008 emissions]

As of this writing, 2008 is the latest year for which the ARB has released official GHG inventory estimates, and a key assumption of this calculation is that 2008 CO_2e emissions are a reasonable proxy for 2010 emissions. Figure 5-79 shows that CO_2e emissions from the HD fleet are approximately 30 million metric tonnes in 2020, which exceeds 1990 levels by roughly 20%. Given the relatively slow turnover of the HD fleet, achieving this 2020 target would require immediate roll-out of zero tailpipe emission vehicles across all eight vehicle categories. Battery electric and fuel cell technologies are mostly in pre-commercial phases for virtually all non-transit bus HD applications. The market for zero emission trucks and buses would have to grow from their current sales volumes in the low hundreds (and limited to a few niche urban applications) to tens of thousands over the course of a few years, and, in the author's judgment, this is likely an unrealistic expectation for recently emerging zero-emission HD manufacturers as well as the fleets putting these vehicles into service.

A critical assumption of the 80in50 scenario involves the CO_2 emission factors for vehicle manufacturing. Using the same per-vehicle CO_2 intensity values for manufacturing as in the previous five scenarios (which are derived from the LEM—see Section 4.3.6.4), CO_2e emissions from vehicle manufacturing are approximately 3.8 million tonnes in 2050, which is roughly three-quarters of the total budget for CO_2e if the scenario is to reach the 80% reduction target of 5 million tonnes. As such, an assumption is made that the CO_2 emission factors (i.e. grams of CO_2 per manufactured vehicles) for all vehicle types are cut in half in 2050 versus 2010 levels. For the 80in50 scenario, this assumption seems reasonable and is likely conservative, given the assumed 100% renewable electrical grid and the fact manufacturing is a relatively electricity-intense process. Using these modified EFs, CO_2e emissions are 1.8 million tonnes in 2050.

The effects of transiting to lower-carbon diesel, NG, and hydrogen are evident in the *Upstream fuels processes* area in Figure 5-79, where there is a 10% reduction in CO_2e from 2030 to 2031 and a 29% reduction from 2040 to 2041. Of course, in reality, such changes in fuel feedstocks and the resulting CO_2e emissions would likely happen much more gradually.

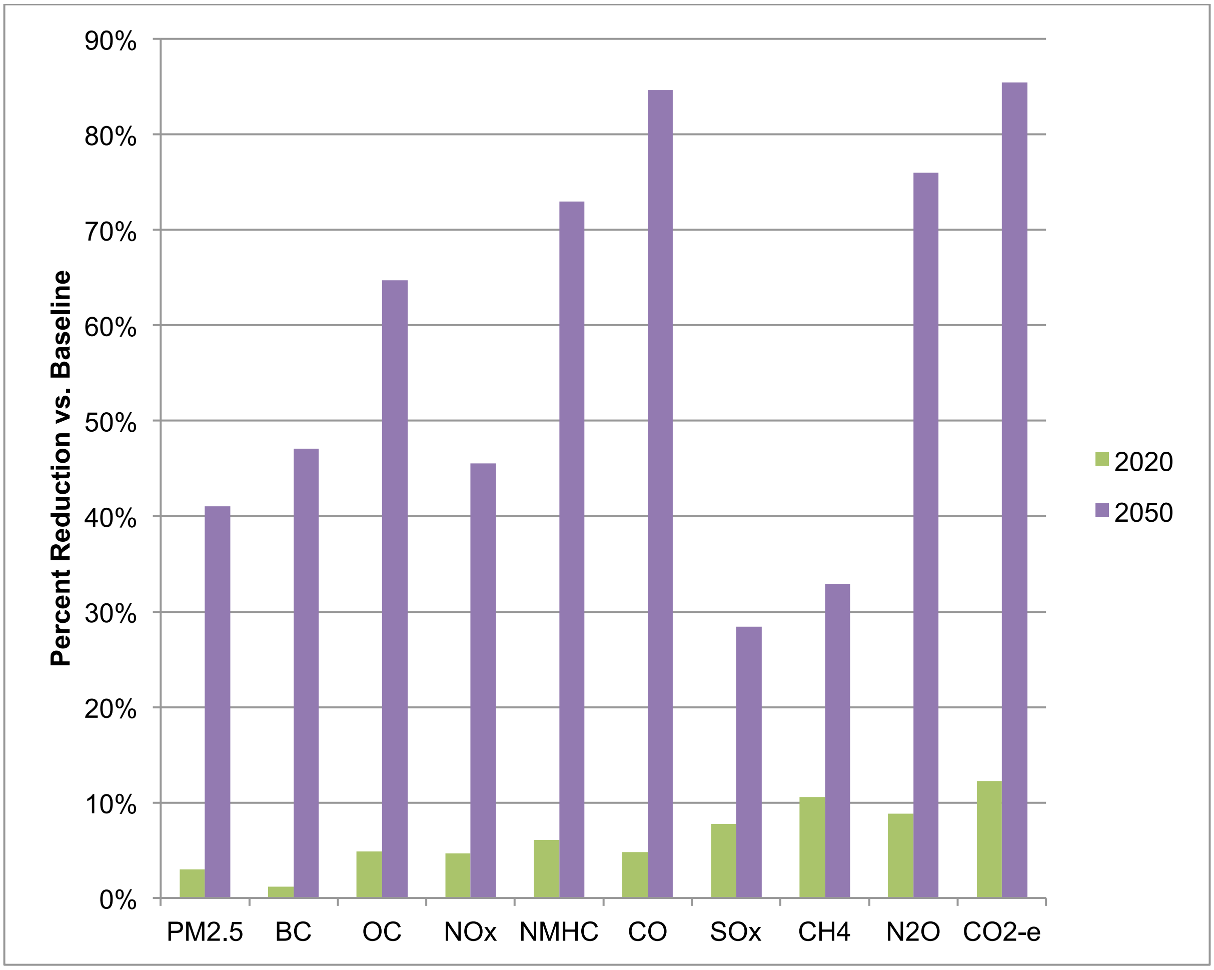

Figure 5-77: Percent reduction in annual emissions in 2020 and 2050 for the 80in50 scenario as compared to the Baseline

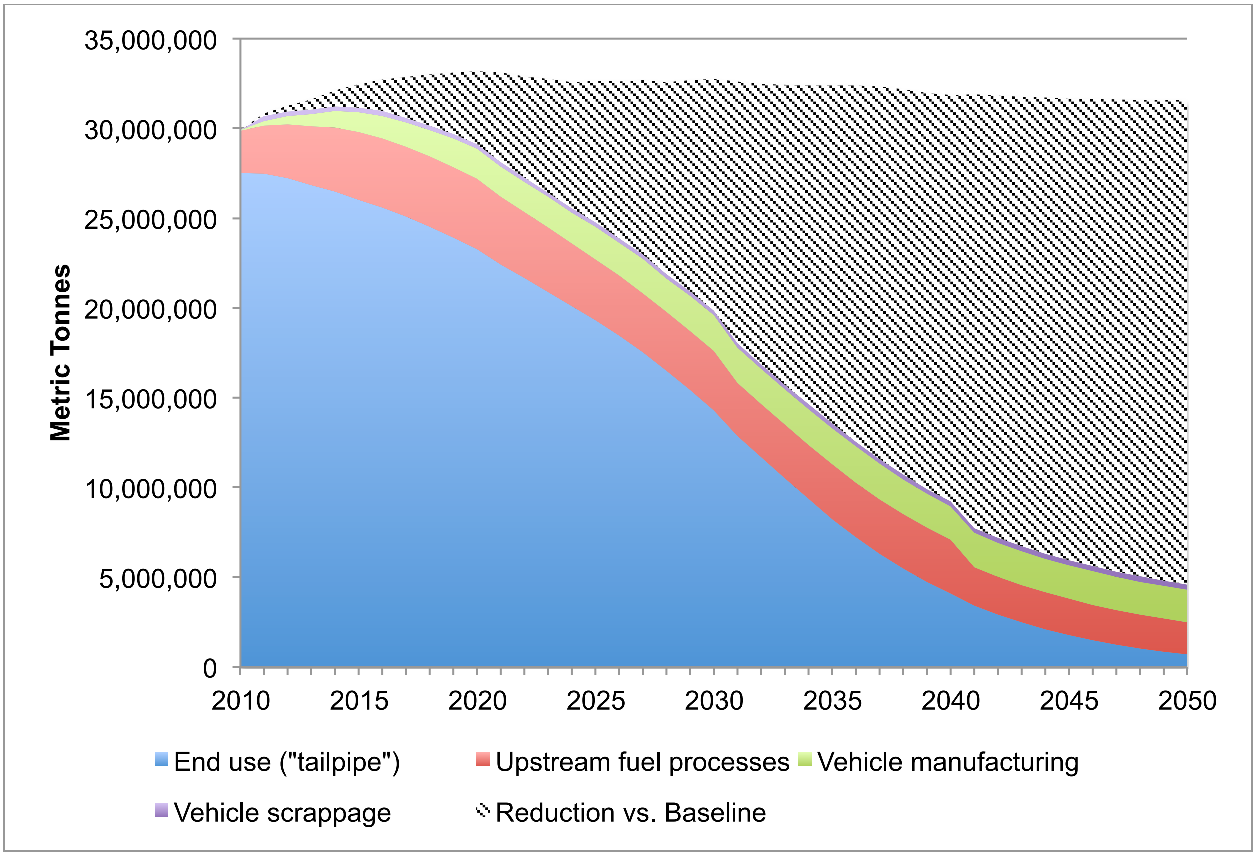

Figure 5-78: CO_2e emissions by lifecycle phase in the 80in50 scenario

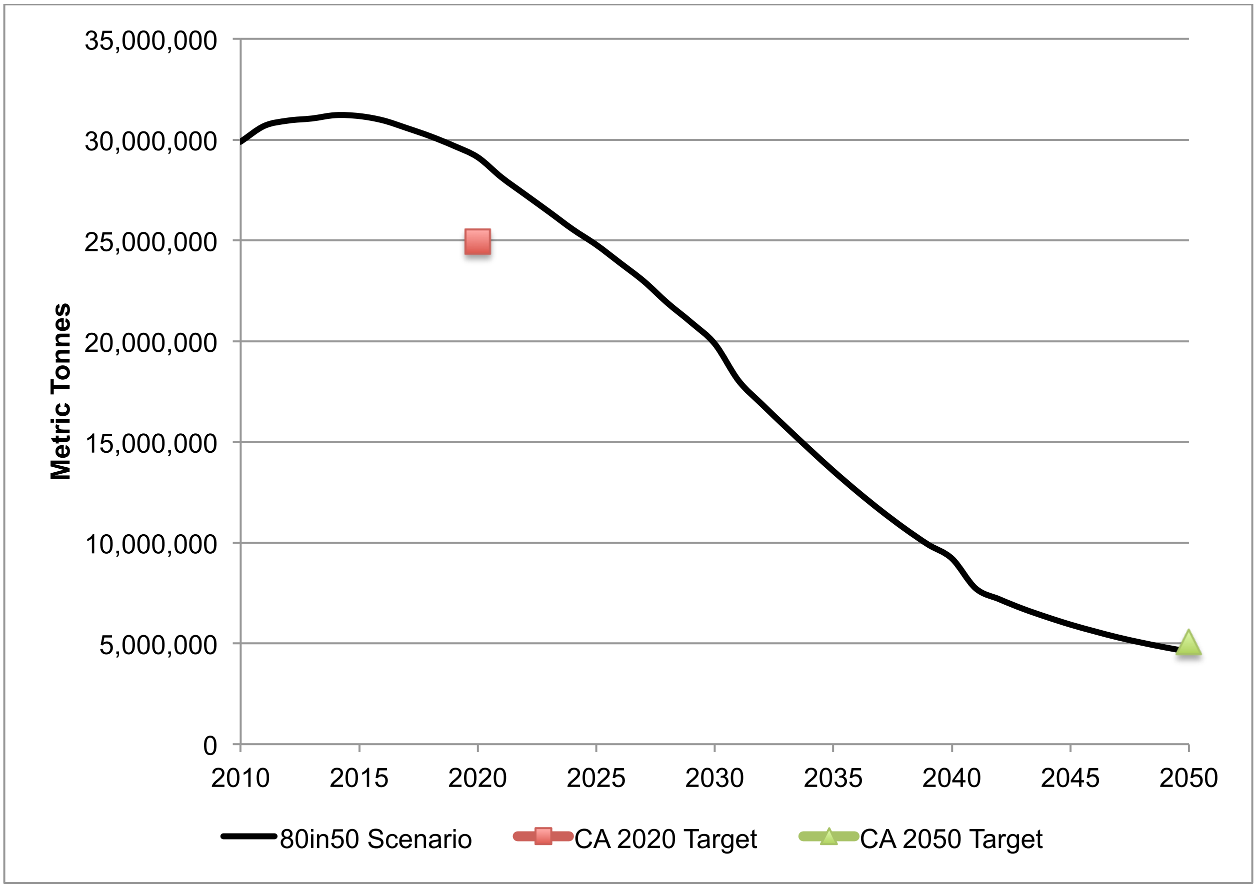

Figure 5-79: CO_2e emissions of the 80in50 scenario versus estimated 1990-level emissions and 80% below 1990-level emissions

5.7.3 Fuel Use Results

The total fuel consumption of the 80in50 scenario represents a substantial reduction versus the Baseline, as is shown in Figure 5-80. Across all fuel types, the total diesel equivalent fuel use in 2050 is 84% less than the Baseline. For diesel and gasoline, the reduction in 2050 is even more striking—96% less petroleum-based fuel is used in the 80in50 scenario as compared to the Baseline. Together, zero tailpipe emission vehicles—hydrogen FCVs and EVs—make up 83% of total energy equivalent fuel consumption and account for 96% of total VMT in 2050.

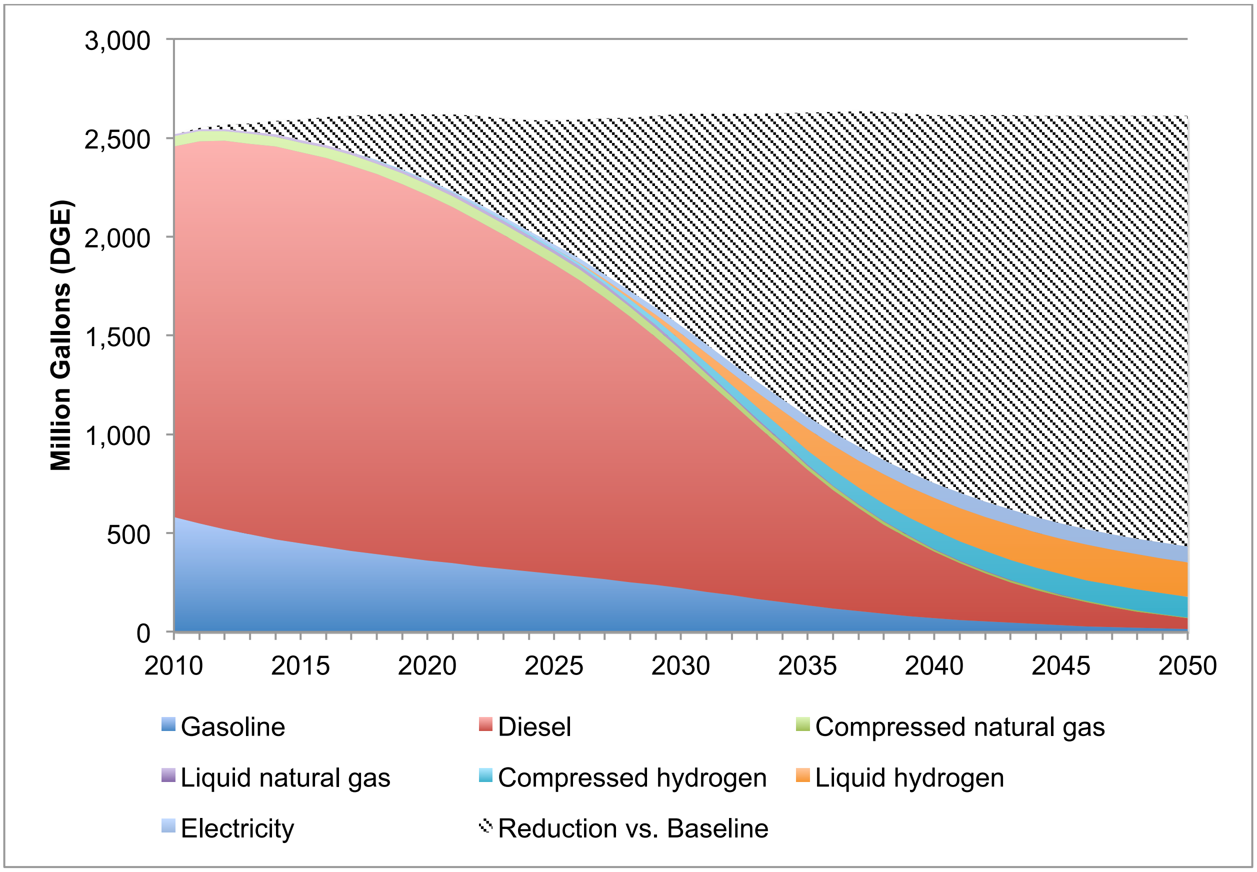

Figure 5-80: Fuel use trends of the 80in50 scenario (million diesel gallon equivalents)

5.7.4 Cost Results

The total costs for all six scenarios are shown in Figure 5-81, and the breakdown by cost area for the 80in50 scenario is shown in Figure 5-82. In comparison to the Baseline, the increased vehicle retail expenses of the 80in50 scenario are offset by fuel cost savings in the first 10 years of the study period. As shown in Figure 5-82 and Figure 5-83, there is a surge in retail costs between roughly 2025 and 2030, as thousands of zero emission vehicles enter the fleet. Learning curve effects drive purchase costs down during this period of rapid adoption, and costs peak around 2030. Over the next 10 years, total cost drop by roughly 25%, and in the final decade costs creep back up such that by 2050, costs are approximately identical to the 2010 value of $19 billion.

The NPV of the 80in50 scenario cost stream is $592 billion, which is 11% lower than the Baseline NPV and 6% lower than the High Efficiency NPV. Out to 2050, the largest savings compared to any of the scenarios are seen in fuel costs. Fuel price projections follow the assumptions made in the previous scenarios and are altered along with the other key uncertain parameters such as learning rates, price floors, and maintenance costs ratios as part of the sensitivity analysis in the next section.

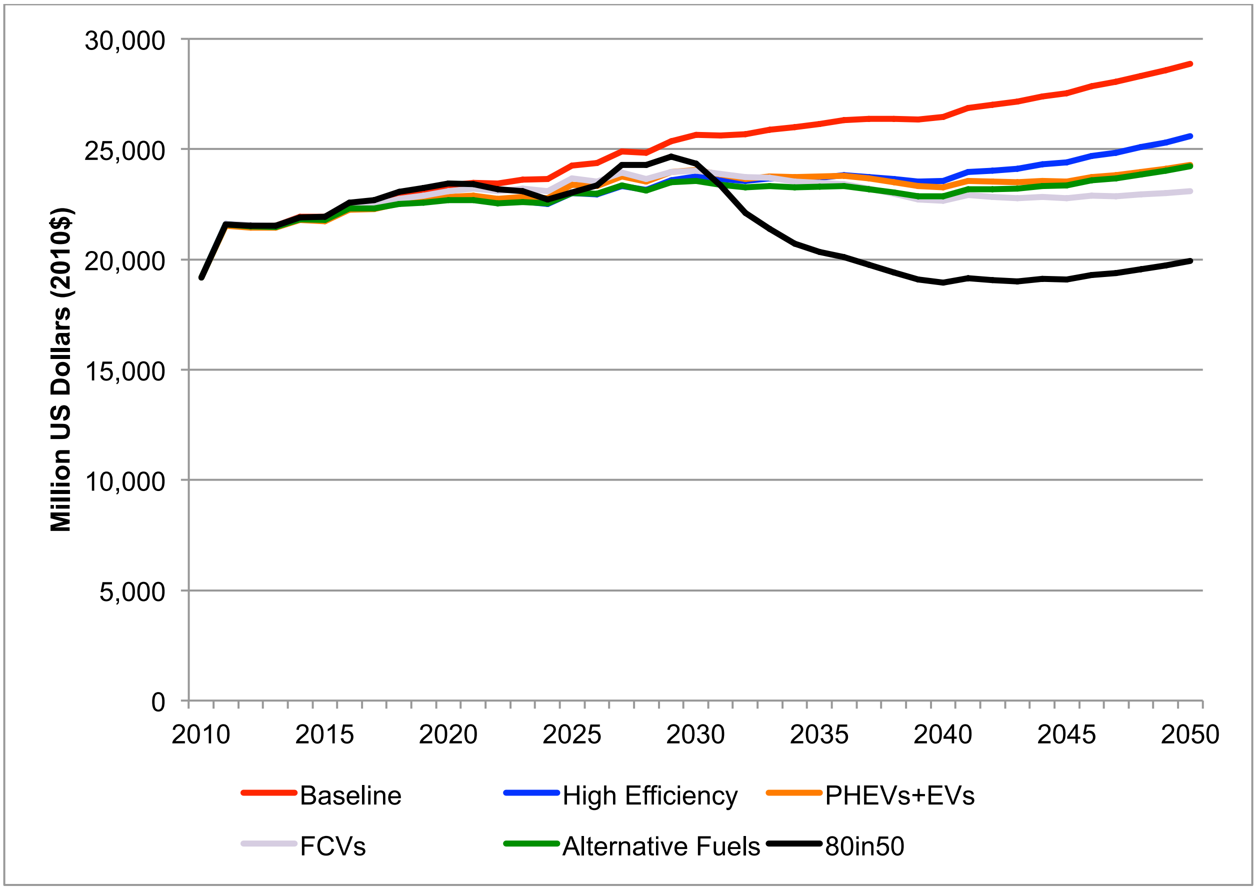

Figure 5-81: Total lifecycle costs of all of the scenarios

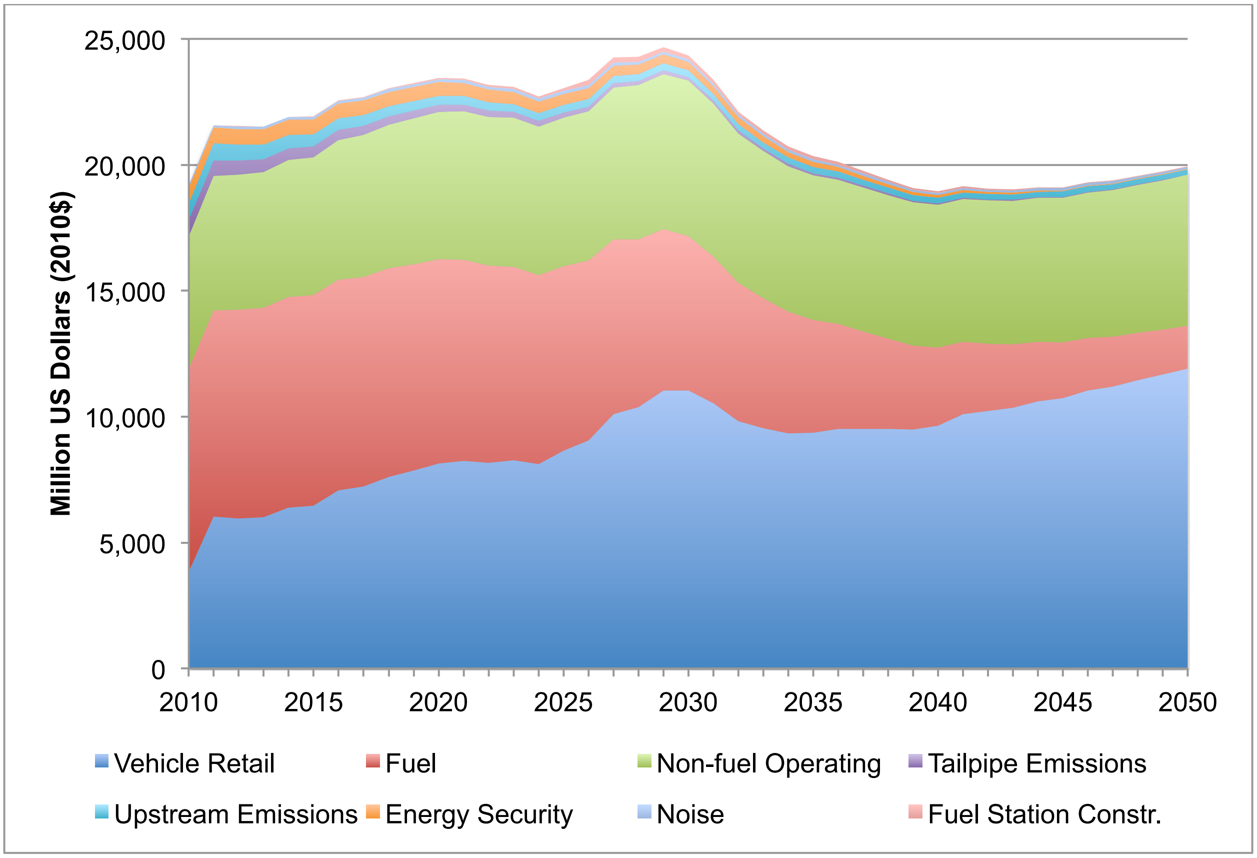

Figure 5-82: Total cost breakdown for the 80in50 scenario

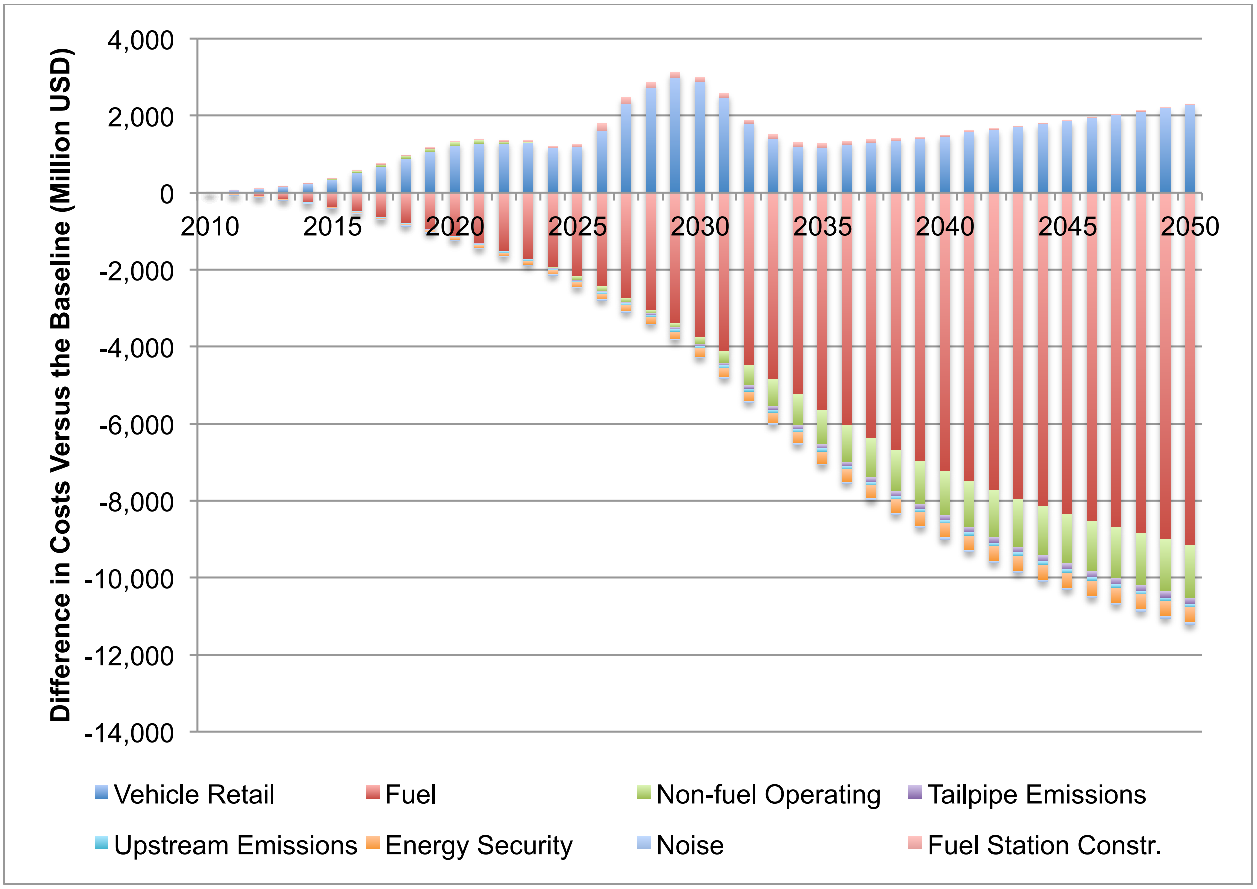

Figure 5-83: Cost differences between the 80in50 and Baseline scenarios (positive values imply costs larger than the Baseline, negative values the inverse)

5.8 Sensitivity Analysis

There are hundreds of data inputs and methodological assumptions that comprise TOP-HDV, and there is an inherent uncertainty associated with each of the input and output modeling parameters. The primary objective of this project is to investigate the *relative* cost differences between each of the six long-term technology pathway scenarios. As such, the focus of the first part of the sensitivity analysis is to study the parameters that have differing cost impacts on each of the six scenarios. Table 5-21 lists the key modeling parameters in TOP-HDV and those that were examined as part of the sensitivity analysis. The parameters in the left hand column such as per-vehicle VMT, sales/scrappage ratio, and choice of CO_2-equivalency factors can have a substantial effect on the absolute value of each of the scenarios; however, when varied, each of these parameters has a negligible impact on the relative total cost differences between the scenarios. For example, if per-vehicle VMT is increased by 50%, costs for all of the scenarios increase substantially, as VMT is directly proportional to fuel and maintenance costs, which are two of the largest contributors to total costs (vehicle retail costs are the third major contributor). However, despite large changes in the absolute value of total costs, the relative costs between each of the six scenarios remain virtually identical.

The sensitivity of the NPV results to each of the parameters in the right-hand column of Table 5-21 was tested by varying each of these variables per the adjustments described in Table 5-22. These adjustments were done for both the Baseline and 80in50 scenarios. These two scenarios were chosen because they represent the two extremes in terms of advanced vehicle and fuel penetration. Whereas the Baseline scenario includes only conventional vehicles, NGVs, and hybrids as well as fossil-based fuels, the 80in50 scenario incorporates all of the vehicle types in TOP-HDV and a variety of alternative and conventional fuels. The results for each scenario are shown in Figure 5-84 and Figure 5-85.

Table 5-21: Key modeling parameters with negligible (left-hand column) and non-negligible (right-hand column) effects on the relative costs of the scenarios

Key Parameters with Negligible Effects on the Relative Costs of the Scenarios	Key Parameters with Non-Negligible Effects on the Relative Costs of the Scenarios
• Sales/scrappage ratios (population growth control) • Per-vehicle 1st year VMT • Annual change in per-vehicle 1st year VMT • Survival rates (i.e. EMFAC vs. MOVES) • Annual % change in emission factors for new MY2011 and later vehicles	• Fuel consumption rates of hybrids and other advanced technology vehicles vs. conventional vehicles • Annual reduction in new vehicle fuel consumption • 2010 retail prices for conventional and non-conventional fuels

• Absolute value of emission factors • Choice of CO_2-equivalency factors and absolute value of factors	• Annual % change in fuel prices • 2010 purchase prices for conventional and advanced technology vehicles (ATVs) • Annual % chance in vehicle purchase price • Learning curve parameters for ATVs • Maintenance and insurance costs for conventional and advanced technology vehicles (ATVs) • Real discount rate

Table 5-22: Modifications for the sensitivity analysis

	Variable Changed by (or to) the Following Amount	
Parameter	**Low Cost**	**High Cost**
Fuel cons. rates of conventional diesel and gasoline vehicles	-10%	+10%
Fuel cons. rates of advanced technology vehicles (ATVs)	-10%	+10%
2010 purchase prices of conventional diesel and gasoline vehicles	-10%	+10%
2010 purchase prices of ATVs	-10%	+10%
2010 retail prices of conventional diesel and gasoline	-10%	+10%
*2010 retail prices of alternative fuels and electricity	-10%	+10%
2010 maintenance costs of conv. diesel and gasoline vehicles	-10%	+10%
2010 maintenance costs of ATVs	-10%	+10%
Annual percent change in conventional fuel prices	-10%	+10%
Annual reduction in new vehicle fuel consumption rates	-10%	+10%
*Annual percent increase in new vehicle prices	-10%	+10%
Price Floor for ATVs	-10%	+10%
* Electricity, alt. fuel annual percent change in price (constant prices over the study period are the default)	-1%	1%
Initial Production Volume Threshold for each vehicle and technology type	Half	Double
Progress Ratio for each vehicle and technology type (95% is the *best estimate* value)	92.5%	97.5%

* Done for the 80in50 scenario only

Note: *In TOP-HDV purchase and maintenance costs can be input directly for 2010 only. For 2011-2050, the costs are controlled with the learning rate input parameters for vehicle purchase costs. The rate of change in maintenance costs is tied directly to the rate of change in purchase costs.*

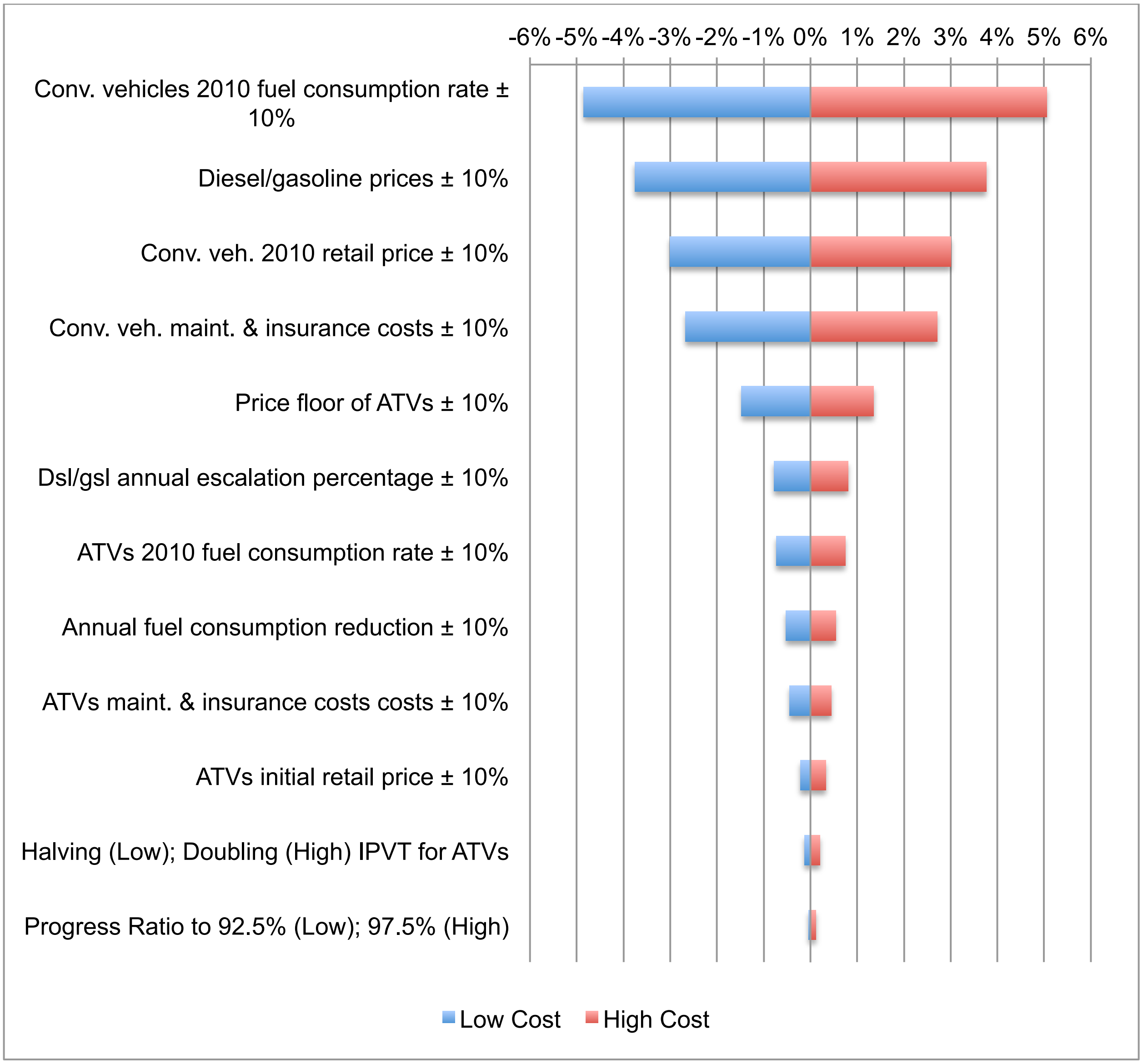

Figure 5-84: Sensitivity results (% change in NPV) for the Baseline scenario

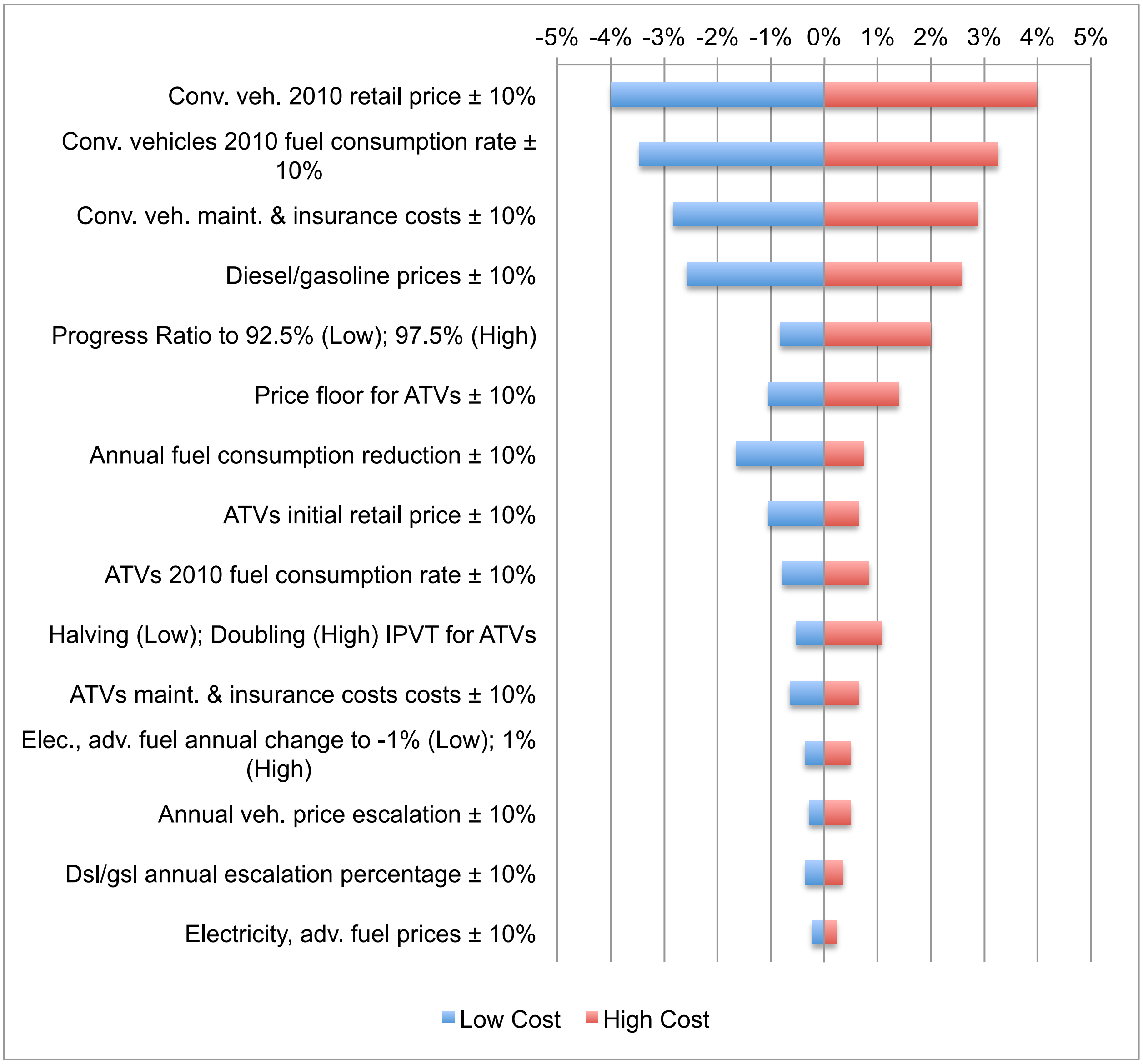

Figure 5-85: Sensitivity results (% change in NPV) for the 80in50 scenario

As shown in Figure 5-84 and Figure 5-85, both scenarios are most sensitive to the inputs regarding conventional vehicles (fuel consumption rates, vehicle purchase prices, and maintenance and insurance costs) and the 2010 price of diesel and gasoline. For both scenarios, each of these parameters is in the top four in terms of their impact on the NPV. Conventional vehicles and fuels are a key component of the Baseline scenario, while there is a vast proliferation of alternative fuels and non-conventional vehicle technologies in the 80in50 scenario. Despite the expeditious transformation of the market in the 80in50 scenario, the principal cost items for conventional vehicles—fuel, vehicle purchase, and maintenance and insurance costs—have the largest impact on the NPV of the scenario. This is due to the fact that while the sales market comes to be dominated by advanced technology vehicles by around 2030, conventional vehicles continue to make up a sizeable portion of the in-use fleet over the entire study period and particularly in the early years. While alternative fuels and advanced technology vehicles make up a majority of the costs towards the end of the study period, the conventional vehicle and fuel costs that occur early on have a much larger impact on the NPV because costs in later years are more heavily discounted. As expected, the parameters that control advance technology vehicle costs and learning effects have a much more significant impact on the 80in50 scenario. The biggest disparity between the two scenarios is seen in the effect of the Progress Ratio. In the Baseline scenario, varying the Progress Ratio between 92.5% and 97.5% results in a minimal chance in NPV. However, in the 80in50 scenario, these variations in Progress Ratio result in a 0.8% decrease and 2% increase, respectively, in NPV. In general, for both scenarios, altering the bottom half of the variables in Figure 5-84 and Figure 5-85 by ± 10% results in a change in NPV of less than 1%.

The second part of the sensitivity analysis involved performing *optimistic* and *pessimistic* runs for each scenario by altering the key parameters for advanced technology vehicles and alternative fuels. Looking out to 2050, there is a great deal of uncertainty associated with many of the modeling parameters, but this is particularly true for non-conventional vehicles and fuels. In the heavy-duty market, many of these advanced vehicle and fuel types are in their infancy commercially, and there are some that are still in the proof-of-concept phase. Particularly from a cost perspective, it is challenging to assign values to these technologies and processes with a large degree of confidence. For that reason, each scenario is varied according to the descriptions in Table 5-23. The pessimistic model runs represent futures in which alternative fuels are more expensive, advanced vehicles are more costly to purchase and operate, and learning effects occur over a longer period of time. The pessimistic model runs are meant to represent an upper bound for total costs for each scenario. Conversely, in the optimistic model runs, advanced technology vehicle are more attractive in terms of capital costs and operating expenses. As shown in Table 5-23, there are not as many parameters altered in the optimistic runs. The reasoning behind this is that the *best estimate* runs for each scenario are already fairly optimistic in terms of advanced vehicle costs and performance, and pushing beyond these levels is unrealistic.

As shown in Table 5-23, the input variables for NG vehicles and hybrids are altered lower and higher by 10%, while the variables for plug-in hybrid, battery-electric, and fuel cell vehicles are changed by ± 20%. This is meant to reflect the greater degree of uncertainty for these vehicle types. By comparison, NG vehicles and hybrids are much more mature technologies and therefore, there is less uncertainty with cost estimates for these vehicle types.

Table 5-23: Parameters for the pessimistic and optimistic model runs

Parameter	**Pessimistic (High Cost)**	**Optimistic (Low Cost)**
Fuel cons. rates of ATVs vs. conventional vehicles	+10%	-10%
2010 purchase prices of ATVs	+10% for NGVs and hybrids; +20% for PHEVs, BEVs, FCVs	-20% for PHEVs, BEVs, FCVs
2010 retail prices of alternative fuels and electricity	+20%	Identical to *best estimate* runs
2010 maintenance costs of ATVs	+10% for NGVs and hybrids; +20% for PHEVs, BEVs, FCVs	-10% for NGVs and hybrids; -20% for PHEVs, BEVs, FCVs

Parameter	Pessimistic (High Cost)	Optimistic (Low Cost)
Annual reduction in new vehicle fuel consumption rates	-20%	Identical to *best estimate* runs
Price Floor for ATVs	+10% for NGVs and hybrids; +20% for PHEVs, BEVs, FCVs	Identical to *best estimate* runs
Progress Ratio for each vehicle and technology type (95% is the *best estimate* value)	97.5%	Identical to *best estimate* runs

In Figure 5-86 through Figure 5-88, the error bars on the NPV totals represent the range established by the optimistic and pessimistic model results. The relative size of the error bars for each scenario is directly related to the degree of penetration of advanced vehicles and alternative fuels. As such, the Baseline scenario has the smallest error bar (and thus, the smallest degree of uncertainty), whereas the variance between optimistic and pessimistic is largest for the 80in50 scenario.

Figure 5-86 and Table 5-24 show that the relative differences in the NPVs for the six scenarios are similar for the best estimate and optimistic model runs. Compared to the Baseline, the NPVs of the non-80in50 scenarios are approximately 6 to 8% lower. The NPV of the 80in50 scenario is roughly 11% and 13% lower than the Baseline in best estimate and optimistic model runs respectively. In the pessimistic model runs, the NPV totals for the six scenarios are clustered more tightly, with the non-Baseline scenarios providing savings in the range of 2 to 5%.

Two additional sets of runs were performed to test the sensitivity of the model to the input assumptions for diesel and gasoline prices over time as well as externality costs. In the *high costs* model runs, the prices for diesel and gasoline are set to escalate at 2% per year (previously, this escalation rate was set to roughly 1.2% for each fuel based on projections by the California

Energy Commission [313]), and the damage cost values for tailpipe emissions, upstream emissions, energy security, and noise are set to “High cost” on the *Scenario Builder* sheet. In the *low costs* runs, diesel and gasoline prices are held constant over the study period, and the externality costs are set to their “Low cost” values. The NPV results for the six scenarios are shown in Figure 5-87 and Table 5-25 for the high costs runs and Figure 5-88 and Table 5-26 for the low cost runs.

Based primarily on the fact that the reduced costs of the non-Baseline scenarios are dominated by fuel savings, it follows that the non-Baseline scenarios are increasingly attractive when fuel prices are higher. Conversely, the cost savings of the non-Baseline scenarios are diminished in the low cost runs. In the low cost pessimistic model runs, the NPV of the FCVs and 80in50 scenarios are roughly on par with the Baseline.

The final part of the sensitivity analysis looks at the NPV impacts for the *best estimate* runs for all six scenarios when changing the real discount rate from 2.1% (which is based on the 30-year interest rate for US Treasury) to 7%. This higher value for the real discount rate is based on total societal cost analyses done by the EPA and NHTSA in support of their HD vehicle GHG and fuel efficiency regulation [105, 189]. The higher the discount rate, the less society values increased or decreased costs in the future. As shown in Figure 5-89, in setting the discount rate to 7%, the NPVs of all six scenarios are more tightly clustered, with the non-Baseline scenarios providing roughly 4-6% savings versus the Baseline.

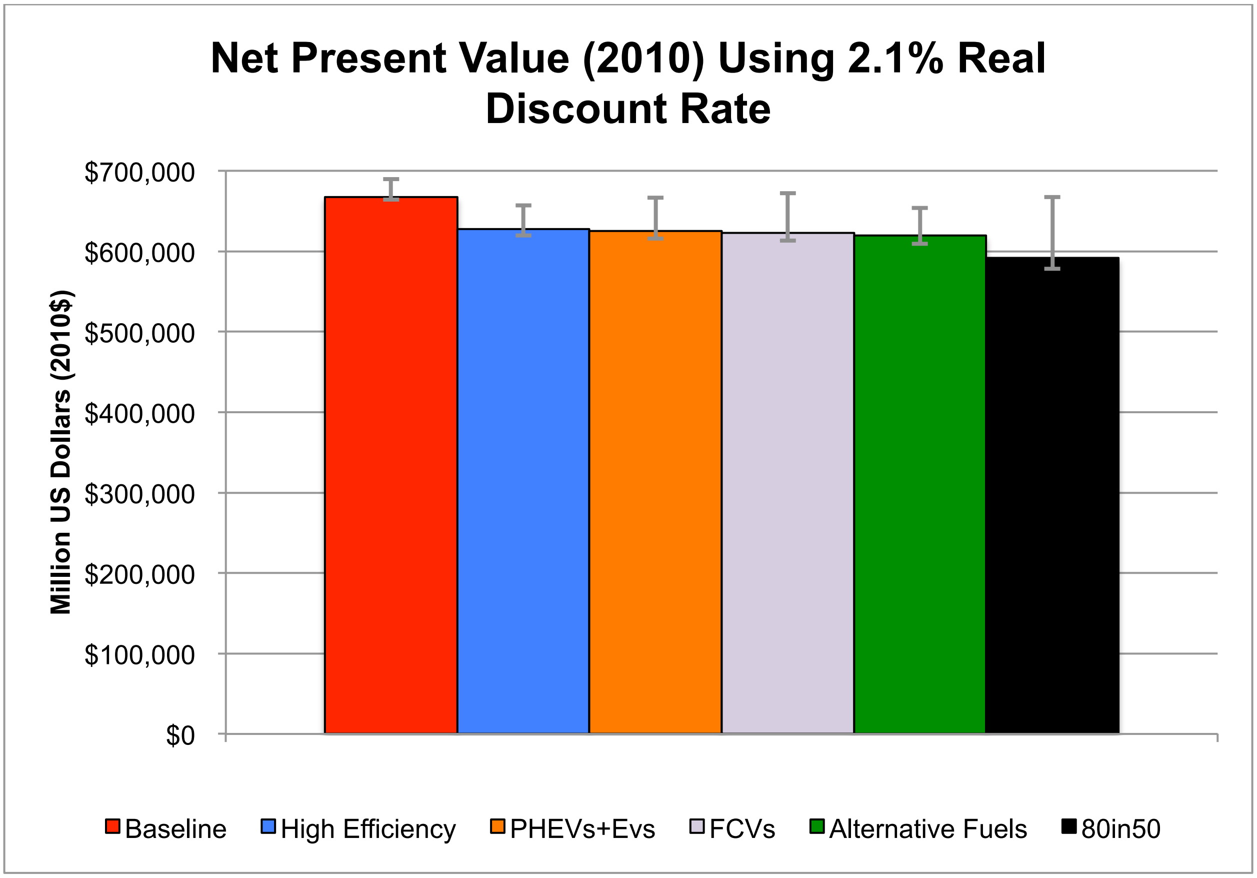

Figure 5-86: NPV results for all six scenarios with optimistic (lower extent of error bar) and pessimistic (upper extent of error bar) model runs

Table 5-24: NPV results for each scenario as compared to the Baseline

Scenario	NPV Percent Difference Versus the Baseline Scenario		
	Pessimistic	**Best Estimate**	**Optimistic**
High Efficiency	-4.7%	-6.0%	-6.7%
PHEVs+EVs	-3.0%	-6.3%	-6.8%
FCVs	-2.4%	-6.7%	-7.6%
Alternative Fuels	-5.1%	-7.2%	-8.1%
80in50	-3.2%	-11.4%	-12.9%

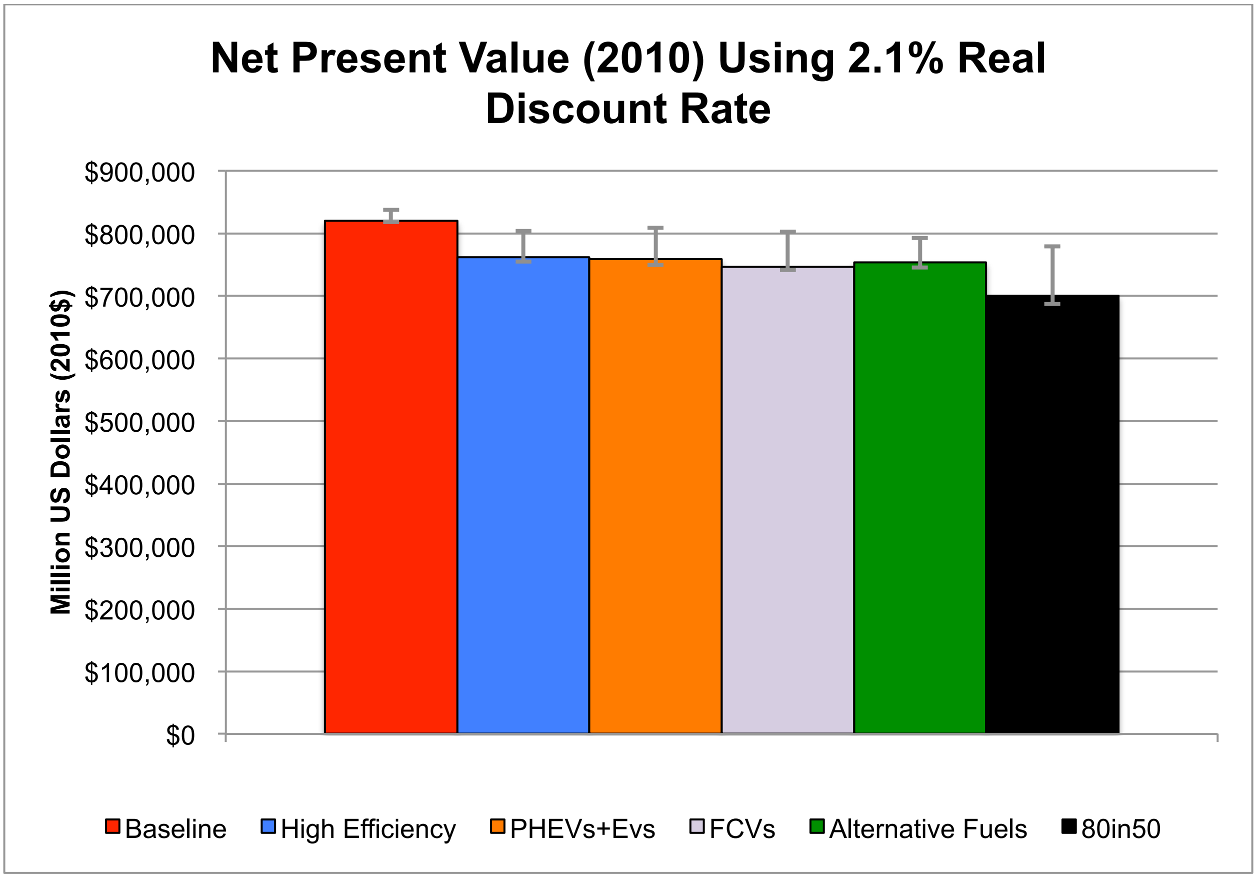

Figure 5-87: NPV results for all six scenarios; high petroleum and damage costs

Table 5-25: NPV results for each scenario as compared to the Baseline; high petroleum and damage costs

Scenario	**NPV Percent Difference Versus the Baseline Scenario**		
	Pessimistic	**Best Estimate**	**Optimistic**
High Efficiency	-4.0%	-7.1%	-7.7%
PHEVs+EVs	-3.4%	-7.4%	-8.4%
FCVs	-4.1%	-8.9%	-9.4%
Alternative Fuels	-5.4%	-8.1%	-8.9%
80in50	-7.0%	-14.5%	-16.0%

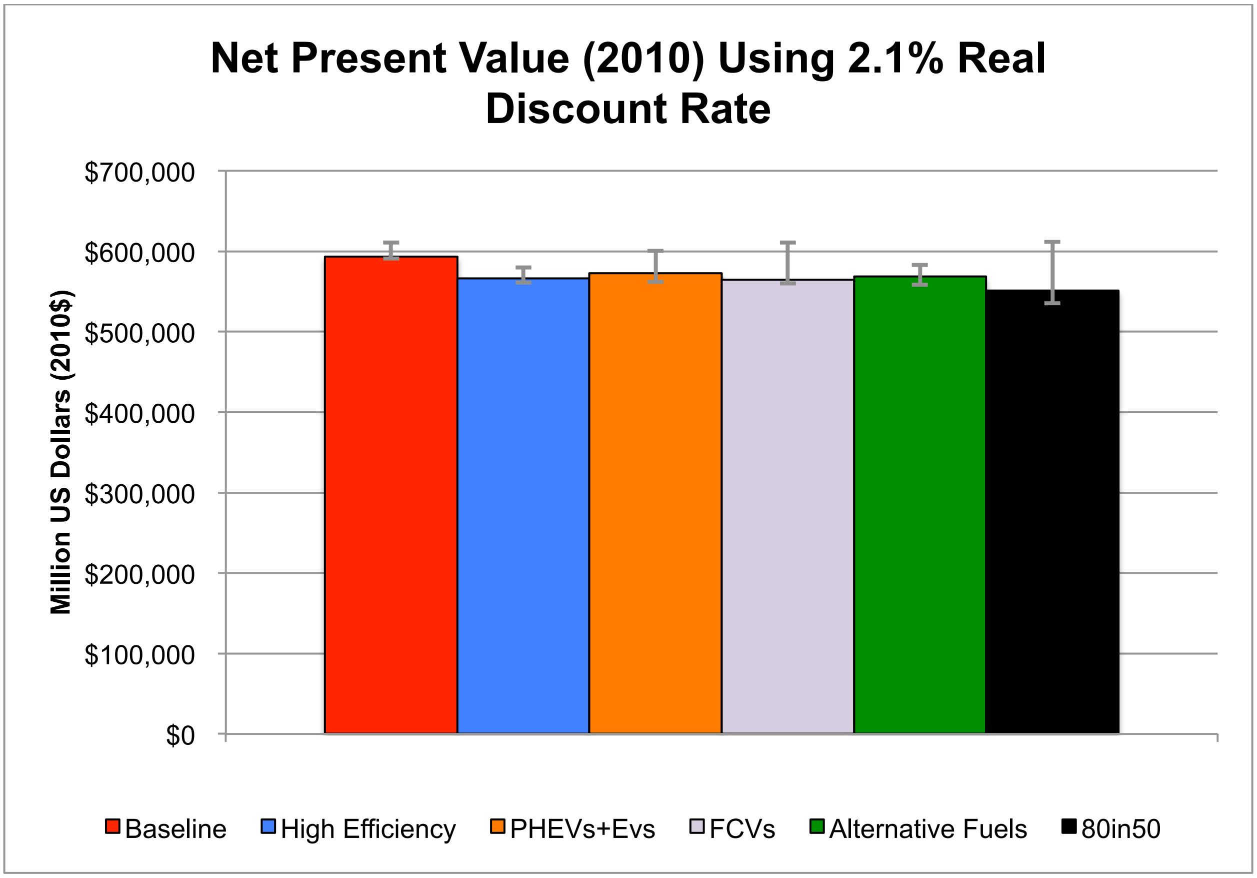

Figure 5-88: NPV results for all six scenarios; low petroleum and damage costs

Table 5-26: NPV results for each scenario as compared to the Baseline; low petroleum and damage costs

Scenario	NPV Percent Difference Versus the Baseline Scenario		
	Pessimistic	Best Estimate	Optimistic
High Efficiency	-4.5%	-4.5%	-4.3%
PHEVs+EVs	-1.8%	-3.5%	-5.1%
FCVs	-0.2%	-4.8%	-5.4%
Alternative Fuels	-4.7%	-4.1%	-5.6%
80in50	-0.1%	-7.1%	-9.5%

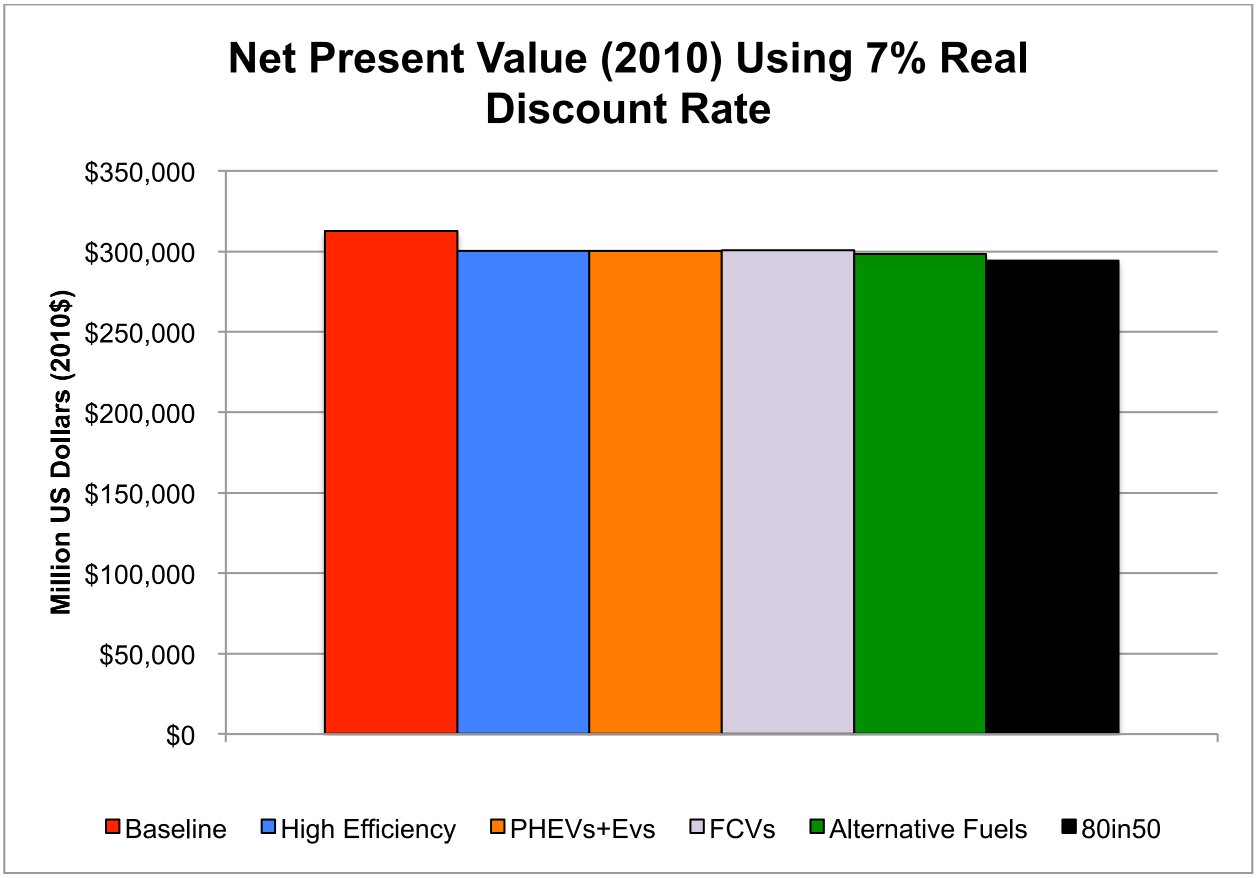

Figure 5-89: NPV results for all six scenarios using *best estimate* input parameters and a 7% real discount rate

6 DISCUSSION AND CONCLUSIONS

This dissertation research investigates the relative emissions, fuel use, and costs of distinct technology transformation scenarios for the on-road heavy-duty vehicle fleet in California. The project estimates end-user expenses from vehicle purchase, fuel, operating, and refueling station construction costs that are incurred by private entities as well as externality costs that result from HD vehicle activity. The monetized externality costs estimated in this study include damages due to criteria pollutant and GHG emissions, expenditures related to securing petroleum resources, and damages due to vehicle noise. Taken together, these private and external costs represent an approximation of total societal costs, which is used in a cost-benefit framework to explore the impact of various scenarios for introducing advanced fuel and technologies in the HD vehicle fleet out to 2050.

The technology potential of trucks and buses over the next four decades is a central focus of this research. The first non-conventional technology to see wide adoption in the commercial vehicle space has been natural gas, with the largest penetration in the transit bus market. For many advanced fuel and vehicle options, transit buses are an incubator for new technologies. Typical characteristics of the transit bus industry such as a high amount of stop-and-go driving and return-to-base operations are important factors for why non-conventional technology options such as natural gas, hybrid, and hydrogen fuel cell vehicles have seen early adoption in this HD segment. However, in recent years, manufacturers have steadily increased the advanced technology and alternative fuel product offerings across a wide variety of HD vocations, though a number of options such as hydrogen fuel cell, battery electric, and plug-in hybrid technology are still in their infancy commercially. Advancements are required for these and other non-conventional technologies in terms of improved reliability, durability, performance, and cost in order for there to be large-scale uptake across the entire HD fleet. Another crucial barrier to advanced technology penetration is the strong tendency for commercial vehicle users to have a high degree of risk aversion. Often —particularly in the early stages of commercialization—the potential fuel savings benefits are outweighed by the potential costs of vehicle downtime or unforeseen maintenance expenses.

Perhaps the most significant driver for continued vehicle efficiency improvements and increased degrees of electrification and use of alternative fuels are fuel cost savings and the reduced burden of dependency on petroleum-based fuels. Particularly from the industry perspective, fuel savings are generally the most important motivation for investing in an advanced technology. In addition, there are many other factors that might encourage a commercial vehicle user to purchase advanced technologies such as institutional sustainability initiatives, “green” branding and marketing, and regulatory compliance. From a societal perspective, fuel savings benefits are also an important motivator; they can lead to decreased costs for goods and services as well as reduced dependence on oil from conflict regions. In addition, reducing externality damages such as climate change and the negative health and environmental impacts of criteria pollutants are important societal benefits for the increased uptake of advanced technologies.

Results from this research suggest that a combination of strong voluntary and mandatory programs that continually encourage the deployment of more efficient and advanced technologies into the market are required if California is to drastically reduce emissions from the HD vehicle fleet. As evidenced in California, the US, and many places around the world, incentives such as vouchers or tax rebates are an important policy measure for spurring early adoption of advanced vehicle technologies. In addition, a number of countries have introduced (or will soon introduce) regulatory performance standards for commercial vehicles. In the US, the Phase 1 regulations that go into effect in model year 2014 are estimated to reduce fuel consumption and GHG emissions up to 23% by model year 2018 compared to a MY 2010 baseline, and Phase 2 standards are currently under development that will likely ratchet down stringency even further in the 2020 to 2025 timeframe.

Despite the broad set of policies already affecting HD vehicles in California, results from this dissertation and other studies demonstrate that increasingly aggressive measures are required if California is to achieve its mandated targets of drastic reductions in GHG and criteria pollutant emissions. The fuel and technology adoption assumptions of all of the non-Baseline scenarios—and particularly the 80in50 scenario—represent a complete transformation of the HD fleet at rates that have not been previously seen in the HD vehicle sector. Such a radical overhaul requires increased cooperation between government, industry, and other stakeholders in order to accelerate technology improvements and ensure that the rapid deployment of advanced technologies does not unfairly burden HD vehicle owners and operators.

6.1 Methodological Contributions and Areas for Improvement

The TOP-HDV model was developed to investigate the research questions posed in this dissertation. The model amalgamates a number of different methodologies and data from a myriad of sources into a simulation tool that estimates the emissions, fuel use, and private and externality costs for distinct technology pathway scenarios for the HD fleet in California. Individually, the methods or calculations used in TOP-HDV are not novel approaches, but they have never before been synthesized. By combining these methods and calculations, TOP-HDV provides an innovative contribution to vehicle modeling and societal cost estimation research.

The following four sections describe the methodological contributions of this dissertation and elements that might be improved or leveraged in future modeling and research.

6.1.1 Lifecycle Emissions and Fuel Use

The first unique contribution of this research is the estimation of the lifecycle emissions associated with heavy-duty vehicles in California. The lifecycle phases include vehicle manufacturing, processes involved in fuel production and transportation, vehicle end use, and vehicle scrappage. No other published research estimates the emissions from all of these sources for commercial trucks and buses in California.

The input data that was used to generate emissions and fuel use results for this research can be updated as better data emerge. However, there are particular shortcomings in the model.

1) While emissions are estimated for all four lifecycle phases, fuel use is only reported for the vehicle use phase in TOP-HDV.
2) Gasoline vehicle emission factors are calculated using ratios from diesel vehicles. A distinct technology category for gasoline vehicles would improve model accuracy.
3) Emission factors for hybrids and PHEVs are calculated using multiplication factors applied to diesel vehicle emission factors. These multiplication factors are identical for every emitted species and are crude estimates based on a limited number of published sources, which are extrapolated beyond their intended scope. Currently, there is a limited amount of emissions testing data for HD hybrids, but as a growing number of these vehicles enter the fleet, researchers from industry, academia, and government will continue to add to the growing body of HD hybrid emissions testing data, which can be used to update relevant TOP-HDV inputs.

4) Only one source was found that estimates the emissions associated with recycling and decommissioning of a HD tractor truck. In calculating the emissions burden for the other seven vehicle categories, a crude assumption was made that scrappage emissions are directly correlated to vehicle curb weight. Also, it is likely that recycling and scrappage efforts vary a great deal based on the technology of the vehicle. For example, large batteries from full electric vehicles or hybrids may have specific handling and recycling requirements during vehicle decommissioning. Although scrappage has a fairly small impact on the overall emissions inventory, the model can certainly be improved in this area.
5) Calculations of the emissions from vehicle manufacturing are fairly simplistic. Grams per pound emission factors are taken directly from the LEM for vehicle chassis and energy storage systems (i.e. battery packs and fuel storage tanks). For fuel cell vehicles, there are separate estimates for the emissions associated with chassis and driveline manufacturing. As with scrappage, the emissions due to vehicle manufacturing generally make a much smaller percentage of total emissions than the vehicle use phase, but this module can certainly be expanded and enhanced to produce more accurate results.

6.1.2 Fuel and Technology Advancements

The breadth of non-conventional fuel and technology options that can be modeled in TOP-HDV is also an important contribution of this dissertation. There have been three studies to date that have investigated fuel and technology evolution out to 2050 for the California HD vehicle market. This dissertation makes meaningful additions to this body of research. However, there are number of elements of the methodology that can be improved.

1) For each of the eight vehicle types, annual percent fuel consumption reductions over time for new vehicles are assumed to be identical for each of the eleven technology options. Given that most of these technology options are in the early stages of adoption in the HD vehicle market, it is difficult to assess their technology potential for increased fuel efficiency. Moreover, even in the case of conventional diesel and gasoline vehicles, estimating the annual percent decrease in fuel consumption over a 40-year period is highly uncertain.
2) The number of non-conventional fuel feedstocks that can be modeled in TOP-HDV is limited. For the diesel, natural gas, and hydrogen pathways, the model is only structured to simulate a maximum of three feedstocks in addition to the conventional fossil pathway. Also, the model cannot change the feedstock contributions for gasoline. However, while the volumetric blend percentage of ethanol is set at 10% for the entire study period, users can change the feedstock percentages for ethanol between corn, cellulosic, and a placeholder feedstock. Another shortcoming of TOP-HDV is that other alternative fuels such as LPG or methanol are not currently integrated into model.
3) Technology groupings in TOP-HDV are highly simplified. For example, as discussed in Section 2.1.5.1, the degree of hybridization (i.e. the reliance on energy contributions from the battery) as well as the hybrid architecture (e.g. series, parallel, or power-split) can take on many different permutations. In spite of these important design permutations, the model simply groups all of these variants under the *hybrid* category.
4) In the model, each of the advanced technology options is assumed to offer the identical functionality (e.g. driving range, towing capacity), reliability, and durability of

conventional vehicles. At present, this is likely optimistic, as many advanced technology options require improvements before they can offer identical performance to their conventional counterparts.

6.1.3 Lifetime End User and Externality Costs

Perhaps the most novel contribution of this research is the integration of heavy-duty end-user and externality costs within the same cost-benefit modeling framework. While there are examples of total societal cost studies for the passenger vehicle sector, no other existing models or research that examine technology evolution for the HD vehicle fleet from a total societal cost perspective were found.

The following are the key areas where cost modules in TOP-HDV can be improved.

1) A critical assumption in this research is that the annual fuel efficiency advancements of the non-Baseline scenarios are possible because of increased vehicle technical sophistication, which leads to annual increases in purchase prices (in 2010$). The way TOP-HDV is structured, the annual percentage reductions in vehicle fuel consumption as well as the annual percentage increase in purchase costs are constant over the study period. Therefore, this methodology posits that for a given percent increase in vehicle purchase price, a predetermined percent decrease in fuel consumption can be achieved, and this relationship is constant over time. At present, there are detailed technology potential and cost assessment studies for the HD vehicle fleet that project out to the 2020 time period, but there are no comprehensive reports for the post-2020 timeframe. The inputs for annual technology potential and increased costs should be updated as new research emerges for the HD vehicle fleet.

2) Fuel prices over time are controlled by annual percentage change inputs. As shown in Figure 5-84 and Figure 5-85, the cost of diesel and gasoline and their assumed percent change over time have a relatively large impact on scenario results, so as updated projections become available from sources such as the California Energy Commission and the Energy Information Administration, the model should be updated accordingly. Also, given that for many of the non-conventional fuel feedstock pathways there is little or no commercial price data available, these estimates warrant updates as the alternative fuel market matures and diversifies.
3) TOP-HDV has three scenarios for the grid mix of electricity feedstocks. The evolution of California electrical grid—specifically, the percentage contribution of renewable feedstocks—will have impacts on the price of electricity. However, in the model, the annual percent change in electricity prices is a user input that is not tied to the choice of the electrical grid mix over time.
4) A key feature of TOP-HDV is that purchase prices and per-mile maintenance costs for advanced vehicles decrease as an increasing number of vehicles enter the fleet. In this learning curve methodology, unit costs decrease as cumulative production (which is assumed to be identical to sales) increases. The inputs for all of the learning curve parameters are estimates based on a small number of sources from the light-duty market. There is a great deal of uncertainty with each of these learning curve parameter estimates, but as more cost and sales data materializes for advanced technology HD vehicles, these inputs clearly deserve to be updated.
5) Externalities are monetized in a very simplistic way in the model. For emissions, oil use, and noise, the total inventory value for each of the six scenarios is multiplied by a dollar-

per-unit damage factor to yield total externality costs. While this very rudimentary externality cost estimation method was deemed appropriate for the scope of this research project, these unit damage cost factors should be updated as more refined unit damage cost estimates become available.

6) One of the greatest challenges associated with commercializing alternative fuel and electric transportation technologies is convenient and affordable access to the fuel. Substantial transitions to non-conventional feedstocks and fuels by 2050 require dramatic growth in alternative fuel and renewable electricity production facilities, as well as transmission and distribution installations. There are significant costs associated with all of the changes to the fueling infrastructure and distribution networks that are necessary to enable the scenarios presented in this research. However, this dissertation is quite limited in the estimation of fuel infrastructure costs, focusing narrowly on estimating the costs of new refueling and charging stations, which represent only a fraction of the total costs posed by transforming the transportation sector to low-carbon fuels and energy carriers (i.e. electricity and hydrogen).

6.2 Research Questions, Empirical Contributions, and Areas for Future Work

In investigating the research questions posed in Chapter 1, this dissertation offers several empirical contributions, which are discussed in this section along with areas for future work.

6.2.1 Research Area 1: Relative Costs of the Six Scenarios

How do the six scenarios differ in terms of NPV (in 2010$)?

Using the *best estimate* input parameters, the reductions in the NPV of costs of the High Efficiency, PHEVs+EVs, FCVs, and Alternative Fuels scenarios compared to the Baseline are quite similar—on the order of 6 to 7%. This translates to approximately $40 to $50 billion (2010$) in savings to both the commercial vehicle industry and the general public over the 40-year study period (discounted at 2.1%). The 80in50 scenario stands out from the other non-Baseline scenarios in terms of cost savings—an 11% reduction versus the Baseline, which represents nearly a $76 billion benefit to society.

In the model runs in which the parameters are set to be unfavorable for advanced technologies (i.e., lower fuel and externality costs, higher costs for advanced vehicle retail and operations), the High Efficiency and Alternative Fuels scenarios provide NPV cost savings of roughly 5%, while the PHEVs+EVs scenario only yields a 2% benefit, and the FCVs and 80in50 scenarios provide virtually no cost savings versus the Baseline. In the runs with advanced vehicle-friendly model settings (i.e., higher fuel and externality costs, lower costs for advanced vehicle retail and operations), the total costs of the High Efficiency, PHEVs+EVs, FCVs, and Alternative Fuels scenarios are again clustered together, delivering savings of roughly 8 to 9%. With these model settings, the NPV of the costs of the 80in50 scenario are 16% lower than the Baseline.

Looking at the variance between the *optimistic* and *pessimistic* runs, the cost results of the PHEVs+EVs, FCVs, and 80in50 scenarios are more much uncertain than the High Efficiency and Alternative Fuels cost results. The higher degree of uncertainty in the PHEVs+EVs, FCVs, and 80in50 scenarios is directly a function of the aggressive adoption assumptions for zero (and partial-zero, i.e. plug-in hybrid) emission vehicles in these three scenarios and the fact that zero emission technology is currently in its commercial infancy in most HD applications, and estimates for both purchase and operational costs are much less reliable than for advanced technologies such as natural gas and hybrid vehicles.

How do the costs breakdown in each of the six scenarios?

End-user costs—that is, expenses incurred by owners and operators of HD trucks and buses—make up the large majority of the total costs, as shown in Figure 6-1 and Figure 6-2. Vehicle retail, fuel, and operating costs dominate total costs in each scenario, making up roughly 95% of costs in 2020 and growing to 96% to 98% of costs in 2050. In 2020, there is a relatively small amount of variance between the six scenarios for each of the cost categories due to the fact that in the non-Baseline scenarios, the large scale penetration of advanced technologies starts to accelerate in the 2025 to 2030 timeframe. By 2050, there is a significant amount of divergence in vehicle retail and fuel costs, while the maintenance and insurance costs for all six scenarios are clustered around 30% of total costs. Versus the Baseline, the most dramatic change in costs in 2050 is evident in the 80in50 scenario, with vehicle retail making up nearly 60% of total costs, while fuel costs represent only 9%.

For all five non-Baseline scenarios, fuel cost savings are by far the biggest benefit. Looking at the net present value of the cost differences versus the Baseline in Figure 6-3, fuel cost reductions comprise between 83% and 94% of cost savings, while vehicle retail makes up between 82 and 99% of additional costs. The NPV of cost differences for maintenance and insurance costs are fairly marginal in all cases expect for in the 80in50 scenario, where they are 10% of total savings.

Figure 6-4 is a subset of Figure 6-3 that focuses on externality and fuel station costs. Across all six scenarios, energy security costs are the largest externality cost. For the non-Baseline scenarios, reductions in energy security costs make up between 54% and 72% of total savings. Benefits due to tailpipe emission reductions are largest for the PHEVs+EVs, FCVs, and 80in50 scenarios, while they are fairly modest for the High Efficiency scenario and actually a cost increase for the Alternative Fuels scenario. All five scenarios show cost reductions for upstream emissions damages. The cost benefits of reduced noise are comparatively minor and are largest for the 80in50 scenario, where they represent roughly 7% of total savings. For fuel station construction, costs of the PHEVs+EVs scenario are on par with the Baseline, while the High Efficiency scenario shows a slight cost savings. For the FCVs and Alternative Fuels scenarios, the increase in fuel station construction costs represents a NPV on the order of $200 to $300 million; however, in the 80in50 scenario, these costs are much higher at a NPV of nearly $1.4 billion.

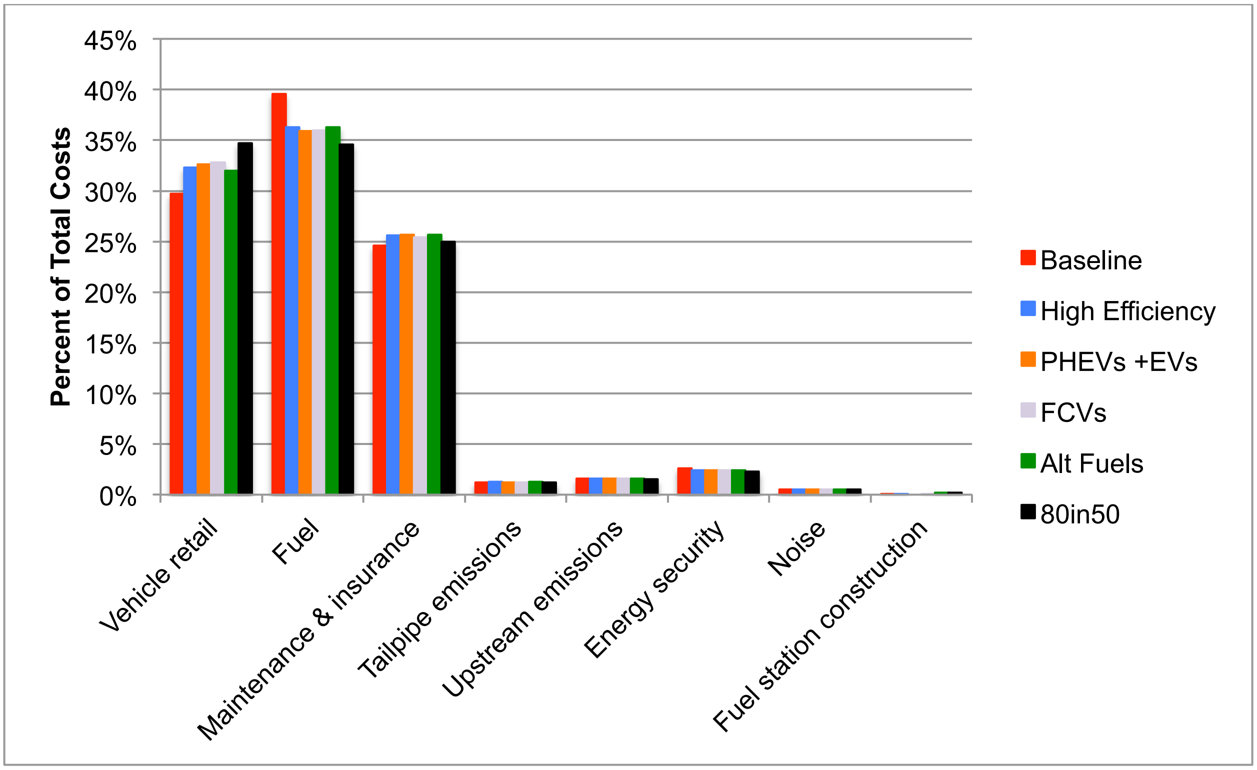

Figure 6-1: Scenario cost breakdowns in 2020

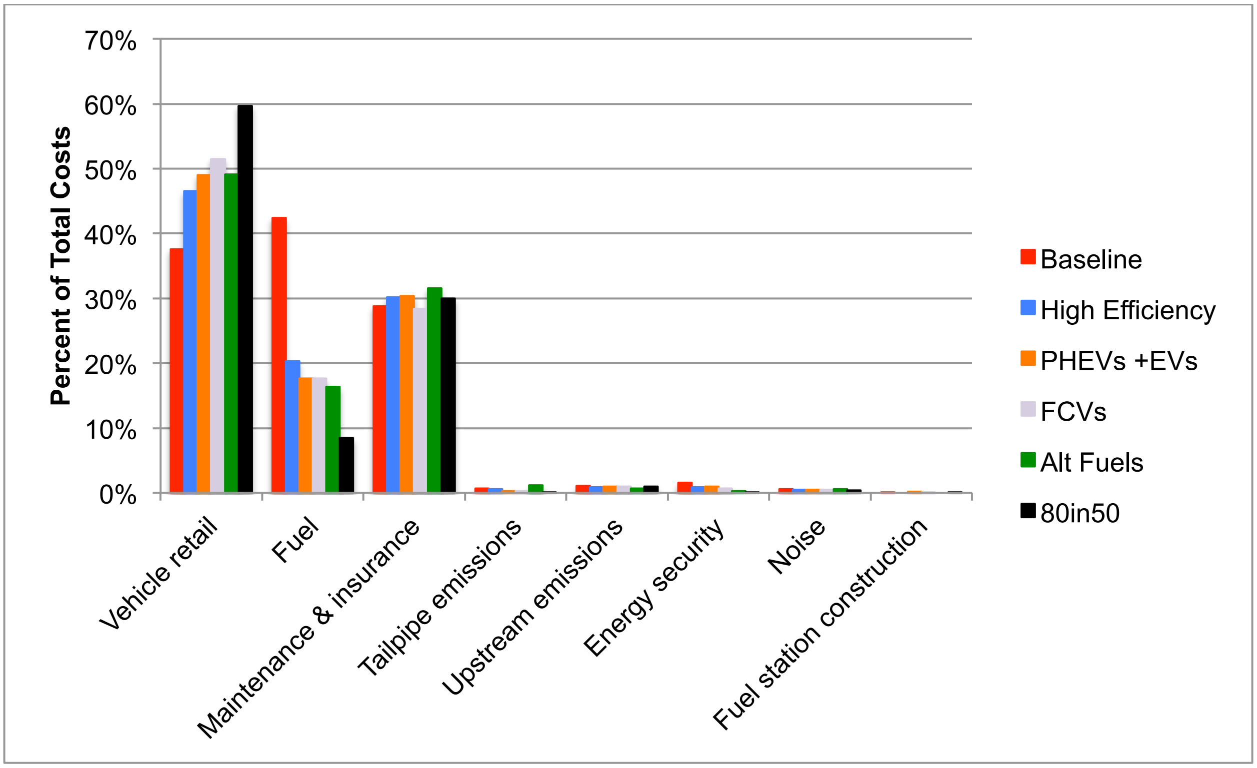

Figure 6-2: Scenario cost breakdowns in 2050

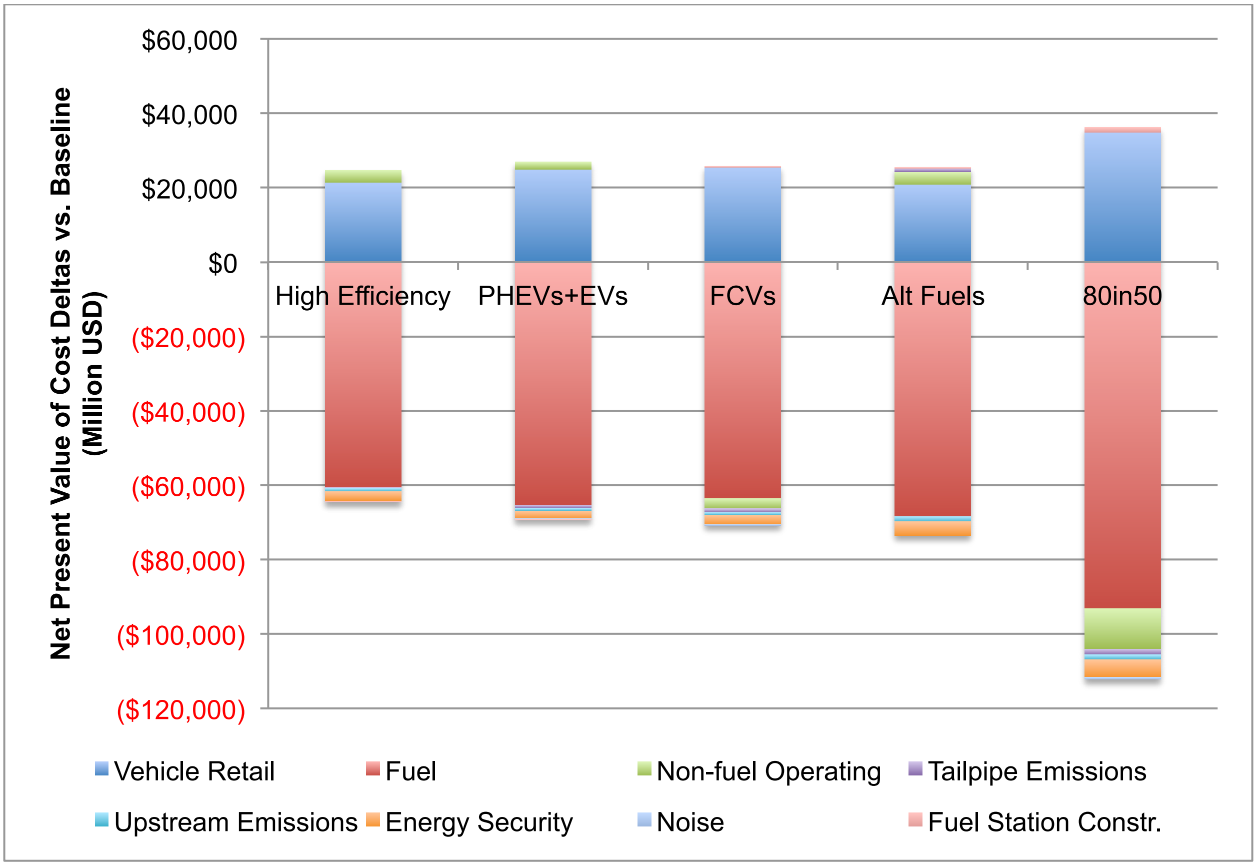

Figure 6-3: Net present value of cost differences versus the Baseline scenario

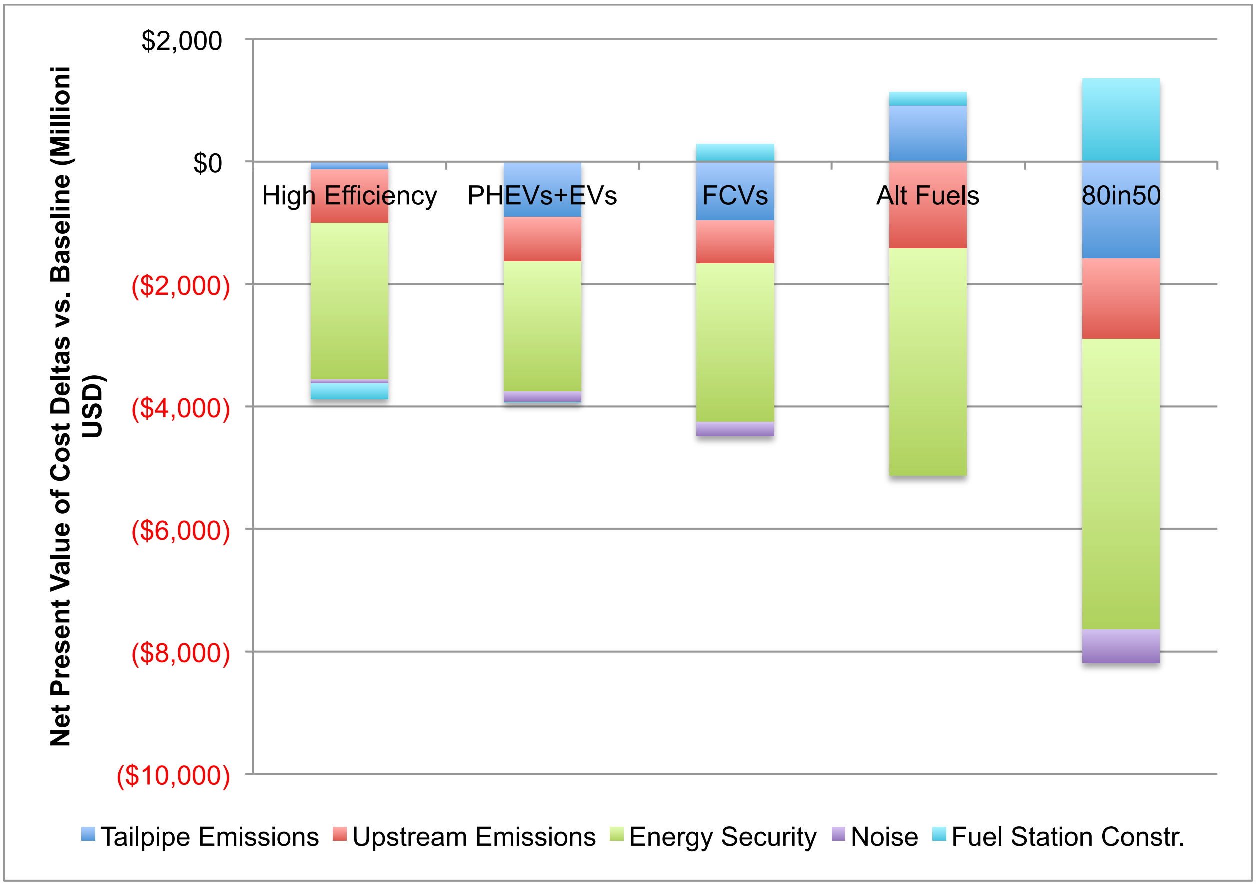

Figure 6-4: NPV of cost differences versus the Baseline for externality and fuel station costs

Looking at the 80in50 scenario, what is the NPV impact of improved vehicle efficiency over time compared to the impact of the rapid adoption of advanced vehicles? What is the impact of the transition to lower-carbon fuels and electricity?

In the *best estimate* model runs, the 80in50 scenario provides roughly an 11% cost savings versus the Baseline. Breaking up the evolution of the HD fleet into three factors: 1) uptake of advanced vehicle technologies, 2) annual percentage reductions in new vehicle fuel consumption for all technology types, and 3) transition to lower carbon fuel feedstocks, the reduction in the NPV of the 80in50 scenario compared to the Baseline as a result of each of these three factors is shown in the colored areas in Figure 6-5, with the total costs of the 80in50 scenario represented by the gray area. Fleet turnover and the rapid introduction of advanced technology vehicles make the most substantial contribution to NPV savings, roughly 87%. Continual advancements in fuel consumption performance in new vehicles represents approximately 12% of the reduction versus the Baseline, and the transition to lower carbon fuel feedstocks contributes the remaining 1% of the savings.

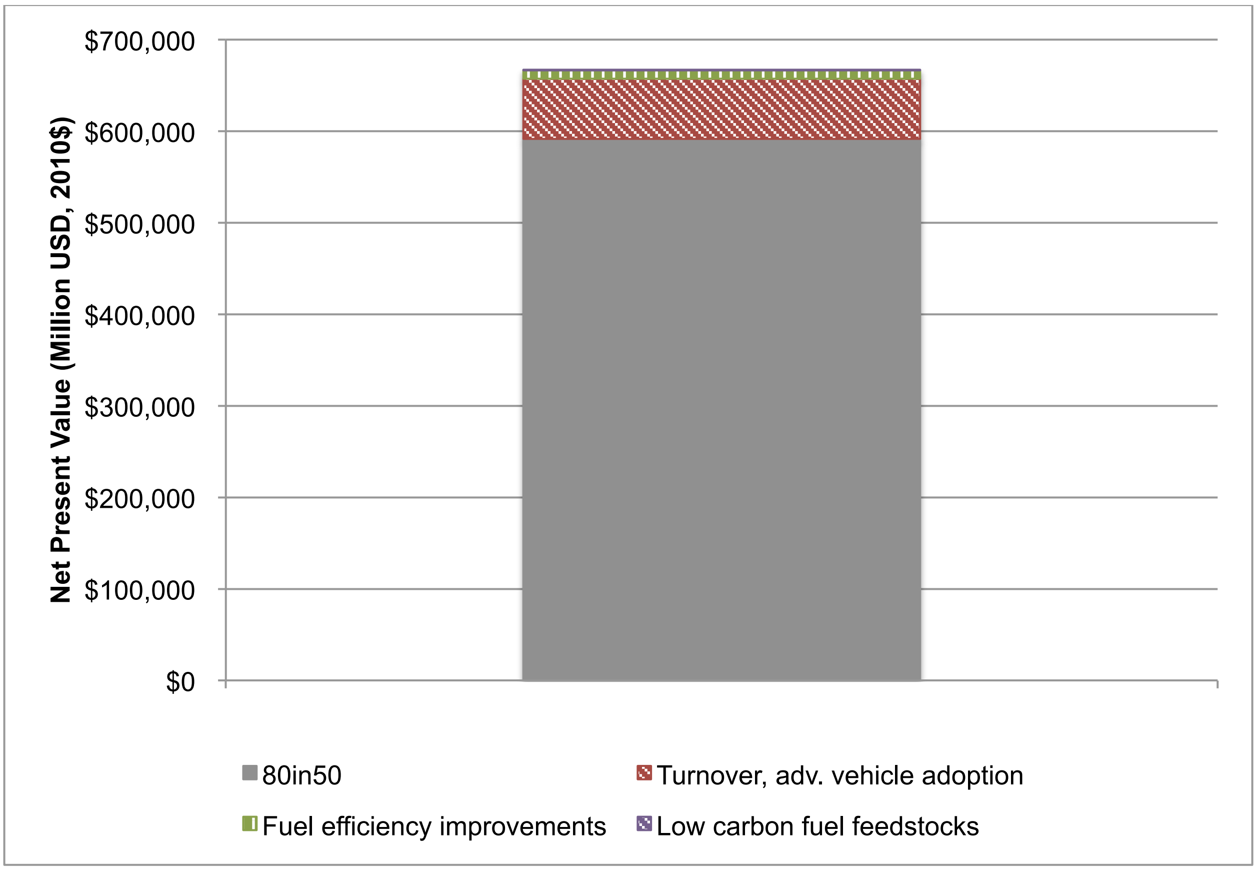

Figure 6-5: Contribution in the reduction in the NPV of costs of the 80in50 scenario from advanced vehicle adoption, annual fuel efficiency improvements, and low carbon fuel feedstocks

6.2.2 Research Area 2: Lifecycle Emissions

How do each of the scenarios compare in terms of emission trends for each of the emitted species as well as CO_2-equivalent emissions?

The cumulative and annual emissions reductions in 2050 compared to the Baseline are shown in Figure 6-6 and Figure 6-7 respectively. In general, cumulative emissions reductions versus the Baseline scenario are on the order of 5 to 30%. With its large penetration of natural gas vehicles, the Alternative Fuels scenario presents some exceptions, as NOx, NMHC, CO, and N_2O emissions are all higher than the Baseline. Cumulative CO_2-equivalent emissions reductions of the four non-80in50 scenarios are all nearly 30%, while the 80in50 scenario eclipses 40%. For all of the emitted species, reductions are largest for the 80in50 scenario, with the exception of SOx and CH_4, where reductions are largest in the Alternative Fuels scenario. However, in the case of CH_4, the superior emission reductions of the Alternative Fuels scenario are likely very sensitive to assumptions about methane leakage in all four lifecycle phases—in particular, from natural gas production and distribution, during NG vehicle refueling, and in on-vehicle processes. The impacts of methane leakage at all stages of the natural gas fuel lifecycle are an important area for future research.

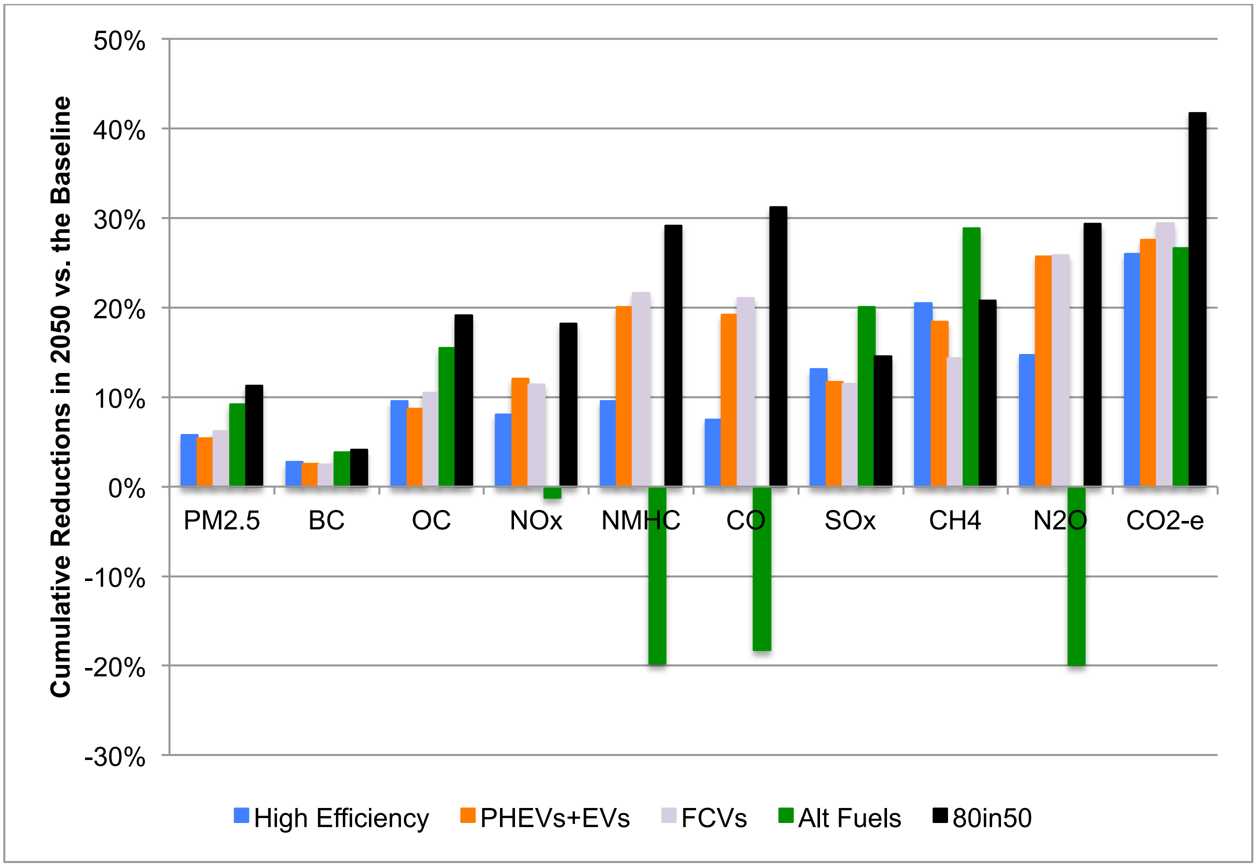

Figure 6-6: Cumulative emissions reductions in 2050 versus the Baseline scenario

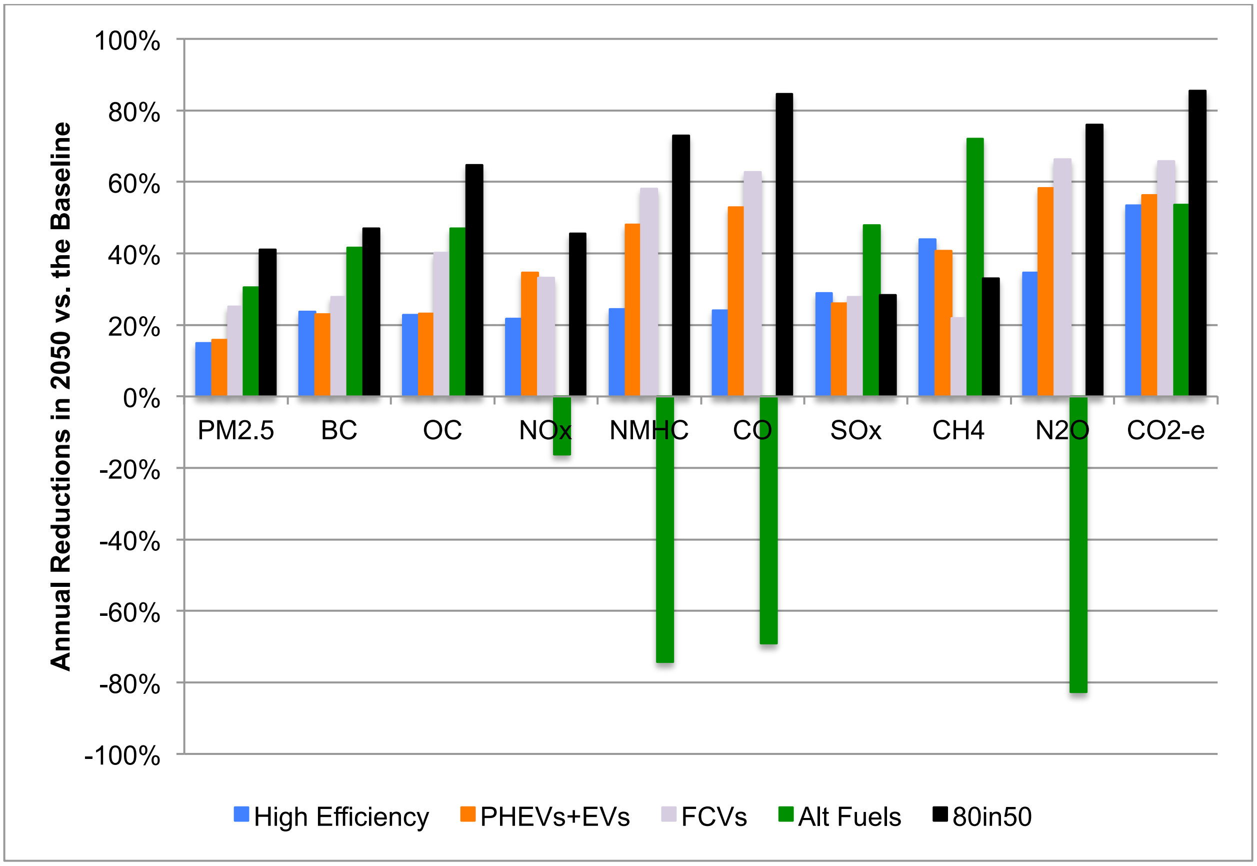

Figure 6-7: Annual emissions reductions in 2050 versus the Baseline scenario

What is the net effect of non-CO_2 emissions on CO_2e totals?

Figure 6-8 and Figure 6-9 show how each emitted species contributes to CO_2e in the High Efficiency and the 80in50 scenarios respectively. As shown in both figures, the net effect of non-CO_2 emissions on CO_2e is relatively negligible. In 2010, black carbon emissions have a strong warming effect. However, as the fleet turns over and an increasing percentage of vehicles are equipped with diesel particulate filters, which are required with MY 2007 and newer vehicles and eliminate 90% or more of $PM_{2.5}$ and BC, the overall effect of BC emissions on CO_2e is reduced substantially by 2020 and almost entirely in 2030 and beyond. Across the entire study period, the large warming effect of methane is counteracted by the cooling effect of SOx emissions. Overall, CO_2e emissions are roughly identical (or slightly lower) than CO_2 emissions.

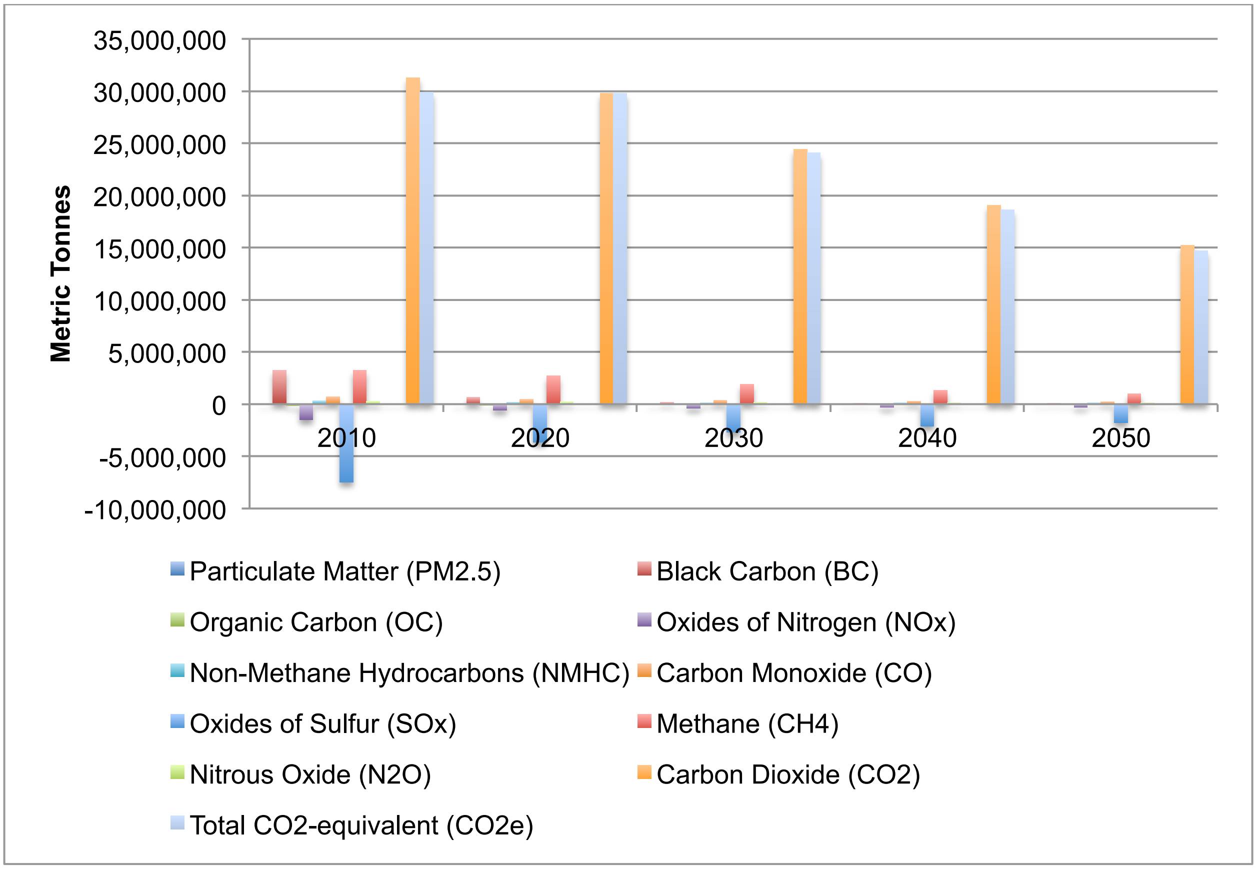

Figure 6-8: CO_2e emissions breakdown for the High Efficiency scenario

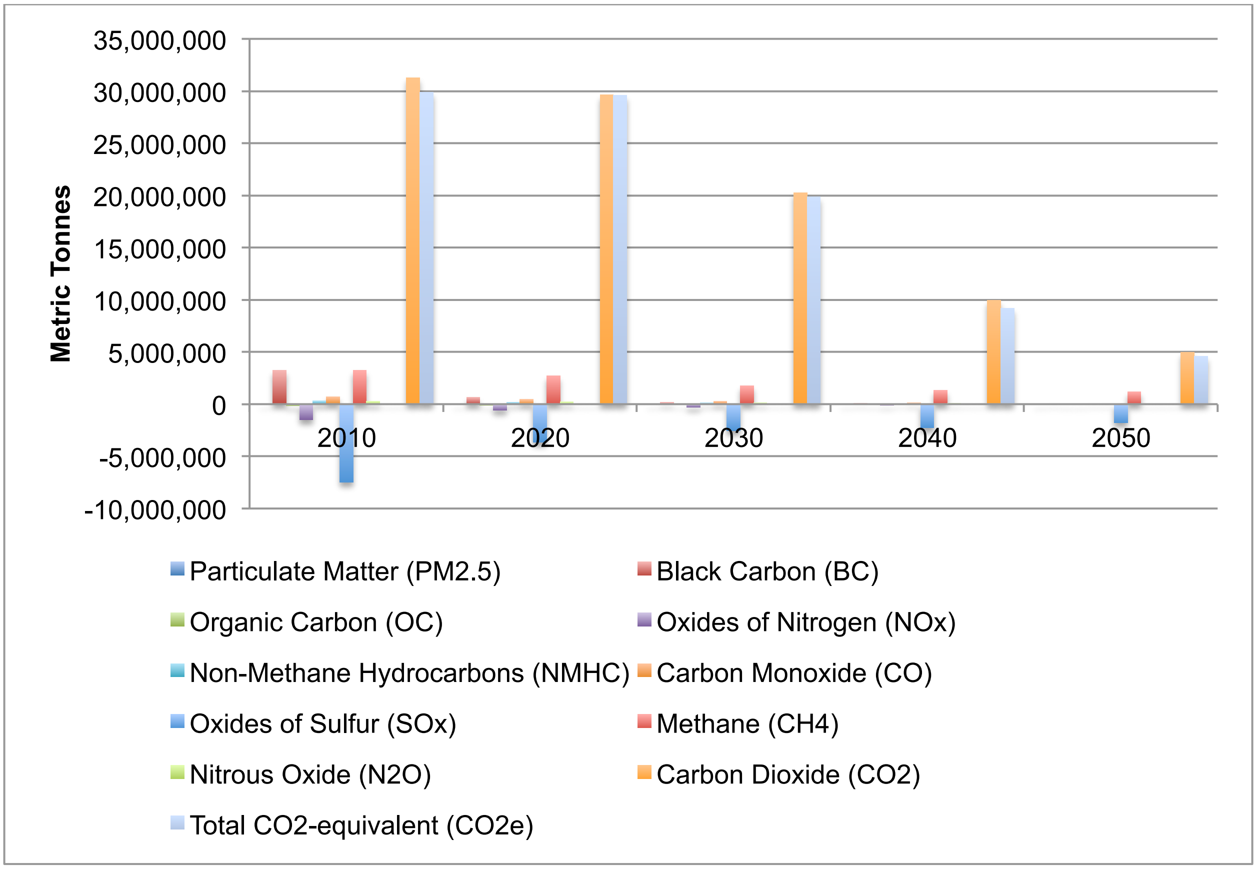

Figure 6-9: CO_2e emissions breakdown for the 80in50 scenario

For each emitted species, what is the contribution from each of the four lifecycle phases: vehicle use, upstream fuel production and distribution, vehicle manufacturing, and end-of-life vehicle scrappage?

The results shown in the Appendix are for the Baseline but are sufficient for giving a broad sense for how the emissions are distributed amongst the four lifecycle phases in each of the six scenarios. For $PM_{2.5}$, BC, OC, NOx, NMHC, and CO, tailpipe emissions are the largest contributor in the early years, but over time fuel production and vehicle manufacturing make up an increasing percentage as overall emission levels decrease. In the case of SOx, CH_4, and N_2O, upstream emissions tend to dominate over the entire time period. For all of the species, emissions associated with vehicle decommissioning are a very small percentage of total emissions.

Looking at the 80in50 scenario, what is the CO_2e emissions impact of improved vehicle efficiency over time compared to the impact of the rapid adoption of advanced vehicles? What is the impact of the transition to lower-carbon fuels and electricity?

In Figure 6-10, the solid gray area represents the total CO_2e emissions of the 80in50 scenario. The dark red, green, and purple dashed areas represent the reductions that are achieved due to advanced vehicle adoption, annual fuel efficiency improvements, and the introduction of low carbon fuel feedstocks, respectively. In the first half of the study period, the annual improvements in fuel consumption rates for all new vehicles are the largest factor in reduced CO_2e emissions. Over time, the impact of advanced vehicle adoption overtakes fuel efficiency improvements as the biggest factor in decreasing CO_2e. The impact of transitioning to lower carbon fuel and electricity feedstocks is marginal in the first 20 years and grows to roughly 10% of total reductions in 2050. Advanced vehicle adoption, fuel efficiency improvements, and lower carbon feedstocks account for 59%, 33%, and 8%, respectively, of cumulative CO_2e emission reductions.

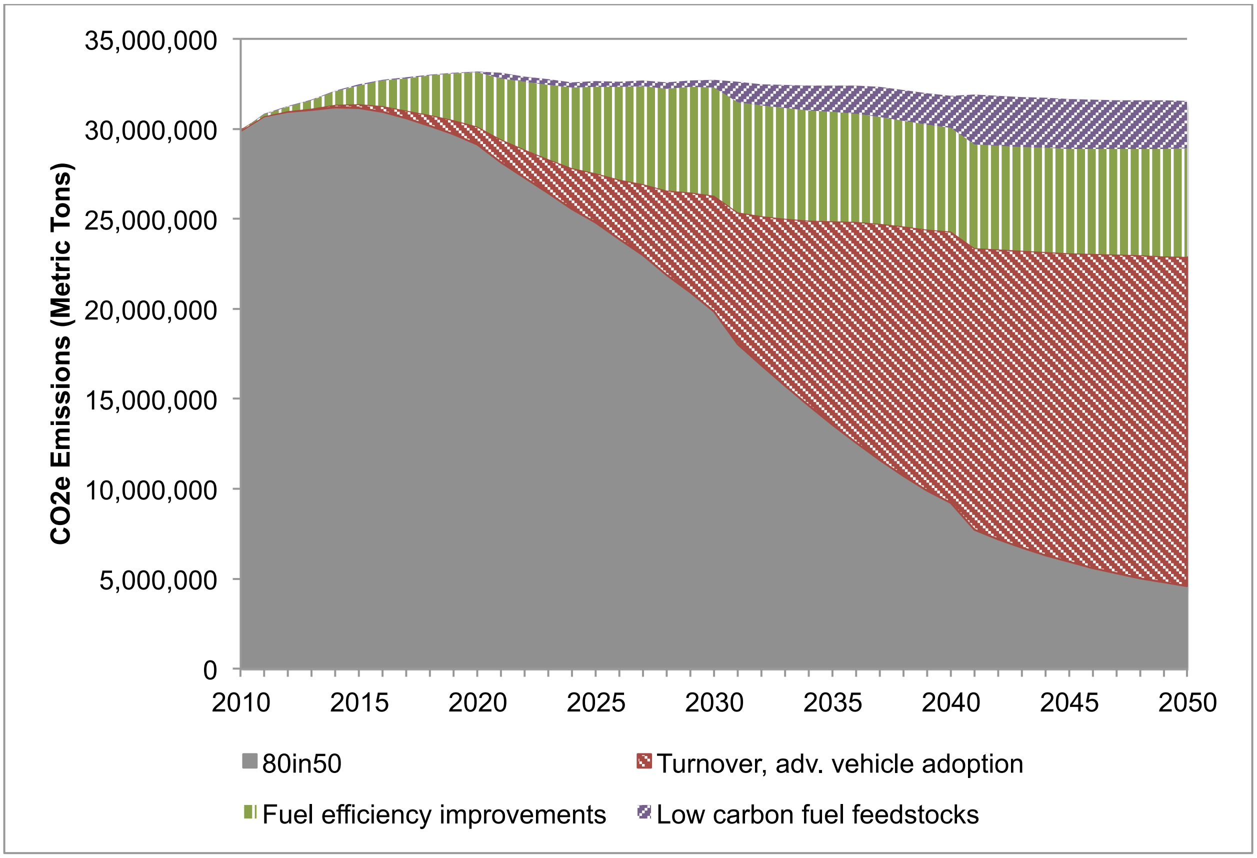

Figure 6-10: Contribution in the reduction in CO_2e emissions of the 80in50 scenario from vehicle adoption, annual fuel efficiency improvements, and low carbon fuel feedstocks

6.2.3 Research Area 3: Fuel Use

How do each of the scenarios compare in terms of fuel use trends?

The fuel use trends for each scenario are shown in Figure 6-11 through Figure 6-14. For conventional fuels (i.e. diesel and gasoline), fuel consumption decreases substantially in all of the non-Baseline scenarios. In 2050, the percent conventional fuel reductions versus the Baseline for the High Efficiency, PHEVs+EVs, FCVs, Alternative Fuels, and 80in50 scenario are 53%, 60%, 67%, 83%, and 96% respectively. Natural gas is featured prominently in the Alternative Fuels, Baseline, and High Efficiency scenarios, accounting for 76%, 25%, and 22% of total diesel-equivalent fuel use for these three scenarios in 2050. The FCVs and 80in50 scenarios are the only scenarios where hydrogen fuel cell vehicles enter the HD vehicle fleet. As shown in Figure 6-13, hydrogen use accelerates much faster in the 80in50 scenario after 2025 and then plateaus towards the end of the study period, whereas in the FCVs scenario, consumption increases fairly steadily in the post-2025 time period. In 2050, hydrogen makes up 65% of total diesel gallon-equivalent (DGE) fuel use in the 80in50 scenario and 24% in the FCVs scenario. The trends for electricity are quite similar when looking at Figure 6-14. In the 80in50 scenario, vehicle electricity use from the grid grows to nearly 5.5 gigawatt-hours, which is roughly 1% of the total projected electricity demand in California in 2050 [216, 332].[33]

[33] See the *Baseline* demand scenarios in McCarthy et al. (2006) and CCST (2011), which project total electricity demand in California to be 420 and 470 terawatt-hours respectively.

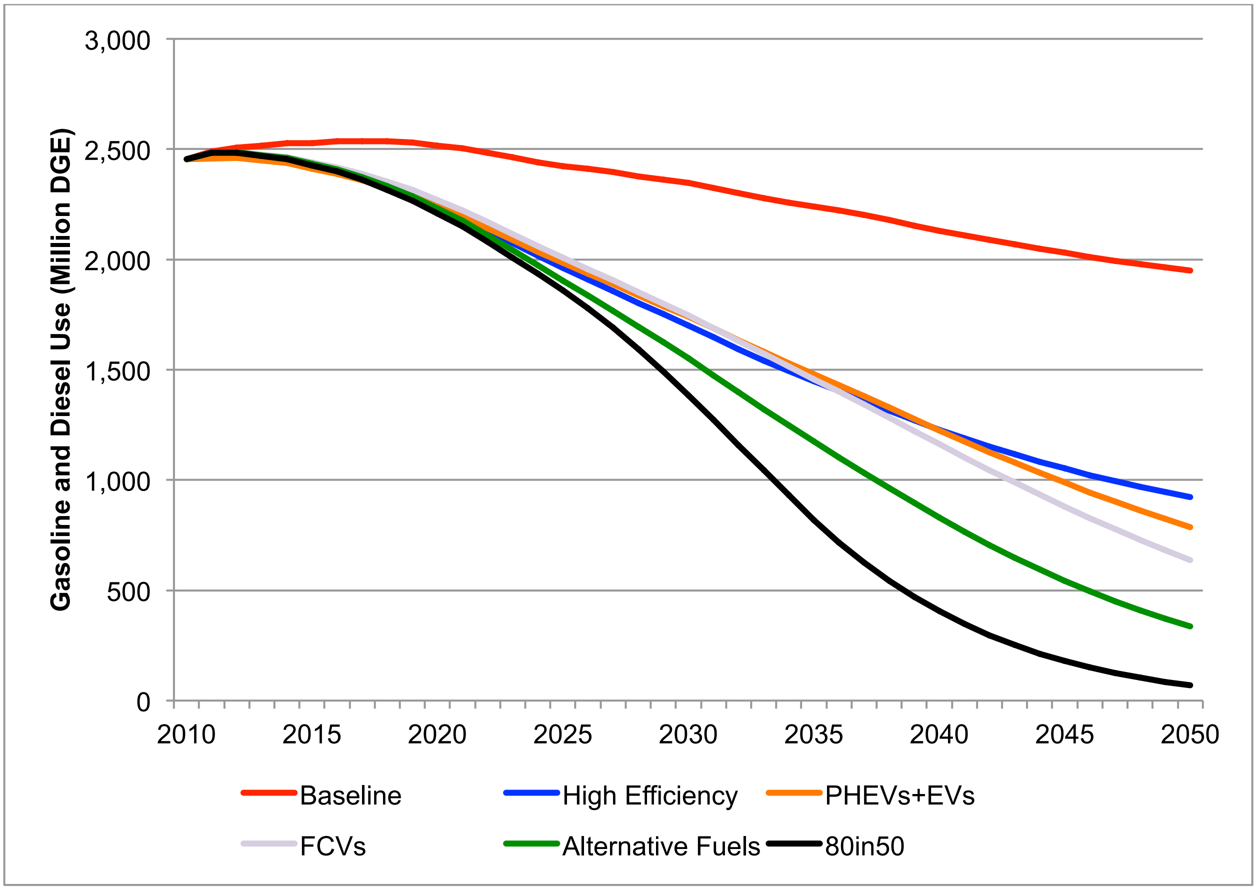

Figure 6-11: Scenario trends for petroleum-based fuel consumption

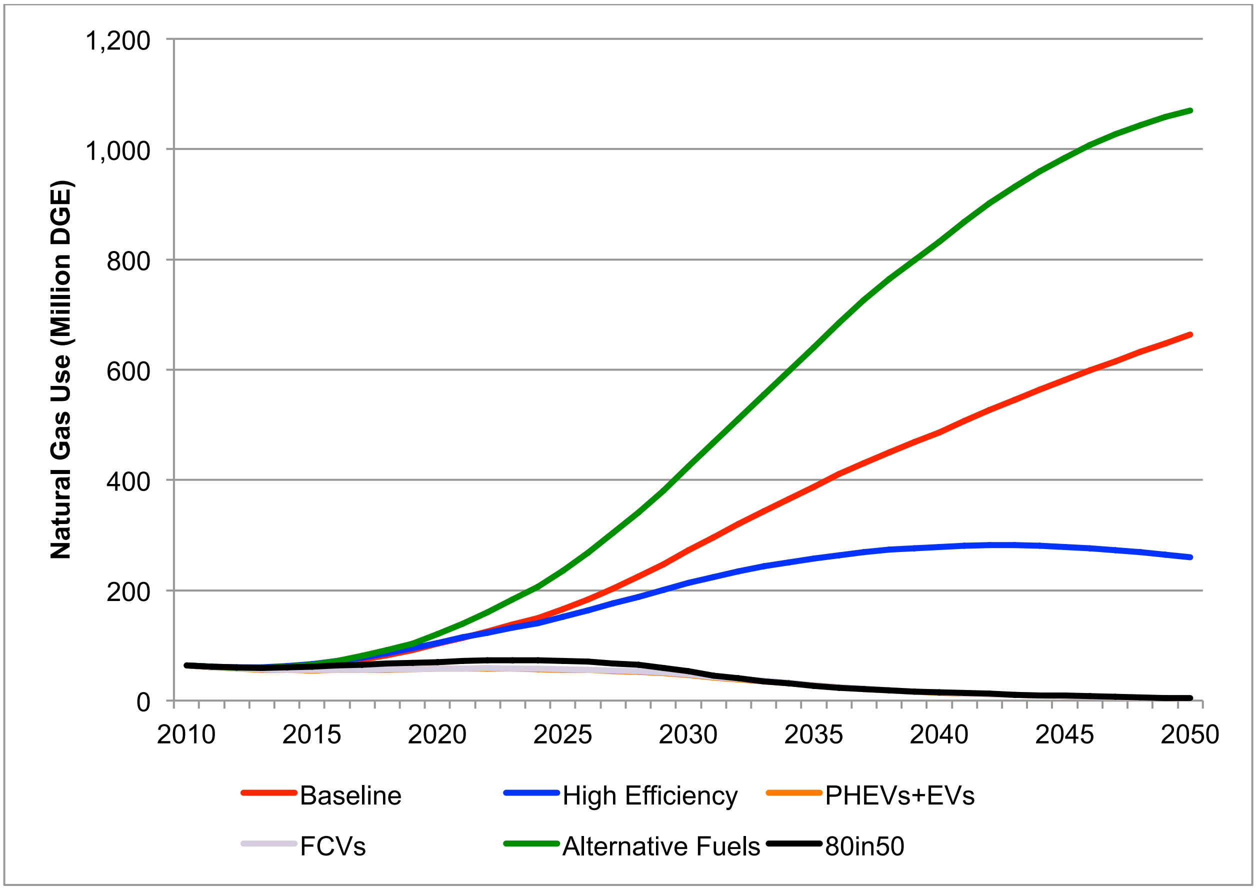

Figure 6-12: Scenario trends for natural gas consumption

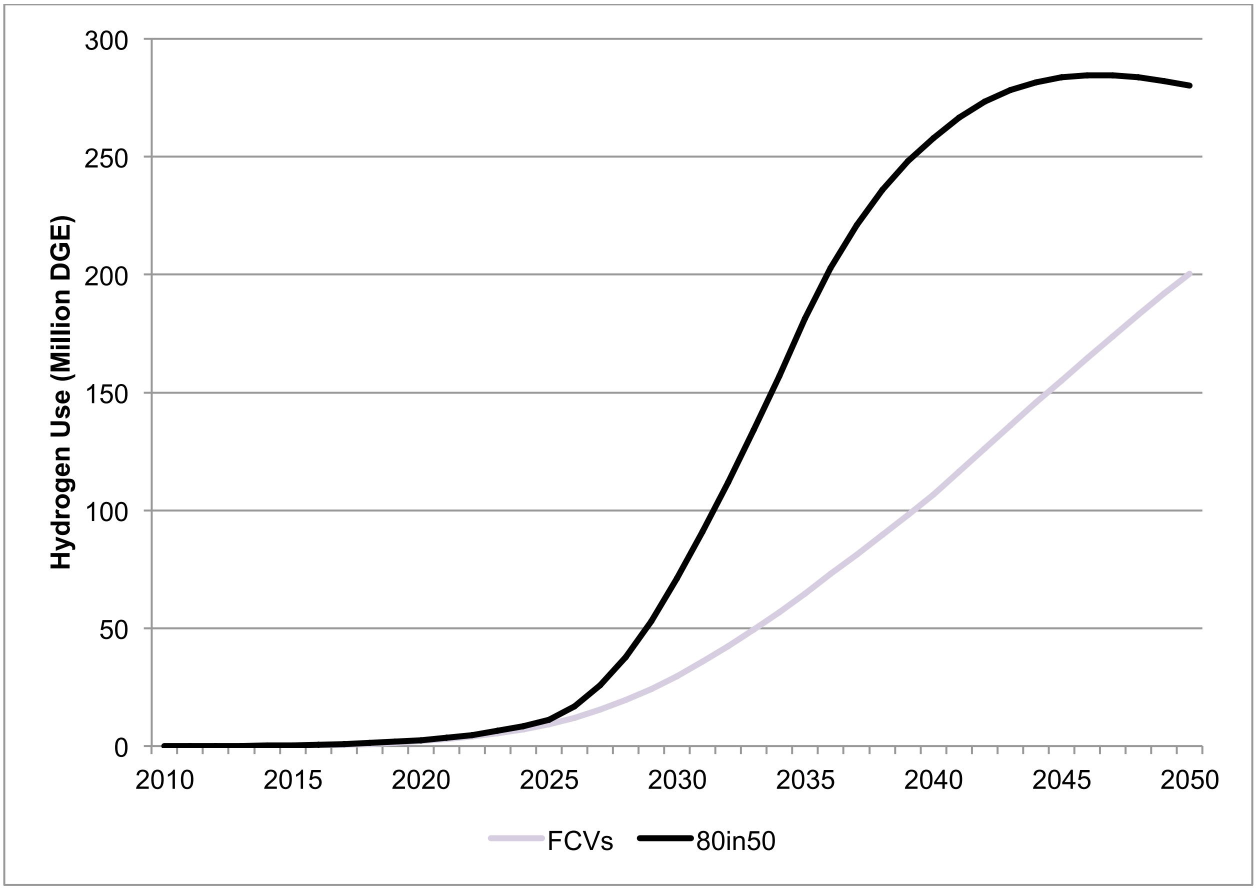

Figure 6-13: Scenario trends for hydrogen consumption

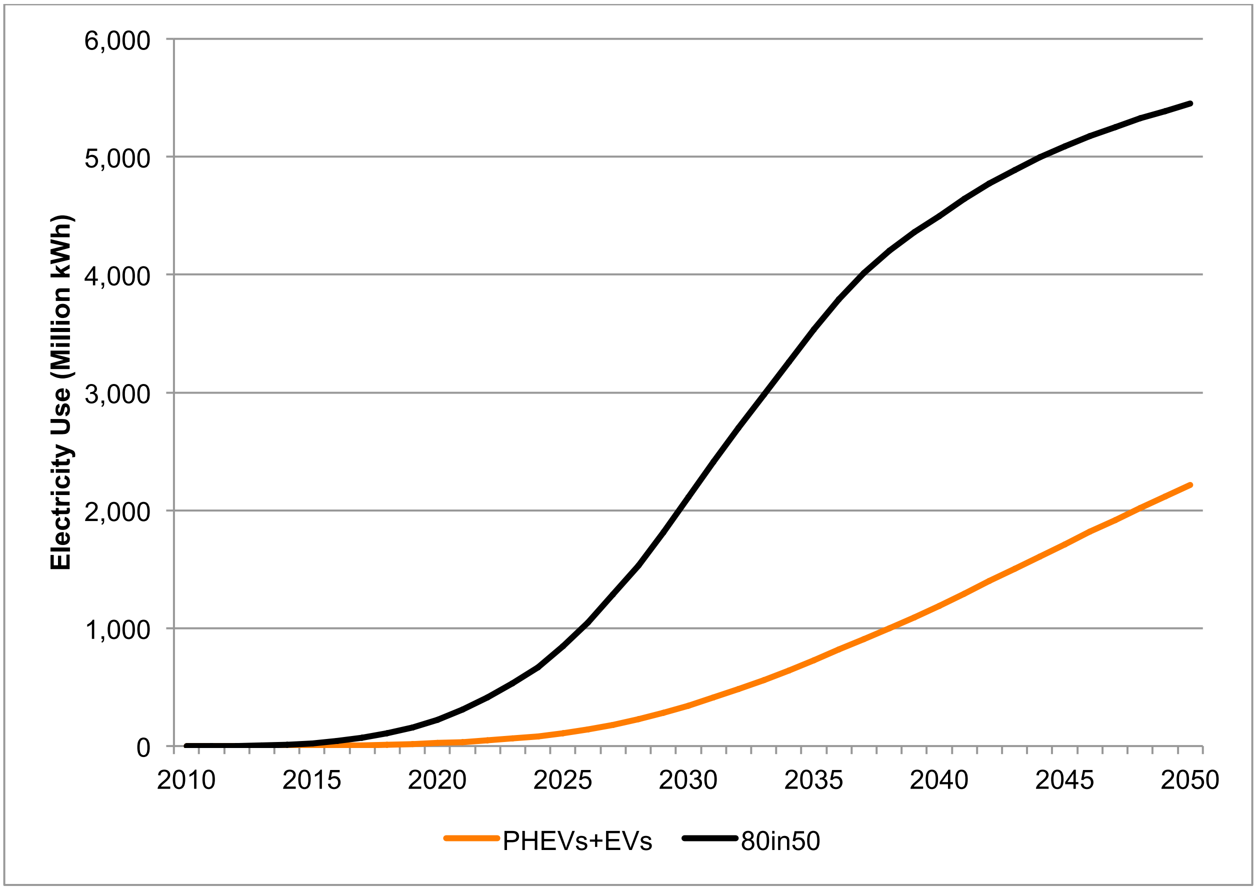

Figure 6-14: Scenario trends for electricity consumption

Looking at the 80in50 scenario, what is the fuel consumption impact of annual improved vehicle efficiency compared to the impact of the rapid adoption of advanced vehicles?

In Figure 6-15, the solid gray area represents the total conventional fuel consumption in the 80in50 scenario. The dark red and green dashed areas represent the reductions versus the Baseline that are achieved from advanced vehicle adoption and annual fuel efficiency improvements respectively. In the first half of the study period, the annual reductions in fuel consumption rates for new vehicles are the largest factor in reduced fuel use. Over time, the impact of advanced vehicle adoption overtakes annual fuel efficiency improvements as the largest factor in decreasing consumption of diesel and gasoline.

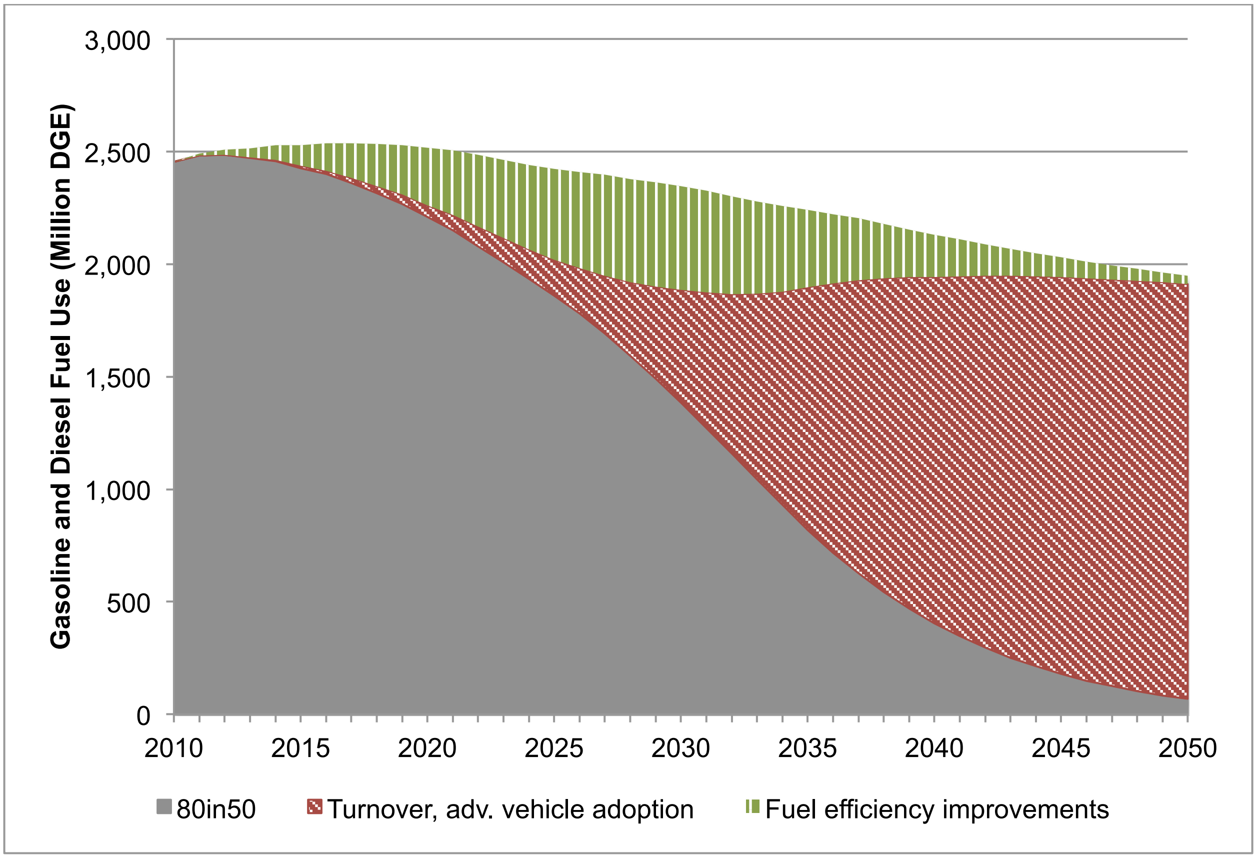

Figure 6-15: Contribution in the reduction in conventional fuel consumption of the 80in50 scenario from vehicle adoption and annual fuel efficiency improvements

6.2.4 Areas for Future Work

Many elements of this dissertation work can be refined and expanded upon in future research.

The TOP-HDV model and the methods that were developed for this dissertation can also be used to study HD fleets in other geographic locations. For example, fleets in other states or the entire nation could be analyzed by simply changing the population inputs and assumptions.

Adapting the model to other countries (particularly countries outside of North America) would also involve making changes to the emissions and deterioration rates as well as the cost data, however.

Other future work can include updating TOP-HDV to incorporate additional technology options such as NG hybrid-electric or LPG ("propane") vehicles or other technologies and fuel feedstock pathways that may emerge in the future.

In addition to generating scenario outputs, TOP-HDV has built-in functionality to produce per-vehicle results. This module was not used in this study, but in-depth analysis can be done at the vehicle level to explore the comparative fuel use, emissions, and costs of various technologies across the eight vehicle categories.

Finally, TOP-HDV can be used to estimate the costs and benefits associated with specific policy measures. For example, regulators in California are exploring the possibility of introducing a regulation that would call for substantial reductions in NOx emissions levels compared to MY 2010 vehicles. The model structure of TOP-HDV is set-up well for performing a cost-benefit analysis of such a regulation. In addition, the tool could be modified fairly easily and used to investigate the net impacts of voluntary programs such as the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program (HVIP).

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APPENDIX A ADDITIONAL TOP-HDV RESULTS

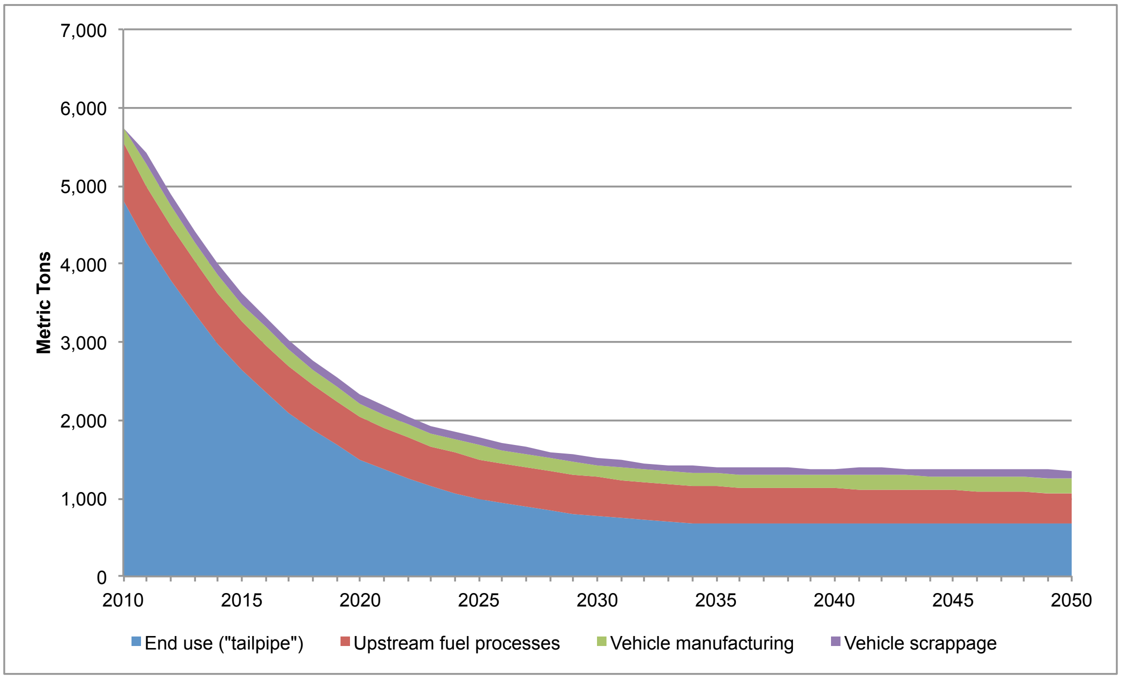

Figure A-1: Particulate matter ($PM_{2.5}$) emissions by lifecycle phase in the Baseline scenario

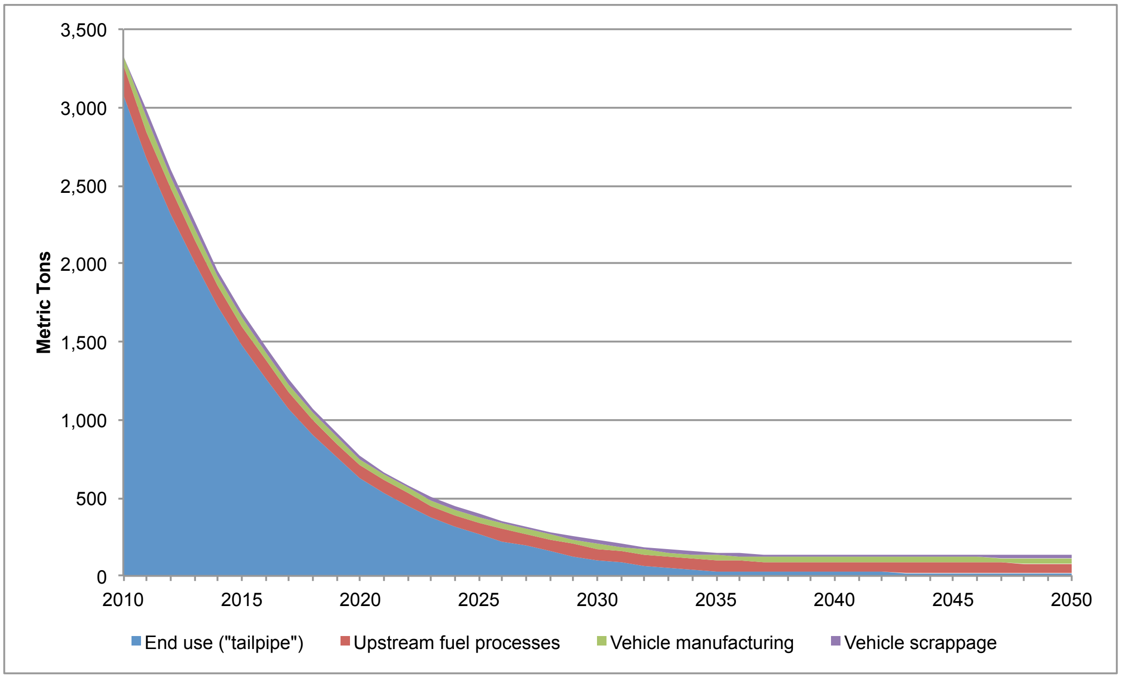

Figure A-2: Black carbon emissions by lifecycle phase in the Baseline scenario

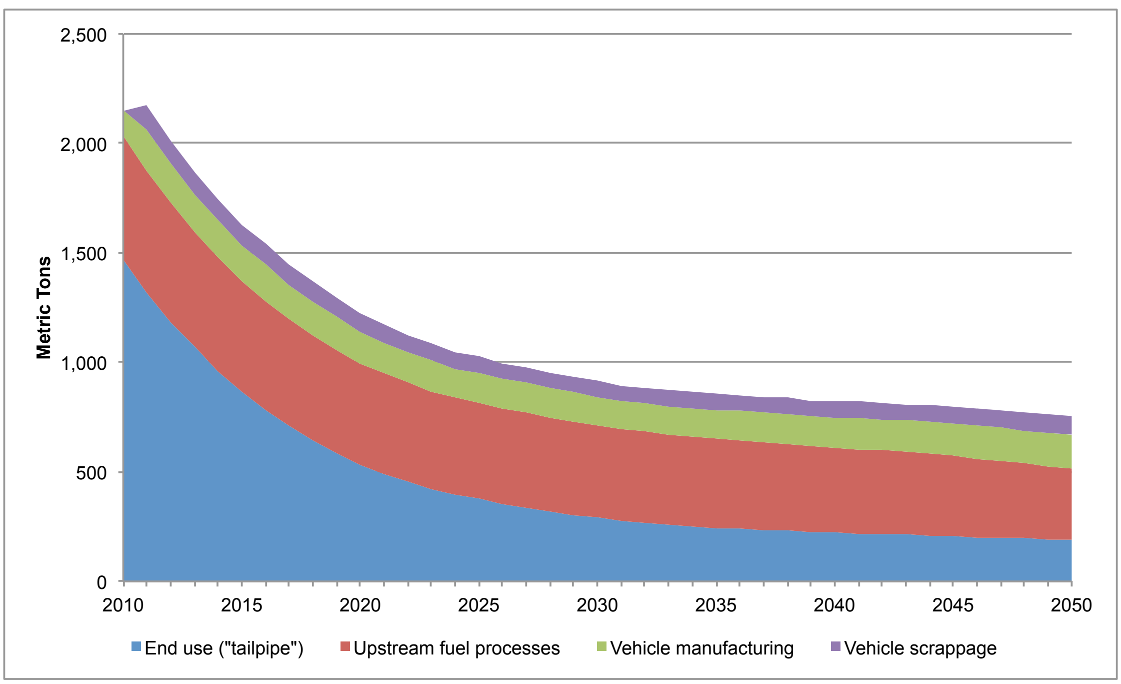

Figure A-3: Organic carbon emissions by lifecycle phase in the Baseline scenario

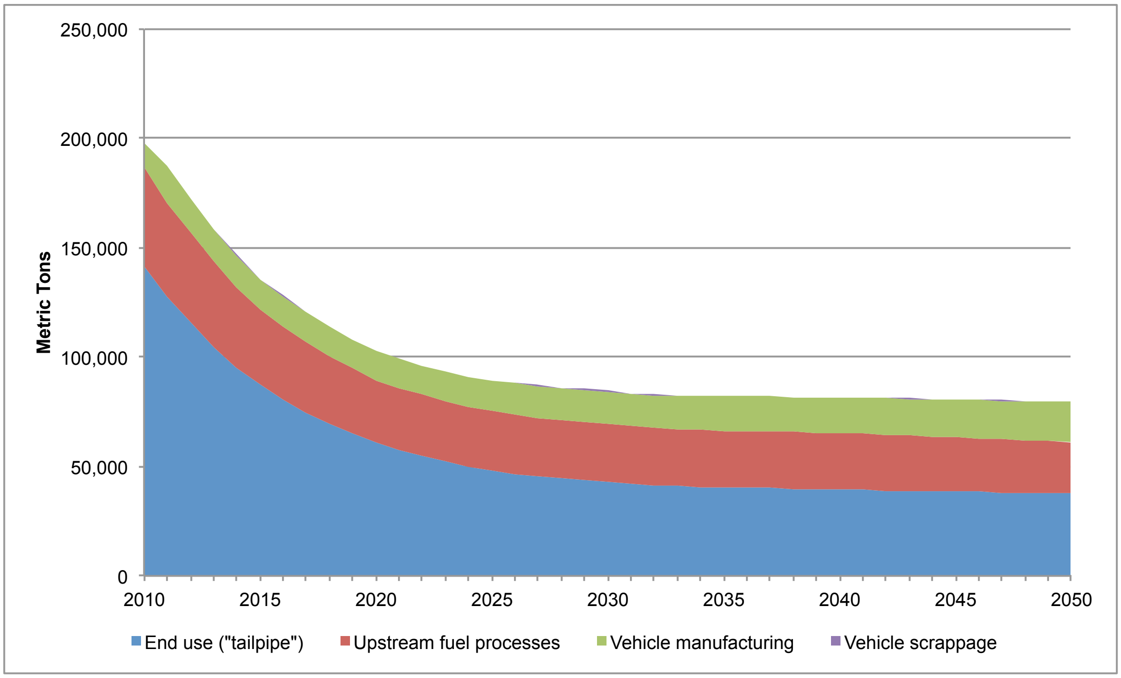

Figure A-4: NOx emissions by lifecycle phase in the Baseline scenario

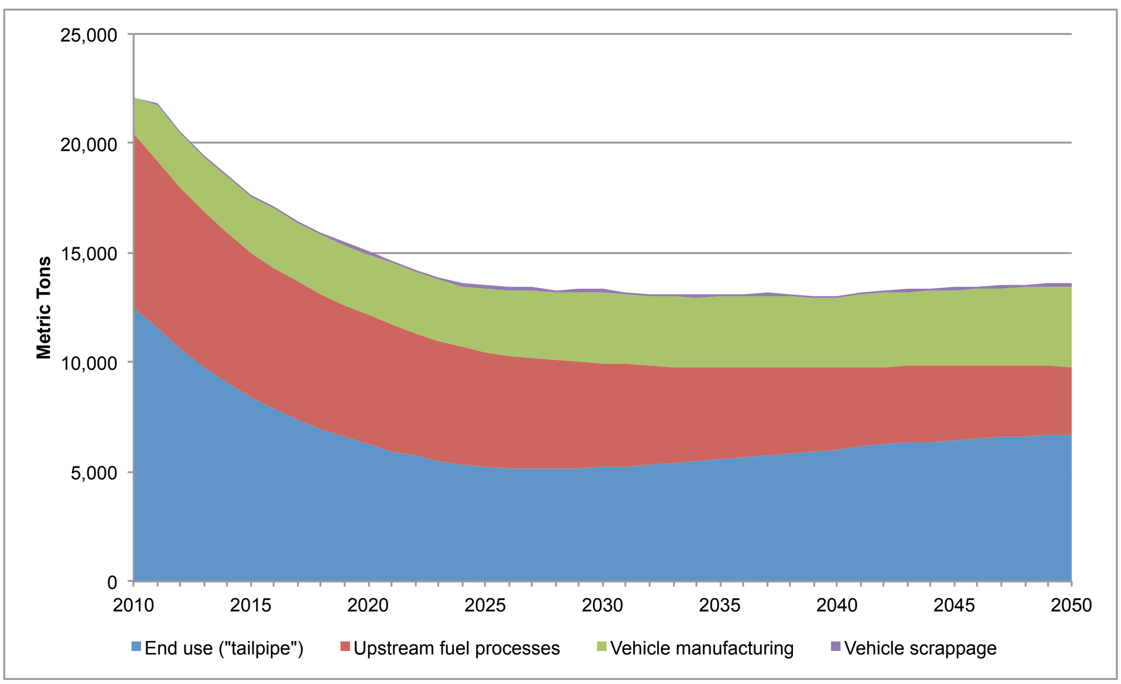

Figure A-5: Non-methane hydrocarbon emissions by lifecycle phase in the Baseline scenario

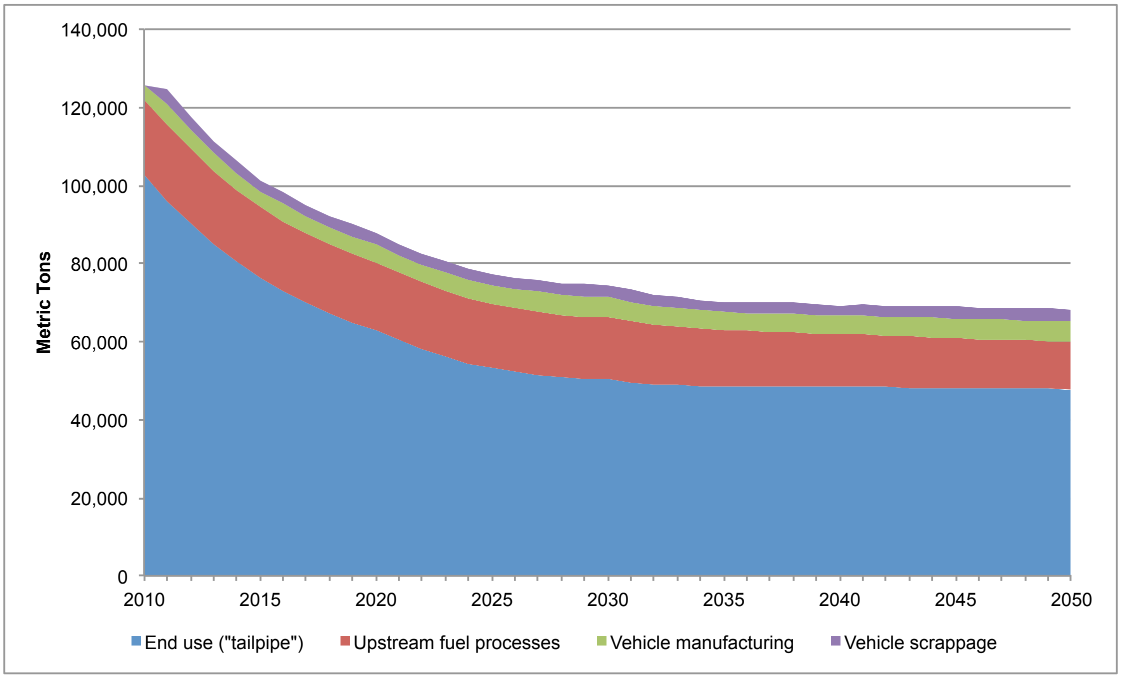

Figure A-6: Carbon monoxide emissions by lifecycle phase in the Baseline scenario

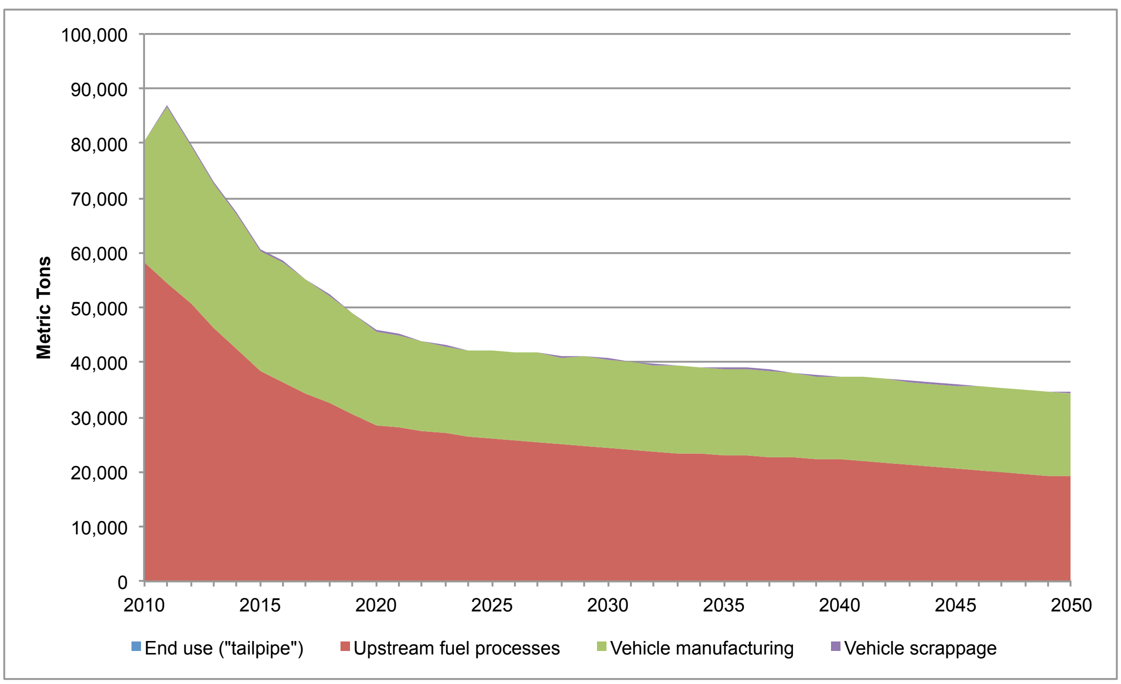

Figure A-7: SOx emissions by lifecycle phase in the Baseline scenario

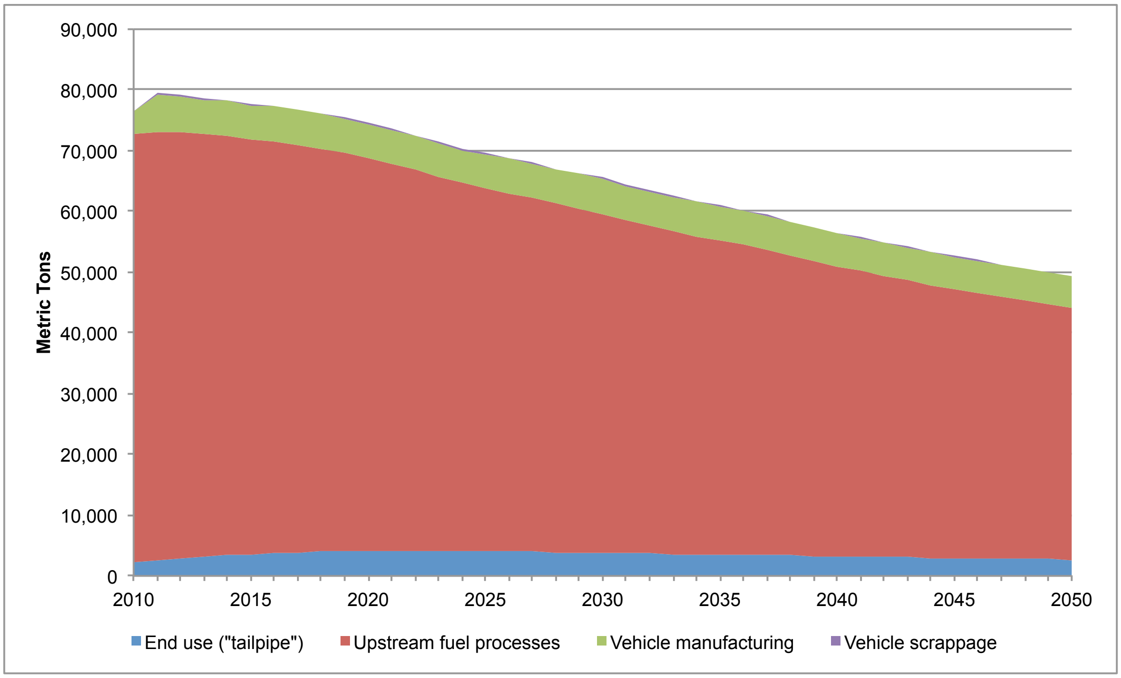

Figure A-8: Methane emissions by lifecycle phase in the Baseline scenario

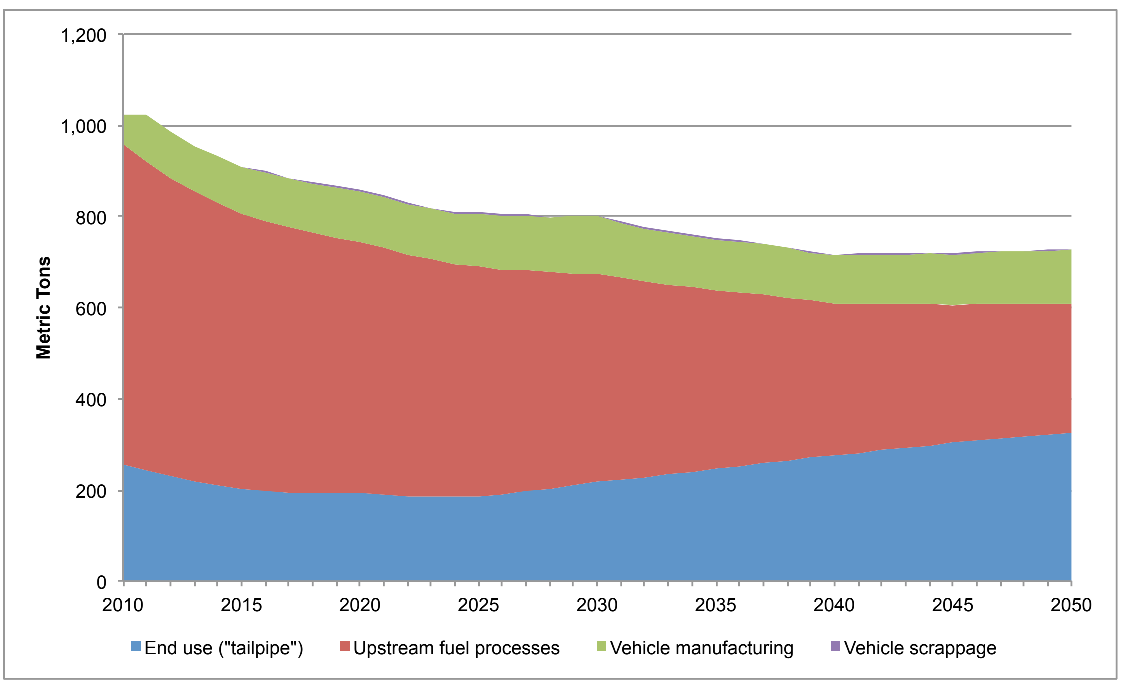

Figure A-9: Nitrous oxide emissions by lifecycle phase in the Baseline scenario