

CHAPTER THREE

HEAVY-DUTY VEHICLES

INTRODUCTION

This chapter describes the results of an analysis of future heavy-duty (HD) vehicle technologies, fuels, and fleet portfolios. An economic modeling framework was used to assess the fuel economy benefits of a range of future engine and vehicle efficiency technologies and alternative fuels.

This chapter focuses on the economic outcomes of a qualitative and quantitative analysis of the medium-duty (MD) and HD vehicle markets. This analysis resulted in several important trends, including the following:

- There is potential for substantial long-term gains in the fuel economy of heavy trucks.
- The economic competitiveness of natural gas can lead to shifts towards natural gas powered trucks in some modeled scenarios.

A range of future scenarios is discussed including the potential for alternate fuels, trends in vehicle efficiency and fuel economy, and possible impacts on national energy use and greenhouse gas (GHG) emissions.

BACKGROUND

Freight movements link commerce, suppliers, markets, and consumers between points of production and consumption. An efficient heavy-truck transportation system is critical to maintaining the competitiveness of the U.S. economy.¹ Expected growth in freight movements is a reflection of an expected expansion of economic activity and

increase in U.S.-international trade, improvements in freight-sector productivity, and the availability of an extensive transportation network. HD trucks, defined here as Class 3 through Class 8 are the linchpin of the nation's freight movement system.²

Heavy-Duty Industry Overview

Although there are far fewer HD trucks than cars on the road, HD trucks are a significant factor in overall transportation energy consumption. According to the Energy Information Association's (EIA) Annual Energy Outlook 2010 (AEO2010), HD trucks consume over 20% of the fuel used in transportation in the United States.³ That share is expected to grow to almost 30% in 2050, based on extrapolations of the AEO2010 Reference Case.

The differences between light-duty (LD) vehicles and medium-/heavy-duty (MD/HD) vehicles require that they be considered separately. Table 3-1 summarizes some of these major differences.

Heavy-Duty Background

Vehicle Segments and Powertrain Types

Figure 3-1 illustrates the usage and weight categories of MD/HD vehicles. Even within a class of vehicles, the range of applications highlights the different uses or duty cycles in the sector.⁴ This diversity is a key characteristic of the MD/HD truck market.

1 U.S. Department of Transportation, "US DOT Strategic Plan FY2010-FY2015: Transportation for a New Generation," April 15, 2010.

2 Class 2b vehicles, such as heavy pickup trucks and light vans, are addressed in Chapter Two, "Light-Duty Vehicles."

3 Energy use does not include recreational boating or pipelines.

4 National Research Council of the National Academies, *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles*, 2010.

	Light-Duty Vehicles	Heavy-Duty Vehicles
Application or Use	Consumer goods typically purchased for delivering the driver and passengers to a destination.	Capital goods to help owner conduct business or perform a specific, dedicated task. Designed for application-specific uses to conduct a job as efficiently as possible with the lowest total cost of ownership.
Purchase Decision	Influenced by a range of variables other than cost, such as interior passenger and cargo volume index and personal choice.*	Cost trade-offs explicitly considered. Fuel economy tends to be a major determining factor.
Vehicle Turnover	Analysis of AEO vehicle survival as a function of age indicates the average lifetime of cars and light trucks is 17 years.†	Sophisticated, first owner fleets turn over vehicles twice as fast as light-duty automotive, with Class 8 long haul turning over in about 3 years.†
Lifetime Fuel Cost	Lifetime fuel cost for an average passenger car is similar to the vehicle's original purchase price.†	Fuel cost is typically the second highest operating cost, which provides an incentive to increase fuel economy. Lifetime fuel costs are nearly five times that of the original purchase price of the vehicle.†
Fuel	Majority powered by gasoline.	Majority powered by diesel.

* The interior volume index ranges from 85 to 160 cubic feet.
† U.S. Department of Energy, *Research and Development Opportunities for Heavy Trucks*, June 2009, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/truck_efficiency_paper_v2.pdf.

Table 3-1. Comparison of Light-Duty and Heavy-Duty Vehicles

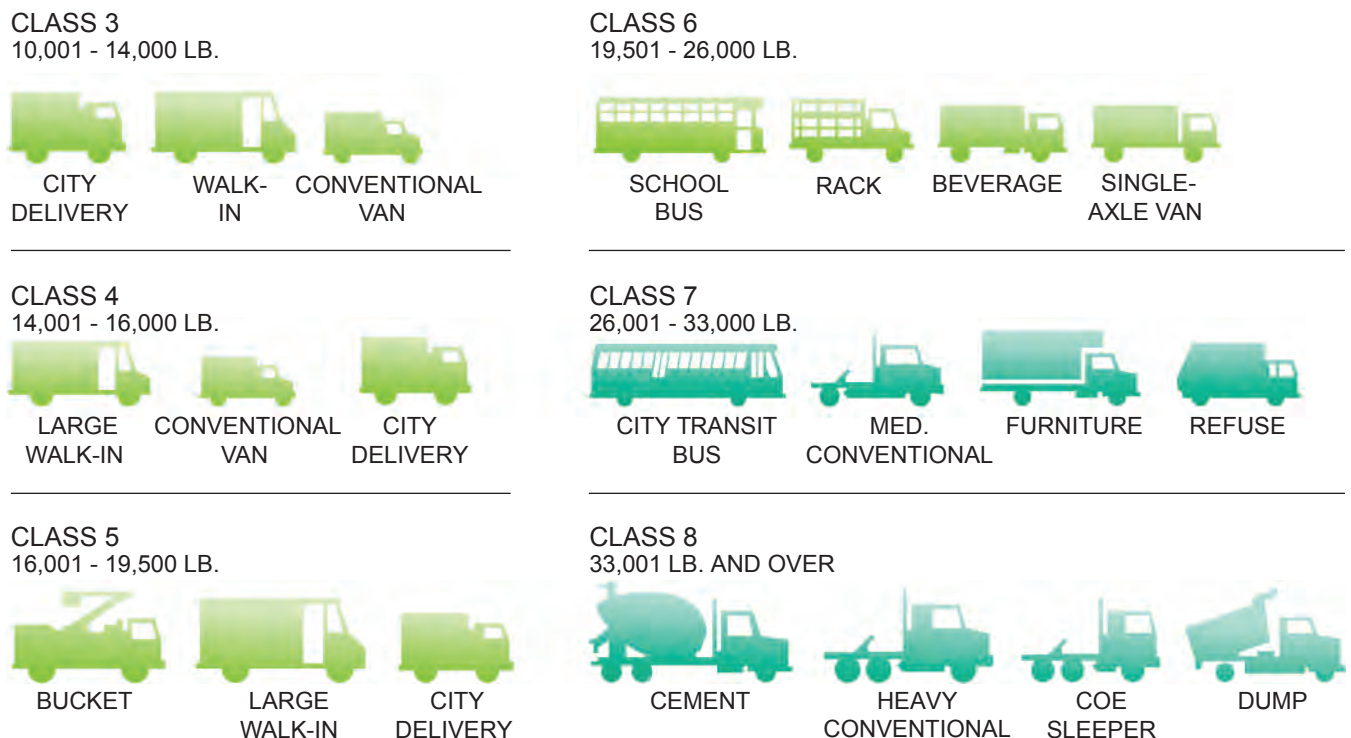


Figure 3-1. Heavy-Duty Vehicle Segments

Table 3-2 summarizes the potential powertrain options considered in this study for different truck market segments. In the case of Class 3-6 trucks, powertrain options include diesel, gasoline, hybridized-diesel, and natural gas. Hybrid options are also included in Class 7&8 single-unit trucks.

Natural gas options are assumed to be available for all classes of truck. Biofuel blends are also considered, and it is assumed that future engines will continue to adopt flexible fuel strategies to burn such blends. Other alternate-fuel options, including hydrogen fuel cells and plug-in electric power, are not explicitly considered here. These options, while technically available in limited niches, tend to be a poor match for truck duty cycles. In particular, battery challenges faced by plug-in electric cars are multiplied many-fold by HD requirements, which include extended life, increased power, and higher energy storage.

Vehicle Classes and Energy Use

The EIA estimates that Class 3-6 trucks represent almost 4 million vehicles on the road today, and this study’s Reference Case shows them growing to over 11 million by 2050. Applications range from minibuses, step vans, and utility vans to city delivery trucks and buses in Classes 4, 5, and 6. These vehicles consume as little as 1,000 gallons per year for some lighter, low-duty cycle applications up to 7,000 gallons per year for the heaviest Class 6 applications. Class 3-6 trucks are used in the following applications: construction, agriculture, for

hire, retail, leasing, wholesale, waste management, utilities, manufacturing, food services, information services, and mining.

Class 7&8 trucks account for over 4.5 million vehicles and are expected to grow to over 7 million in 2050 in the Reference Case. Class 7 and Class 8a trucks include buses, dump trucks, trash trucks, and other hauling trucks. These trucks represent heavy working trucks consuming typically 6,000–8,000 gallons of fuel per year for Class 7, and 10,000–13,000 gallons of fuel per year for Class 8a. Class 8b trucks are typically long-haul trucks weighing more than 33,000 lbs. that have one or more trailers for flatbed, van, refrigerated, and liquid bulk. Class 7 represents some 200,000 vehicles, while Class 8a and Class 8b consist of 430,000 and 1,720,000 respectively. These trucks consume typically 19,000–27,000 gallons of fuel per year and account for more than 50% of the total freight tonnage moved by trucks.

As shown in Figure 3-2, Class 8b trucks consume two-thirds of the fuel used by trucks overall. The high fuel use by these trucks is due to their heavy weight and their very high mileage. The average new Class 8b truck travels over 100,000 miles per year, with some trucks traveling 200,000 miles or more in a year.

Vehicle Miles Traveled

With anticipated future economic growth and associated freight activity, vehicle miles traveled

Market Segment	Powertrain Architectures*
Class 3-6 Medium- and heavy-duty vehicles with single rear axles	<ul style="list-style-type: none"> • Class 3-6 Conventional Diesel • Class 3-6 Conventional Gasoline • Class 3-6 Hybrid (Diesel) • Class 3-6 Natural Gas
Class 7&8 Single Unit Heavy-duty vehicles with two or more rear axles	<ul style="list-style-type: none"> • Class 7&8 Conventional Single Unit (Diesel) • Class 7&8 Single-Unit Hybrid (Diesel) • Class 7&8 Single-Unit Natural Gas
Class 7&8 Combination A tractor and one or more trailers and a gross combined vehicle weight of up to 80,000 lbs.†	<ul style="list-style-type: none"> • Class 7&8 Combination Conventional (Diesel) • Class 7&8 Combination Natural Gas
<small>* The natural gas vehicles included in the model are assumed to be a mixture of compression ignition and spark ignition engines. More details on the model inputs and assumptions are contained in Appendix 3A at the end of this chapter.</small>	
<small>† Weights greater than 80,000 lbs. are allowed in specific circumstances.</small>	

Table 3-2. Powertrain Architectures by Market Segment

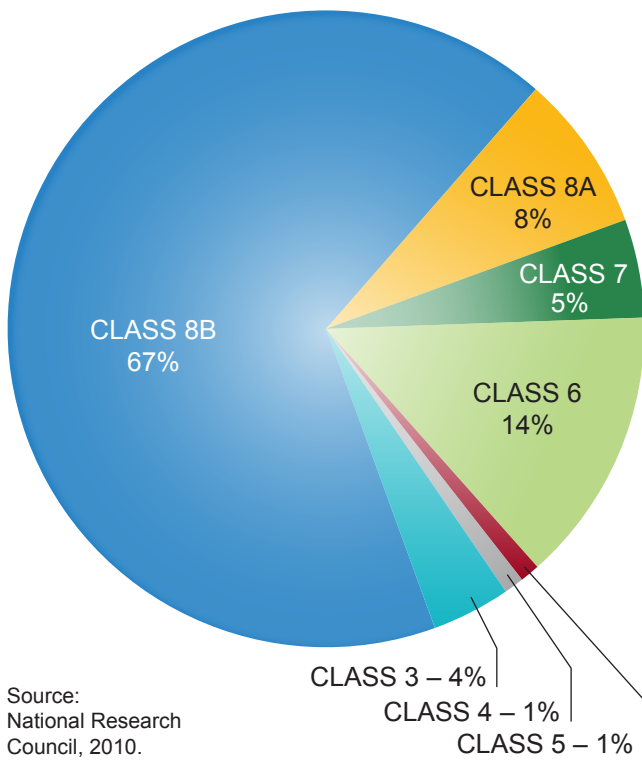


Figure 3-2. Share of Fuel Consumption by Class

(VMT) is expected to rise in the MD/HD sector.⁵ The study Reference Case shows VMT growth more than double by 2050, as shown in Figure 3-3. The increase in Class 7&8 VMT closely parallels the growth in the goods producing sector of the economy, particularly manufacturing. The VMT growth in Class 3-6 closely aligns with the growth in total GDP, which includes services, wholesale, retail, and goods-producing sectors.

MD/HD VMT projections are subject to uncertainty because they are tied to forecasted economic activity. Subsequent versions of the AEO suggest slower growth in MD/HD truck VMT as shown in Table 3-3.

In order to reduce future GHG emissions and/or energy consumption of the MD/HD fleet, vehicle technologies must improve efficiency enough to offset this VMT increase. Even if the fuel economy of new vehicles doubles by 2035, GHG emissions will still rise compared to 2005 due to increased VMT.

⁵ VMT has grown more quickly for heavy-duty vehicles than for light-duty vehicles, resulting in MD/HD vehicles assuming a growing share of total transportation-related petroleum consumption.

If VMT does indeed grow at this projected rate, the industry may be challenged to produce sufficient trucks to keep pace with demand. Future growth of freight movement may be constrained by bottlenecks in the freight industry such as the availability of trucks and drivers, the capacity of road networks, congestion, and other factors. Figure 3-4 shows the Department of Transportation’s prospective on expanded freight networks from 2002 to 2035.

Chapter One, “Demand,” provides a more comprehensive discussion of freight transportation by truck, rail, and water and includes more detailed observations on the future trends of freight industry VMT.

Engine and Vehicle Technology

The commercial vehicle market has significant structural and behavioral differences from the passenger car market that affect technology deployment. Technology solutions tend to be application-specific in the MD/HD market. Unlike LD where hundreds of thousands of units in production is the norm, the scale of MD/HD production is relatively

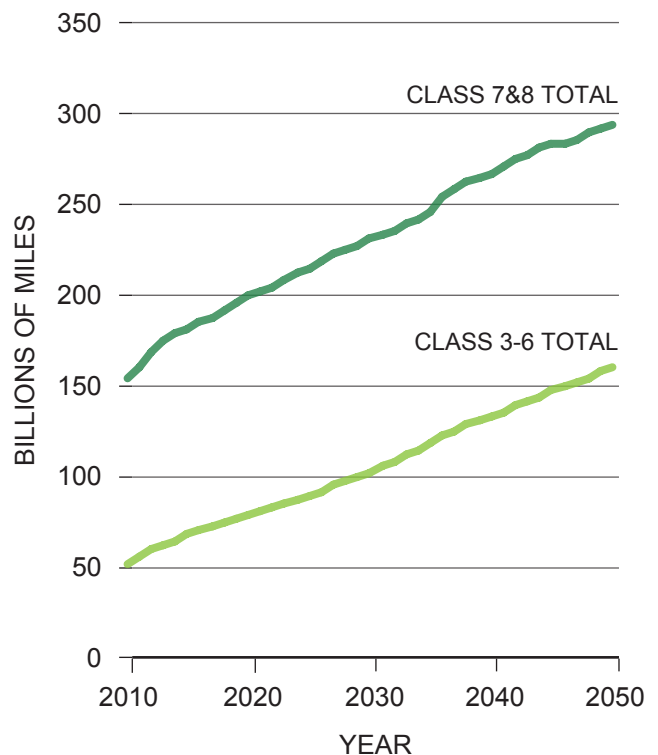


Figure 3-3. Vehicle Miles Traveled for Heavy-Duty Vehicles from the Study Reference Case

	Study Reference Case (AEO2010 VISION)	AEO2011	AEO2012 Early Release
Billion Miles	362	335	344
Delta to Reference	—	-7.5%	-5%

Table 3-3. Comparison of Annual Energy Outlook’s Projections of Vehicle Miles Traveled for Medium- and Heavy-Duty Trucks in 2035

low. This can be a significant obstacle to technology deployment, as cost reductions through high-volume production are more limited. When technology solutions yield economic benefits, they tend to be widely and quickly adopted, generally through new vehicle sales. But even when adoption rates are high, widespread fleet penetration tends to be slow due to slow fleet turnover in many segments.

A wide variety of technologies can be employed to improve fuel economy, and to enable the use of alternative fuels. These range from incremental near-term technologies, such as reduced engine friction and more efficient tires, to higher impact advanced technologies such as hybridization or advanced combustion schemes. Such technologies are likely to be implemented only as they become economically attractive to truck buyers, or as regulations require them. According to a 1997 American Trucking Association survey, technology must typically pay for itself in fuel savings within a two- to three-year timeframe before a majority of truck purchasers will consider adoption.

The incremental adoption of such technologies is likely to improve the fuel economy of the fleet over time. Compared to the LD market, the technologies considered in the MD/HD fleet comprise fewer alternative fuel options and more incremental advances in traditional technologies. Fuel economy impacts the economic competitiveness of alternate fuel pathways, which must also show adequate pay-back in order to be adopted. These tradeoffs and some potential future scenarios for the U.S. trucking fleet are analyzed in the next sections.

METHODOLOGY

A modeling framework was developed to analyze potential future scenarios for the U.S. MD and HD trucking fleet. The framework is described here in general terms to provide some context and a general

understanding of its characteristics and methods. Specific implementations and detailed assumptions are contained in Appendix 3A, “Modeling Methods and Assumptions,” found at the end of this chapter.

Modeling Principles

Models are useful to evaluate potential future scenarios and have limitations. Given the complexity of the U.S. trucking industry and the myriad of developments in technology, fleet operations, road networks, and other factors, it is not possible to predict the future state of the industry. The model applies a consistent and well-documented set of input assumptions and uses them to calculate economic outcomes.

Several principles were employed consistently in the development of the model.

- Principle One: Study Synthesis Approach**
Throughout the modeling framework, quantitative inputs are based on previously published, publicly available data. In many cases, the evaluation of specific trends has been evaluated by experts in industry, academia, and government organizations.
- Principle Two: Economic Motivation of Trucking Industry**
Trucking is a profit-driven business and truck buyers make decisions based on maximizing profits and minimizing total costs of ownership. The model assumes decisions are made by rational economic actors seeking the lowest total cost of ownership of a vehicle. Emissions and safety regulations have a major impact on the truck market, and must be factored into any calculations.
- Principle Three: Previously Validated Tools**
Modeling tools include the VISION model developed by the Department of Energy and maintained by Argonne National Laboratory, as well



TRUCK VOLUMES AND PERCENTAGES

- AADTT <10,000 & AADTT/AADT <0.25%
- AADTT <10,000 & AADTT/AADT >=0.25%
- AADTT >=10,000 & AADTT/AADT <0.25%
- AADTT >=10,000 & AADTT/AADT >=0.25%

Note: AADTT is Average Annual Daily Truck Traffic and includes all freight-hauling and other trucks with six or more tires. AADT is Average Annual Daily Traffic and includes all motor vehicles.

Source: U.S. Department of Transportation, Federal Highway Administration, Office of Freight Management and Operations, *Freight Analysis Framework, version 2.2*, 2007; U.S. Department of Transportation, *Freight Analysis Framework, Version 3.1*, Federal Highway Administration, Office of Freight Management and Operations, 2010.

Figure 3-4. Major Truck Routes on National Highway System in 2002



TRUCK VOLUMES AND PERCENTAGES

- AADTT < 10,000 & AADTT/AADT < 0.25%
- AADTT < 10,000 & AADTT/AADT >= 0.25%
- AADTT >= 10,000 & AADTT/AADT < 0.25%
- AADTT >= 10,000 & AADTT/AADT >= 0.25%

Note: AADTT is Average Annual Daily Truck Traffic and includes all freight-hauling and other trucks with six or more tires. AADT is Average Annual Daily Traffic and includes all motor vehicles.

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Figure 3-4 (continued). Major Truck Routes on National Highway System in 2035

as the TRUCK 5.1 model, to predict market shares between different truck powertrains.⁶

Modeling Framework

The modeling framework is described here at a high level to describe the model’s features and basic operation. Three steps are performed to execute the full model:

1. The vehicle attribute calculation⁷
2. The market share computation⁸

6 Papers describing both modeling tools can be found online in this study’s web-only resources on the NPC website.

7 Vehicle attributes are calculated using the Optimizer spreadsheet, which selects the vehicle attributes (cost and fuel economy) based on such variables as oil price, cost-of-fuel-economy, etc. The Optimizer spreadsheet was developed by study group members for this study and is further described in Appendix 3A.

8 Market Shares are calculated using TRUCK 5.1, an extension of the previously published TRUCK 4.0 model (used by the Department of Energy’s Vehicle Technologies Program), which makes an economic comparison between competing trucks of different fuel types, and computes future market shares based on the lowest cost of ownership. The TRUCK 5.1 heavy vehicle market penetration model was developed specifically for this study. The model and its documentation can be found on the NPC website.

3. The fleet energy and emissions calculation using the VISION tool.

These steps are reviewed briefly in Figure 3-5. More details regarding model inputs and assumptions can be found in Appendix 3A.

The model uses assumptions regarding the future development of emerging technology and new infrastructure for alternate fuels. The scenarios considered here are not “business as usual,” but assume a substantial continued investment in the underlying technologies for fuel-economy improvement. This underlying assumption of ongoing technology gain is constrained by data found in published literature, quantifying the best estimates of many sources on the costs and benefits of such technologies. In the case of infrastructure, and particularly infrastructure for natural gas, widespread infrastructure is generally assumed to be available. This avoids the difficult issue of transition. Transition issues are addressed in a separate section within this chapter and in more detail within Chapter Five, “Infrastructure.”

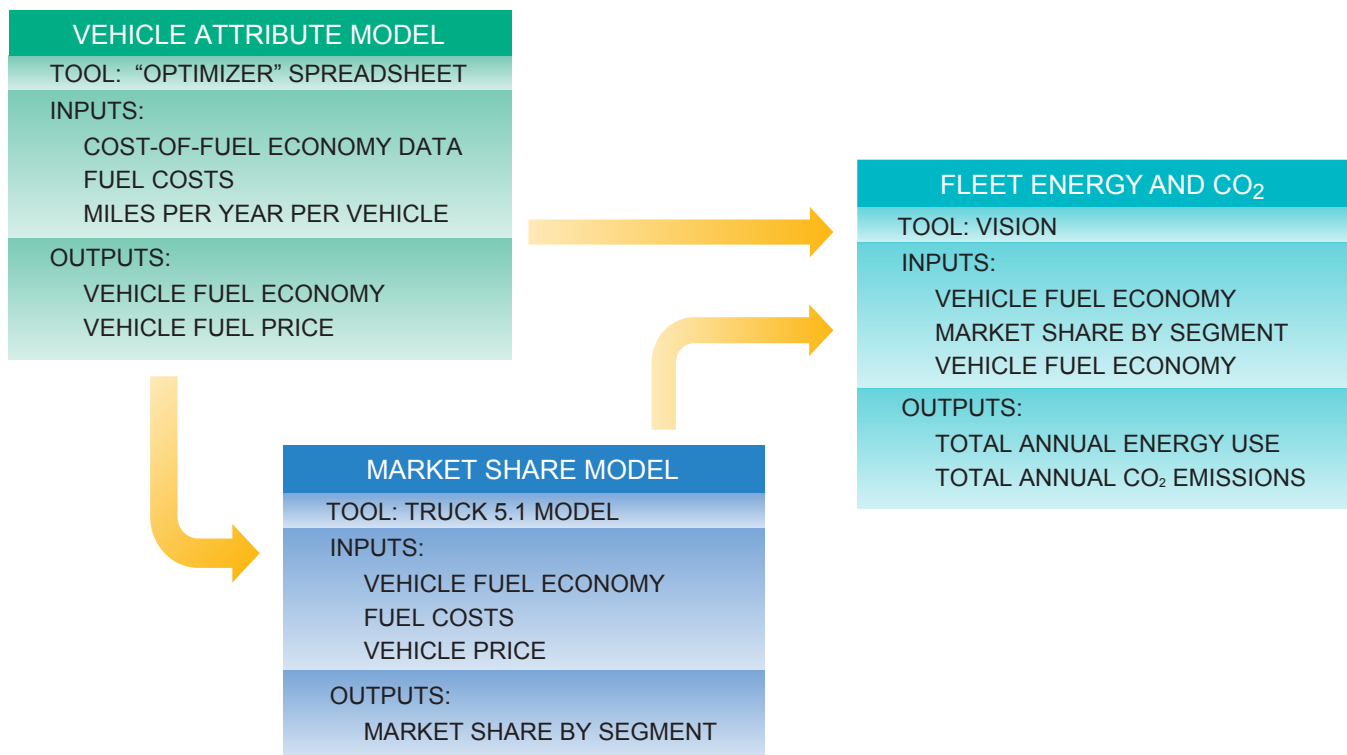


Figure 3-5. Summary of Each Tool in the Modeling Framework

Vehicle Attribute Calculation

Truck and engine design characteristics were considered to determine which fuel economy technologies would likely be included in future vehicle releases. The vehicle attribute calculation then determines how much technology the market desires in various classes of vehicles for five-year increments from 2010 to 2050.

Published data describing a range of views on the cost and effectiveness of fuel-economy technologies were assembled into a “cost of fuel economy curve” for each vehicle segment and powertrain architecture.⁹ The technology mix was chosen using this data-based approach, by optimizing the total cost of the truck and fuel over a three-year period. This calculation was repeated in five-year increments for each combination of vehicle type and oil price case. The result of each calculation is a vehicle price and a vehicle fuel economy that varies by vehicle type and evolves over time. The inputs and outputs of the model are shown in Table 3-4.

The modeling methodology employs upper limits on the annual increase in fuel economy and vehicle price, as listed in Appendix 3A. These limits are imposed to reflect the slow pace of change in the trucking industry as indicated by historical trends.¹⁰

Vehicle Market Share Calculation

Within a given market segment each powertrain architecture competes against alternate architectures for market share. The market share calculation performed mimics market competition by assigning higher market shares to more cost-effective solutions. A version of the established TRUCK 5.1 model is used for this purpose. This modeling framework is based on survey data of truck drivers and buyers regarding the typical payback time required for adoption of new technologies and the rate of update of new technologies. It also uses the vehicle purchase price and fuel economy as inputs.

⁹ “Cost of Fuel Economy” curves for each class of heavy-duty vehicle are provided in Appendix 3A.

¹⁰ According to VISION, the steepest historical rate of change in truck fuel economy over a decade, in any class of truck, is 2.4%. This ceiling is imposed on future annual increases in order to restrain the model, which would otherwise predict immediate unrealistic gains in truck fuel economy.

VEHICLE ATTRIBUTE CALCULATION

INPUTS:

- Cost of fuel economy measures taken from public data
- Fuel costs based on AEO2010
- 2010 vehicle prices and fuel economy, taken from AEO2010

OUTPUTS:

- Vehicle price for each powertrain type
- Vehicle fuel economy for each powertrain type
- Outputs provided in 5-year increments from 2010 to 2050

Table 3-4. Vehicle Attribute Calculation Inputs and Outputs

As with the design-point calculation, the market share model performs a trade-off between the cost of technology and the fuel savings of that technology. The market share model mimics the behavior of buyers in aggregate in selecting between powertrain types. The inputs and outputs of the model are shown in Table 3-5.

Fleet Energy and Emissions Calculation

The fleet energy and emissions calculation is performed with the VISION tool. This tool takes input information on new vehicle price and fuel economy, as well as market shares, and calculates

VEHICLE MARKET SHARE CALCULATION

INPUTS:

- Vehicle price as determined by vehicle attribute calculation
- Vehicle fuel economy as determined by vehicle attribute calculation
- Payback decision criteria, calculated from mileage distribution data from a 2002 Vehicle Inventory and Use Survey (VIUS) and payback adoption criteria from a 1997 American Truck Association survey

OUTPUTS:

- Vehicle market shares for each powertrain type

Table 3-5. Vehicle Market Share Calculation Inputs and Outputs

fleet-wide parameters such as energy use and carbon emissions. Results are broken down by fuel type so that carbon emissions can be traced to specific fuel types. Inputs and outputs to the VISION model are shown in Table 3-6.

A block diagram showing the three-step calculation process was shown in Figure 3-5. The methodology is similar to that used in the LD vehicle analysis of this study with modifications made as necessary to reflect the HD vehicle market. For example, where various segments of LD vehicles are assumed to have the same mileage per year, heavy-truck mileage varies widely with vehicle segment, requiring a different calculation of payback and other mileage-related parameters.

FLEET ENERGY AND EMISSIONS CALCULATION
<p>INPUTS:</p> <ul style="list-style-type: none"> • Vehicle price as determined by vehicle attribute calculation • Vehicle fuel economy as determined by vehicle attribute calculation • Vehicle market share for each powertrain type
<p>OUTPUTS:</p> <ul style="list-style-type: none"> • Fleet-wide energy use, broken down by fuel type • Fleet-wide carbon emissions, broken down by fuel source • Other parameters related to the national fleet

Table 3-6. *Fleet Energy and Emissions Calculation Inputs and Outputs*

Fuel Costs

The four primary fuels considered for use in MD/HD vehicles are diesel, gasoline, compressed natural gas (CNG), and liquefied natural gas (LNG). Additionally, bio-derived gasoline substitutes including ethanol¹¹ and bio-derived diesel fuel are also considered in the fuel mix. Price projections for diesel and gasoline are taken from the AEO2010 Low, Reference, and High Oil Price Cases extrapolated out to 2050. Bio-derived fuels are assumed to be available in the market at a supply capacity ranging

¹¹ Bio-derived replacements for gasoline include ethanol and biogasoline, with ethanol generally comprising the majority.

from 0.05 to 0.36 quadrillion BTU (quads) per year of bio-derived diesel fuel; and between 1.11 and 7.68 quads per year of bio-derived replacements for gasoline.¹² In all scenarios, biofuel is available at a price that is equivalent to the petroleum fuel they would displace.

Natural gas fuel prices have been developed for the study using the AEO2010 estimates of industrial gas prices as the feedstock and including provision for liquefaction, compression, road distribution, dispensing capital, and taxes as appropriate. Oil and natural gas are close to energy price equivalence in the AEO2010 Low Oil Price Case, and diverge significantly in the AEO2010 Reference and High Oil Price Cases. Using this basis, the fuel price assumptions are shown in Figures 3-6, 3-7, and 3-8 for each of the three oil price cases. Prices are shown on a diesel equivalent gallon basis; the price for the volume of fuel that contains the same amount of energy contained in a gallon of diesel fuel (138,700 BTU).

The fuel prices considered within the MD/HD analysis framework are a fixed set of assumptions. This analysis does not consider any elasticity in price based on changes in supply and demand, or for price convergence on an energy equivalent basis.

The fuel prices shown are central to the analysis for these reasons:

- For each fuel pathway, the price of fuel drives the determination of optimum fuel economy over time.
- The relative price of fuels plays a strong role in future market shares for new vehicles. The resulting market shares and vehicle attributes determine the overall fleet characteristics in terms of fleet composition, energy use, fuel use by type, and GHG emissions.

Infrastructure and Technology Assumptions

The assumptions contained within the model are described in detail in Appendix 3A. It is assumed that multiple fuel-saving technologies are available and widely adopted over time in the truck industry. The underlying assumption is that technology

¹² The cited total amounts of biofuel are available simultaneously to both light-duty and heavy-duty vehicles.

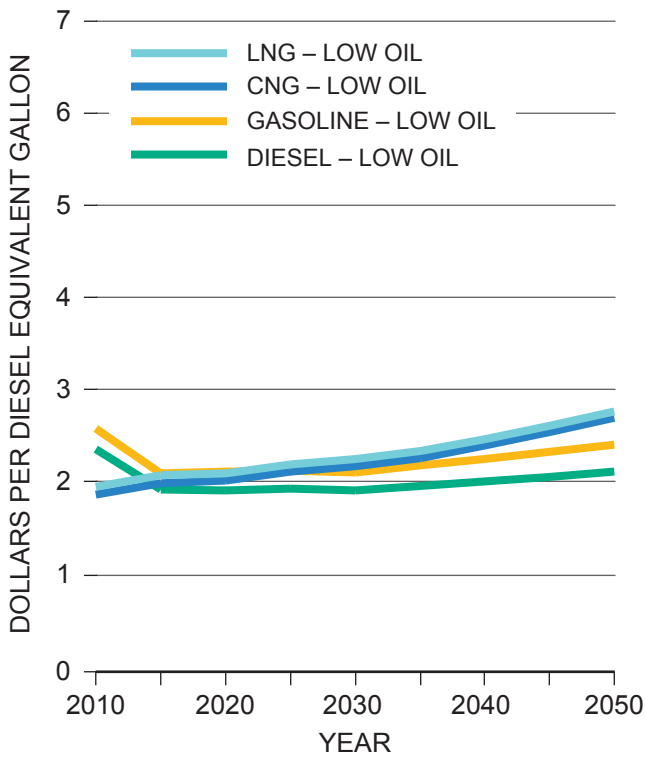


Figure 3-6. *Dispensed Fuel Price Assumptions – Low Oil Price Case*

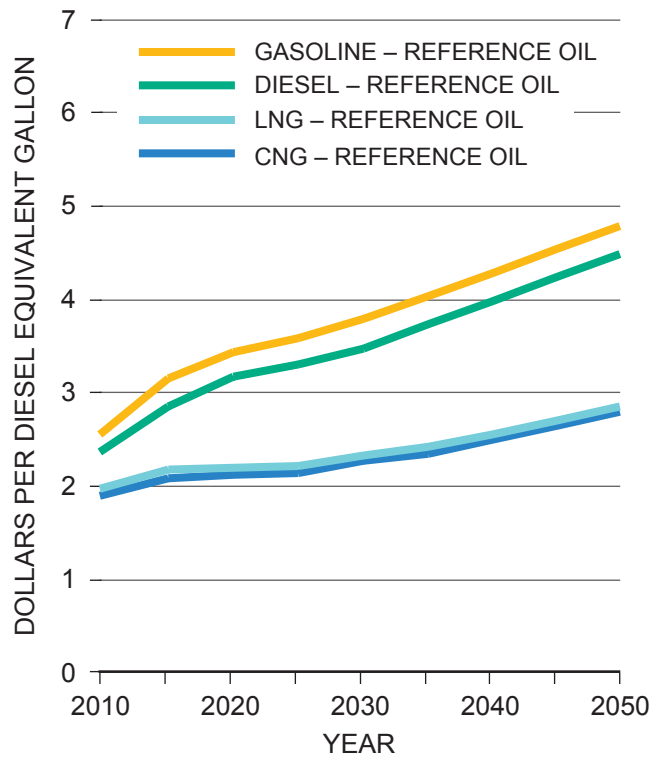


Figure 3-7. *Dispensed Fuel Price Assumptions – Reference Case*

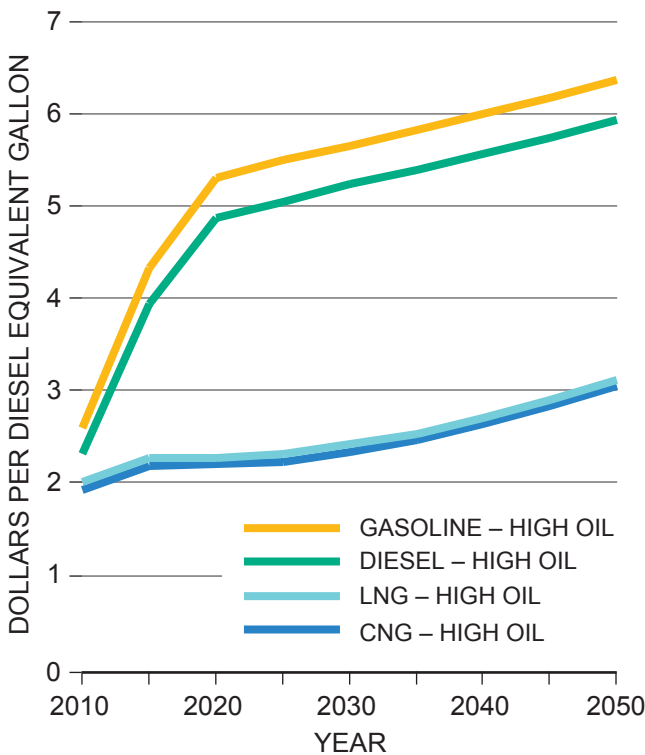


Figure 3-8. *Dispensed Fuel Price Assumptions – High Oil Price Case*

development will yield substantial improvements in fuel economy, at a decreasing initial cost over time. Challenges associated with infrastructure transition are not included in the modeling framework due to the difficulty of capturing transition complexities within the model.

It is worth noting that market success has a substantive effect on the rate of technology advancement that truck and engine manufacturers consider in their product lines. The modeling approach could not contemplate this inter-relation between market success and fuel economy technology adoption.

RESULTS AND DISCUSSION

Vehicle Attributes and Market Shares

The availability of advanced powertrain and vehicle technologies, along with alternative fuel technologies is expected to result in improved fuel economy of future trucks. The analyses explored

the potential for adoption of these technology advances, based on assessments of whether fuel cost savings generated by technology would be sufficient to offset the cost of the new technology. The resulting operating economics were then used to suggest market share potential.

This section reviews potential future scenarios for new vehicle fuel economy, new vehicle price, and market share of new vehicle sales. Class 7&8 is considered first, followed by Class 3-6 trucks. An integrated view of the truck fleet is provided in the Findings section later in this chapter.

Class 7&8 Truck Attributes and Market Shares

Class 7&8 Combination Vehicles: New Vehicle Fuel Economy

There is a strong economic motivation to improve fuel economy in Class 7&8 combination trucks (tractor-trailer trucks with gross vehicle weight >33,000 lbs.). Based on the technology packages available to improve engine, driveline,

and tractor-trailer efficiency attributes, fuel economy is expected to increase with time for both diesel and natural gas fueled trucks. Figures 3-9, 3-10, and 3-11 show the trend of average fuel economy as well as the minimum and maximum range.

The modeling shows a substantial opportunity for improving the fuel economy of diesel trucks, in some cases almost doubling by 2050 as fuel prices increase and the cost of fuel economy technology decreases with time. Diesel fuel economy enhancements are achieved through a combination of improved combustion and aftertreatment efficiency, high efficiency air handling and heat recovery systems, improvements in drive train, and aerodynamic enhancements to tractors and trailers that reduce drag load.

Through 2035, the rate of increase in fuel economy is projected to be similar for diesel and natural gas for all oil price scenarios, due to the assumed limits discussed in the modeling framework. The efficiency trends for diesel and natural gas diverge after 2035 with diesel fuel economy increasing

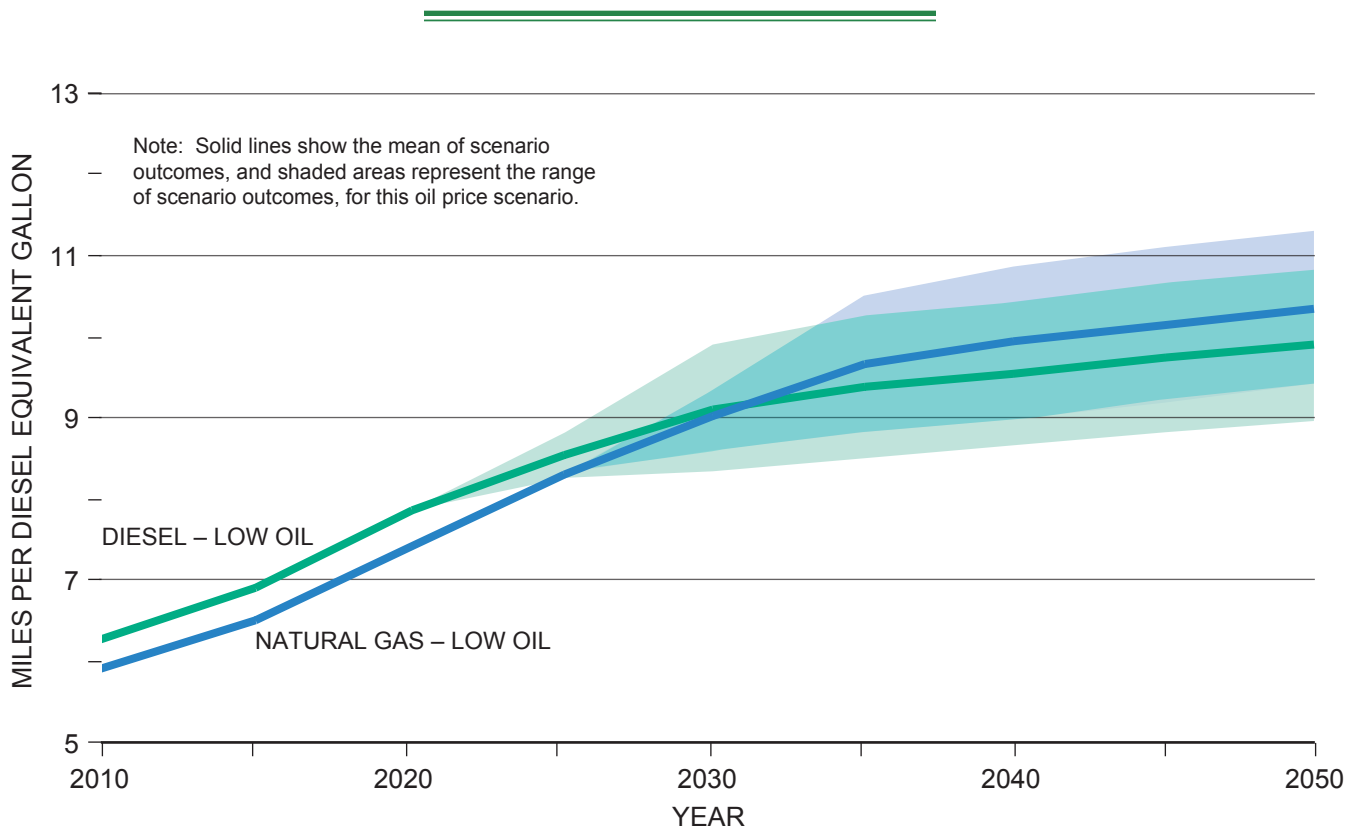


Figure 3-9. Fuel Economy Over Time for New Diesel and Natural Gas Class 7&8 Combination Trucks – Low Oil Price Case

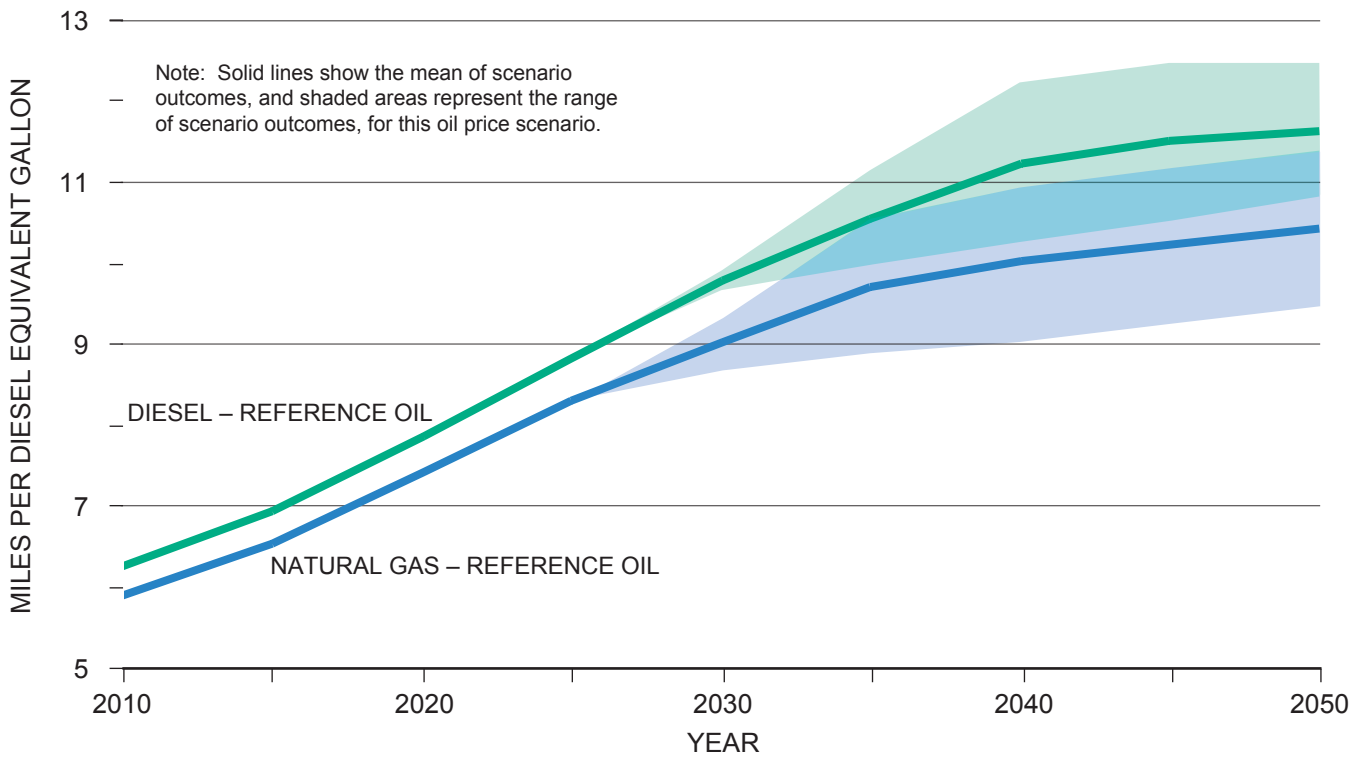


Figure 3-10. Fuel Economy Over Time for New Diesel and Natural Gas Class 7&8 Combination Trucks – Reference Case

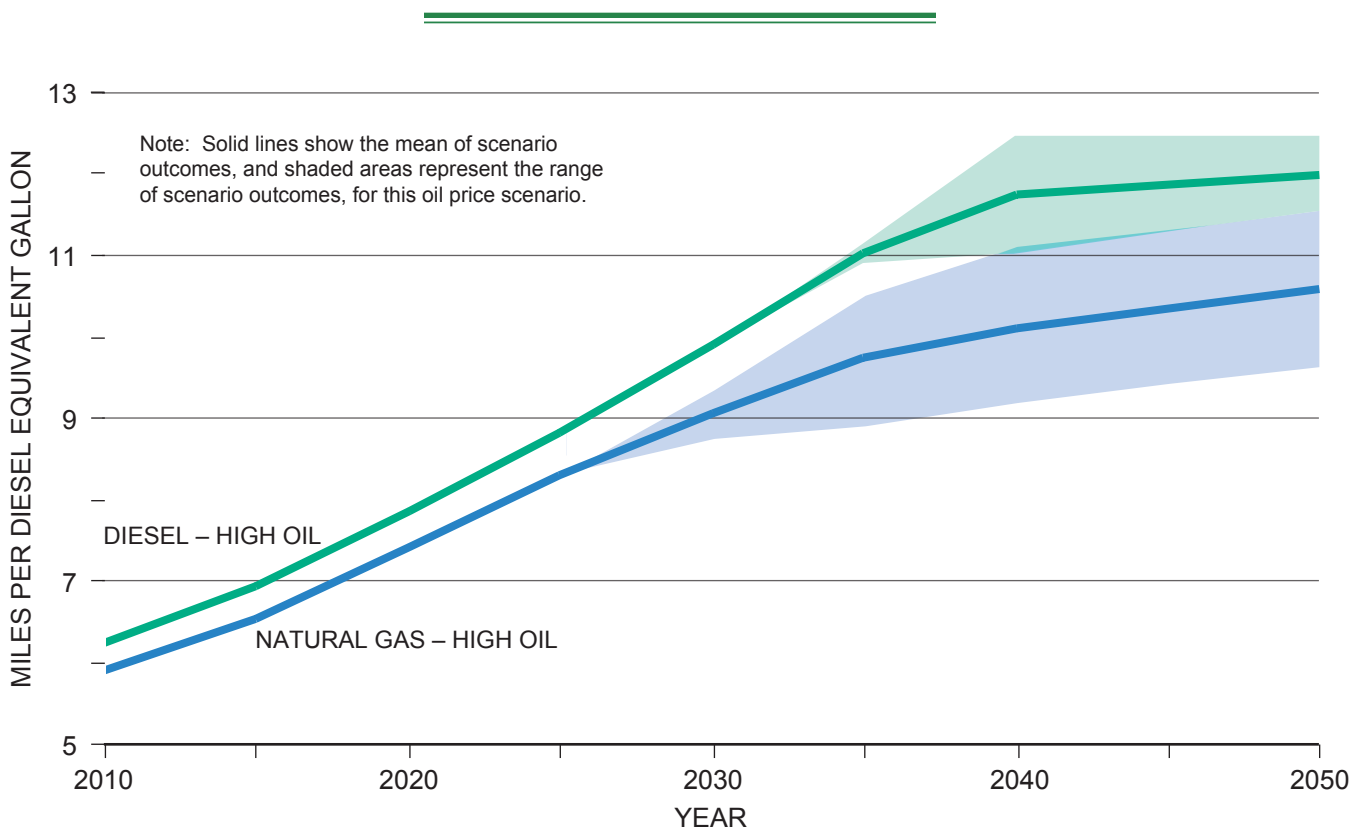


Figure 3-11. Fuel Economy Over Time for New Diesel and Natural Gas Class 7&8 Combination Trucks – High Oil Price Case

faster than natural gas. Diesel fuel economy is estimated to double by 2050 compared to 2010. In the years from 2035 to 2050, fuel economy gains are strongly linked to fuel price scenarios. In the case of diesel, under the Reference and High Oil Price Cases, dispensed fuel prices continue to increase through 2050, justifying the adoption of increasingly costly fuel economy technology, leading to an estimated diesel fuel economy that is twice that of 2010.

The simulations performed here do not explicitly consider the recently finalized Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) regulations for CO₂ and fuel economy. According to the EPA's regulatory impact analysis, these regulations will require increases in the fuel economy of new trucks in coming years, estimated at between 7 and 20% overall improvement by 2017. These estimates are shown on Figure 3-12, as compared to the Class 7&8 fuel economy results from modeling. Generally speaking, the simulation results show fuel economies near the high end of the EPA's estimated range. Although the result shown here is for Class 7&8 combination

trucks only, other segments of the market exhibit similar trends.

**Class 7&8 Combination Vehicles:
New Vehicle Price**

Advances in fuel economy are dictated by the curves representing cost of fuel economy technology and the assumed amount of time required to reduce the cost of new fuel economy technologies. Figures 3-13, 3-14, and 3-15 show the range of Retail Price Equivalent (RPE) of diesel and natural gas Class 7&8 combination trucks that are associated with the fuel economy improvements driven by fuel prices. RPE is the estimated cost of a new vehicle with attributes described by the Vehicle Attribute Model.

Diesel truck prices are shown to increase with time as a result of the addition of increasingly costly fuel economy technology. In the most extreme cases, there is an estimated 30% increase (under high oil price conditions) by 2050. These RPE increases are consistent with minimizing the cost of driving within the first three years of vehicle

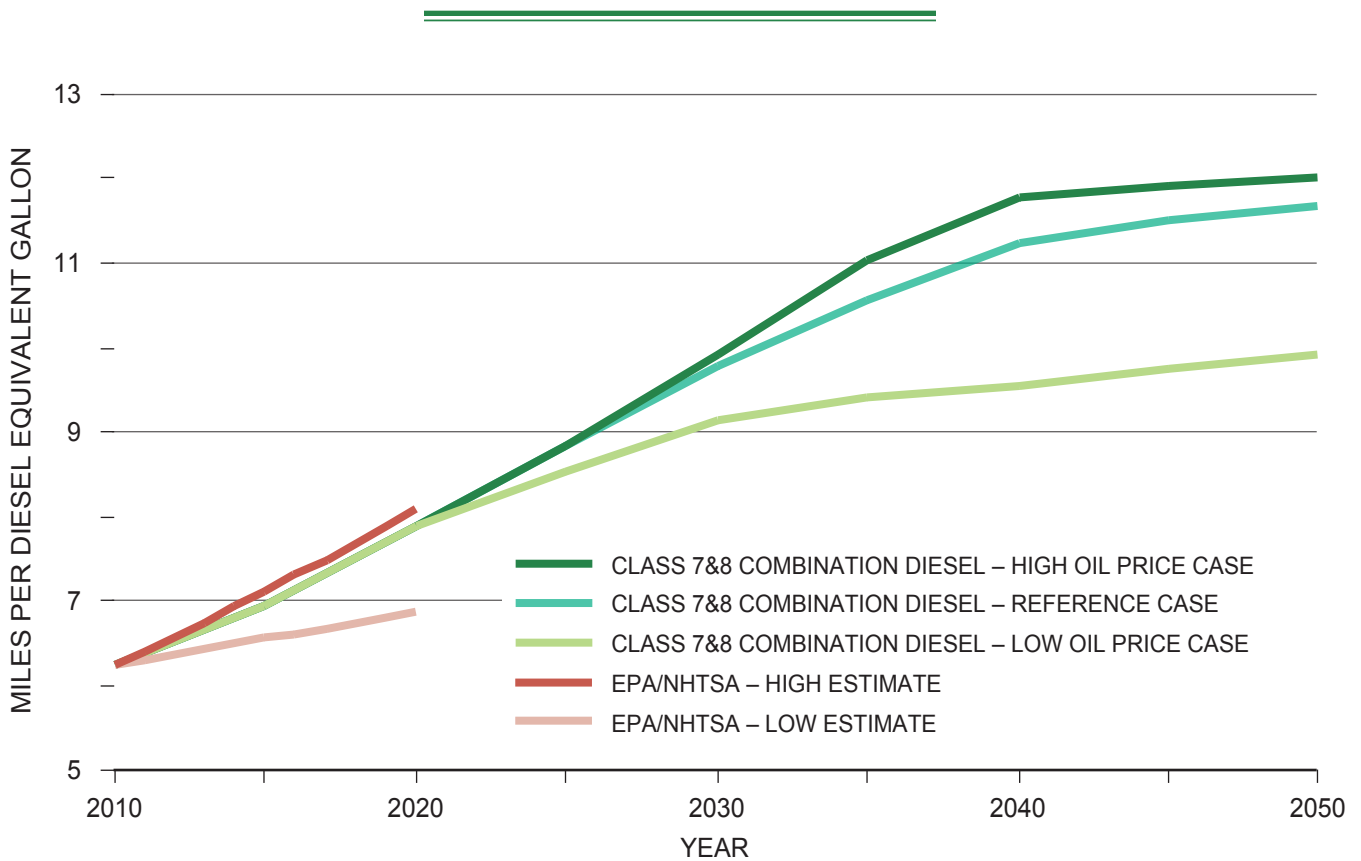


Figure 3-12. Class 7&8 Fuel Economy

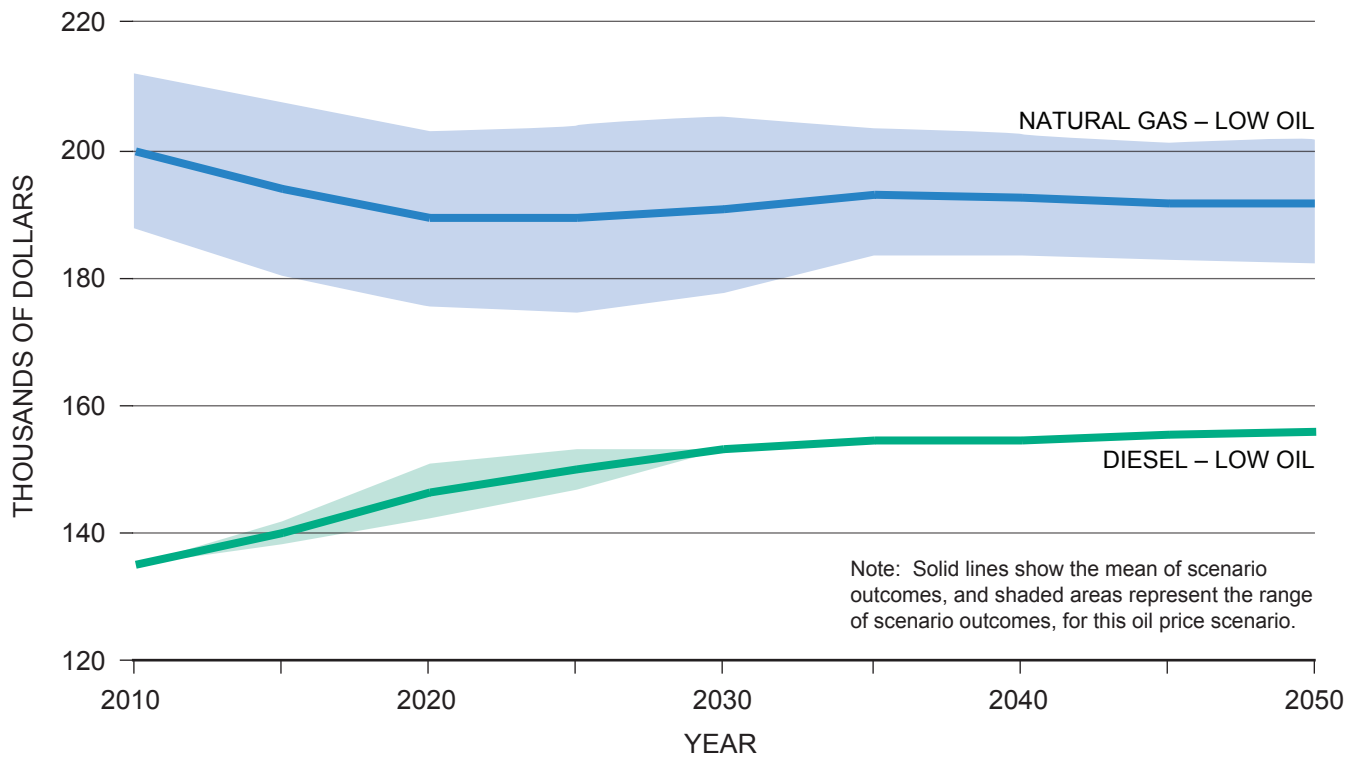


Figure 3-13. *Estimated Retail Price Equivalent of Class 7&8 Combination Diesel and Natural Gas Trucks - Low Oil Price Case*

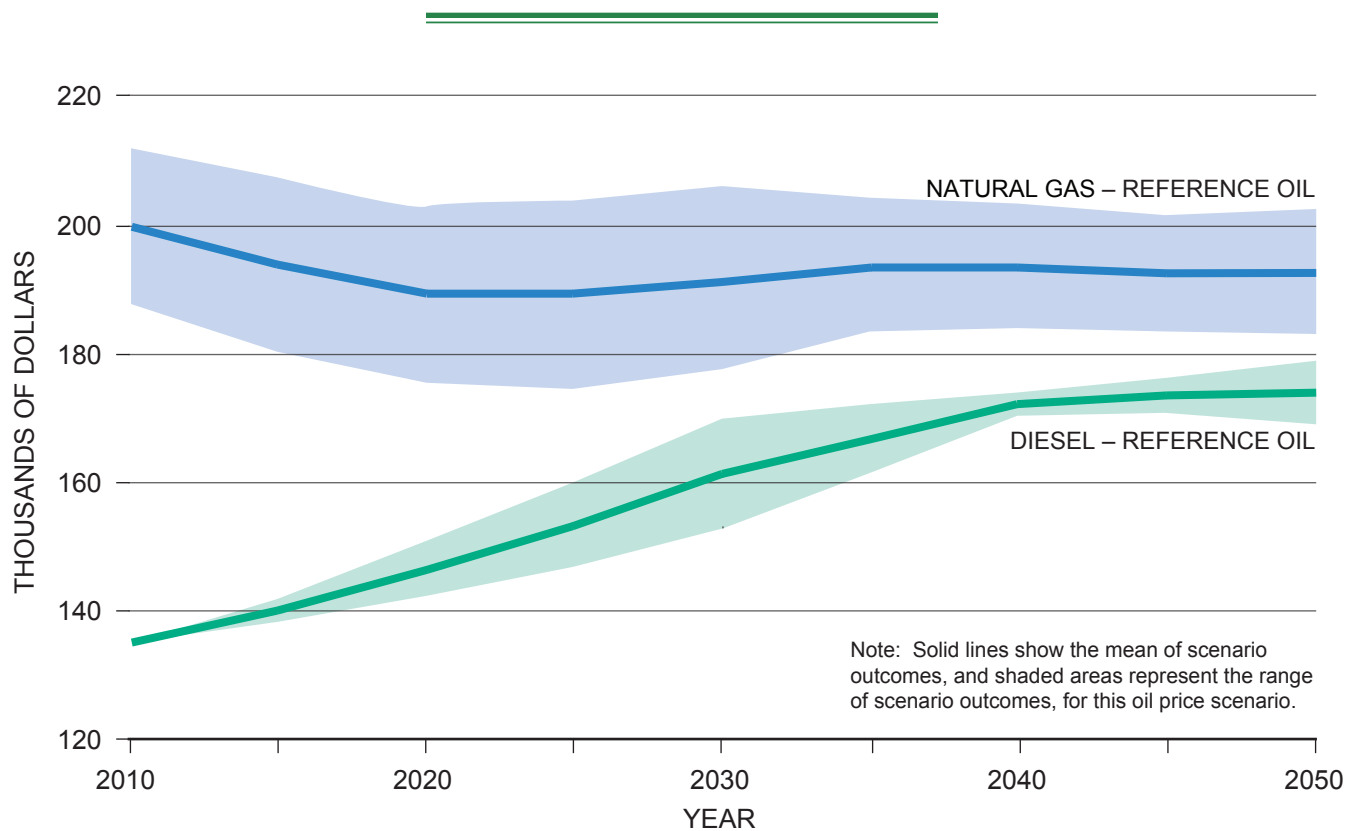


Figure 3-14. *Estimated Retail Price Equivalent of Class 7&8 Combination Diesel and Natural Gas Trucks - Reference Case*

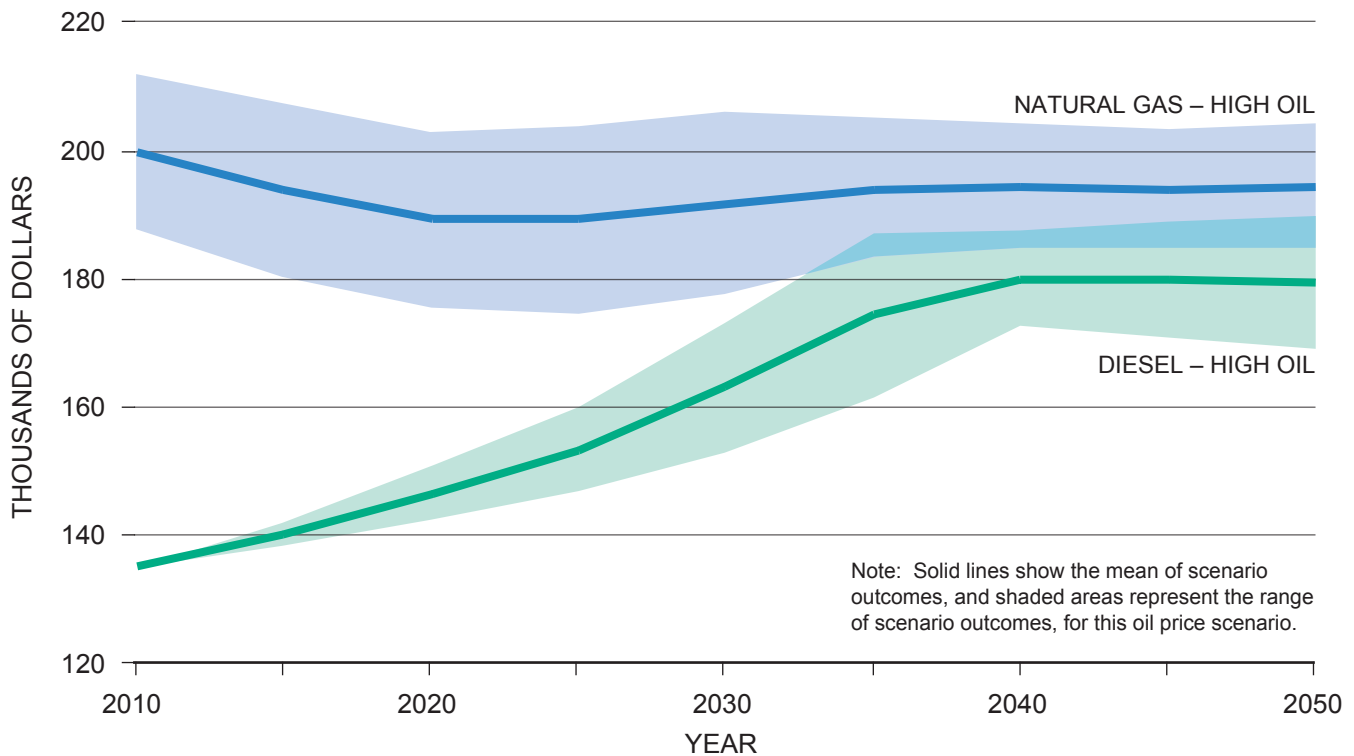


Figure 3-15. *Estimated Retail Price Equivalent of Class 7&8 Combination Diesel and Natural Gas Trucks – High Oil Price Case*

operation. However, this vehicle cost increase may present a challenge to fleet owners in larger capital requirements.

In the near term, there is a significant RPE premium for natural gas fueled trucks because of the cost of fuel storage and the low volume production costs of engines and vehicle integration. Over time, the price premium for natural gas trucks relative to diesel trucks is expected to narrow through cost reductions in natural gas technology.

The natural gas fleet in Class 7&8 has been modeled as a 50-50 mix of spark ignition (SI) and compression ignition (CI) technologies, and the results shown represent that blended technology mix. The RPE of an SI vehicle is lower, and therefore closer to that of the baseline diesel vehicle, compared to a CI natural gas vehicle.

With the increase in capital requirements for both diesel and natural gas vehicles, it is possible that fleets may look at longer vehicle ownership cycles. This potential change in purchasing behavior was not considered within the modeling approach.

Class 7&8 Combination and Single-Unit Vehicle Market Shares

The TRUCK 5.1 model develops estimates of market share of new vehicle sales by technology. The market share is derived from a ranking of the relative economic payback time for the different technologies under the fuel price variations assuming that all technological and logistical barriers are overcome. The market shares described are mileage-weighted, and reflect the share of miles driven by new vehicles, as opposed to simply the vehicle share itself. This is important when considering fuel use, because it is likely that higher mileage trucks will include different fuel and powertrain strategies as well as different preferences for alternatives.

In Class 7&8 combination trucks, where diesel is the primary fuel choice today, the effect of relative fuel prices has a significant impact on diesel market share, as illustrated in Figures 3-16, 3-17, and 3-18. In the Low Oil Price Case, where diesel fuel price is lower than natural gas, diesel remains the sole player. If oil prices increase and diesel prices trend higher than natural gas, the fuel costs savings in this

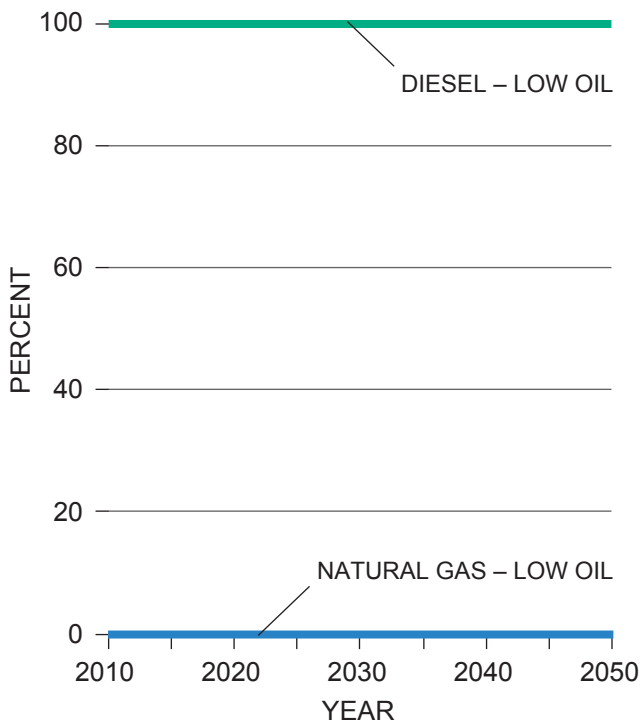


Figure 3-16. Class 7&8 Combination Market Shares of New Diesel and Natural Gas Trucks – Low Oil Price Case

high mileage segment begin to increase the market share of natural gas trucks. The analysis indicates that the market share of natural gas trucks will increase steadily with time to an average peak of 40% by 2045 in the Reference Case. In the High Oil Price Case, the transitional shift may occur faster, passing 40% by 2025.

The range of cost assumptions related to both fuel economy technology and natural gas system costs has some impact on market share under the Reference Case. In the High Oil Price Case, the market share is largely insensitive to these uncertainties, again a consequence of the importance of fuel costs on vehicle economics.

The total vehicle stock is projected to increase to satisfy the growing freight and VMT demand. Although diesel market share may be eroded by natural gas vehicles under certain conditions (see Figures 3-19, 3-20, and 3-21), the changing market shares may not have substantive impacts on the annual sales volumes of diesel trucks. In the AEO2010 Reference Case, total Class 7&8 truck sales were estimated to increase to approximately

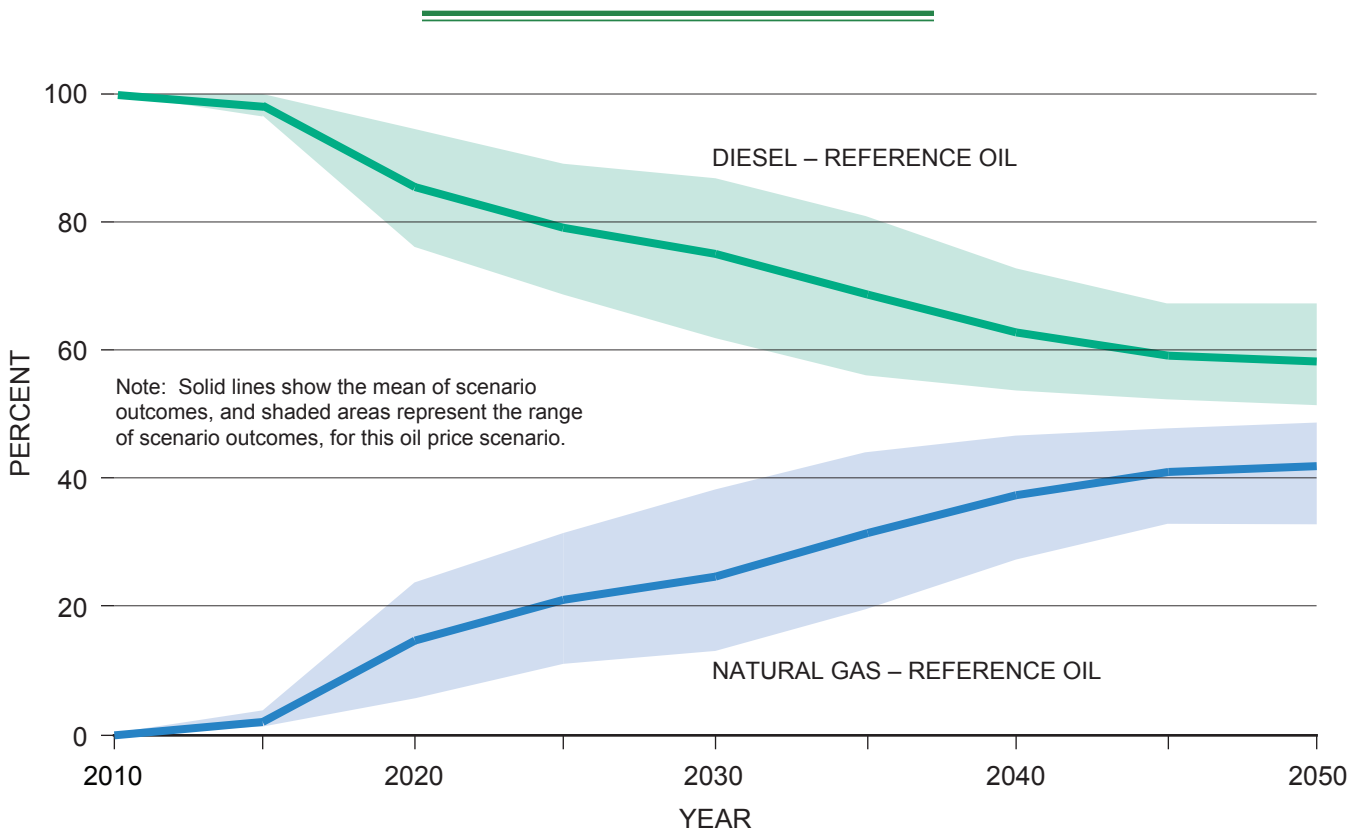


Figure 3-17. Class 7&8 Combination Market Shares of New Diesel and Natural Gas Trucks – Reference Case

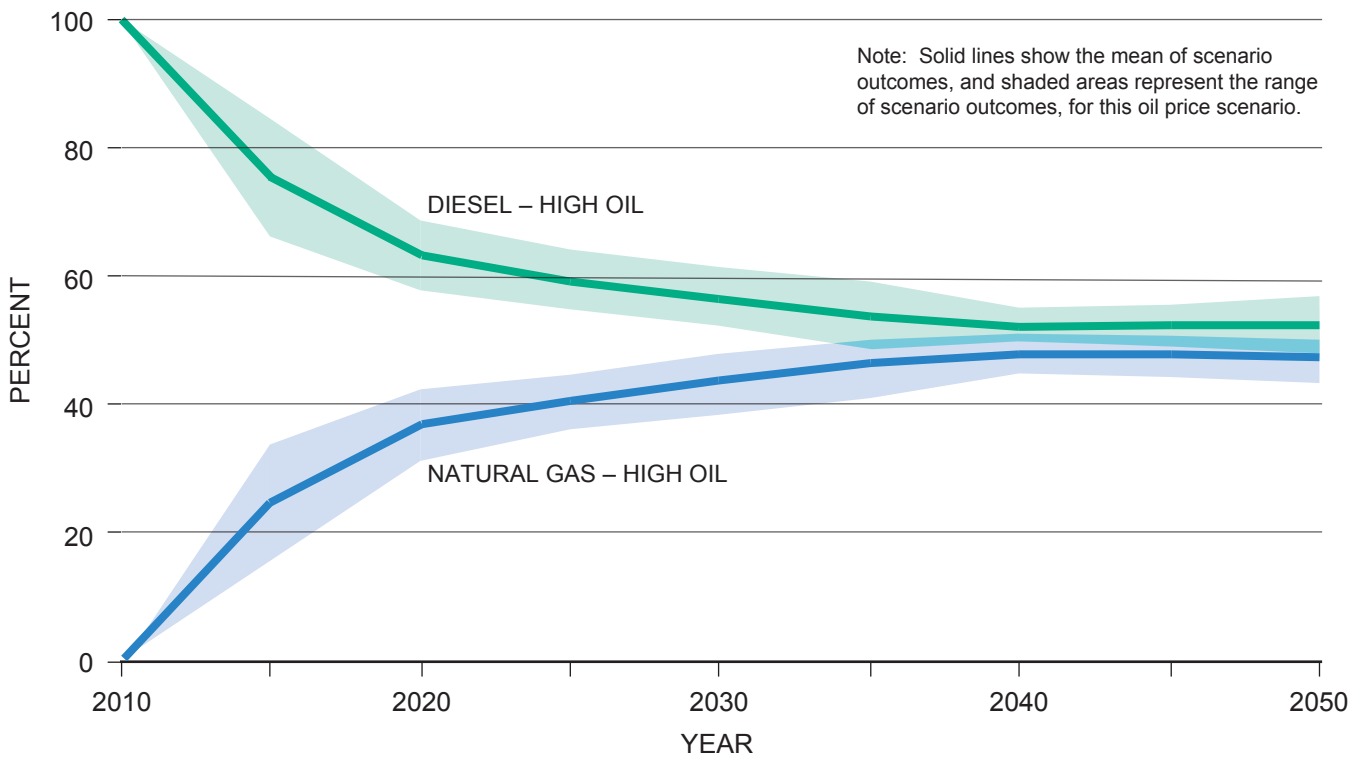


Figure 3-18. Class 7&8 Combination Market Shares of New Diesel and Natural Gas Trucks – High Oil Price Case

300,000 units in 2035. If, as illustrated in Figures 3-20 and 3-21, diesel market share in that time frame is 60–70% of new sales, sales volumes of diesel trucks would be in the range 180,000 to 210,000 units. This is not substantially different from sales observed in the last five years.

As noted earlier, natural gas engines are assumed to be a 50-50 mix of spark ignition and compression ignition. This simplifying assumption avoids prejudging the relative merits of the CI and SI technologies. However, these assumptions do have a material impact on the modeled market share results. A shift toward 100% SI engines may increase market shares by around 10–15%; where a shift to 100% CI engines may decrease the market share by similar amounts. A shift toward 100% CI engines would result in higher fuel economy than the 50-50 mix, improving fuel economy by 10–15% because SI engines generally have lower fuel economy. While the model highlights the economic competitiveness of natural gas trucks generally, the model cannot determine the optimal market outcome of specific natural gas engine technologies.

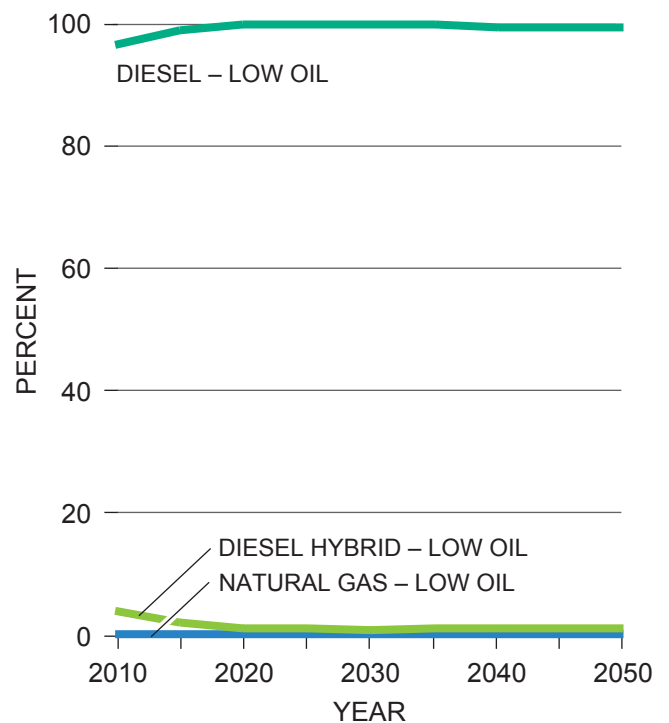


Figure 3-19. Class 7&8 Single Unit Market Shares of New Diesel and Natural Gas Trucks – Low Oil Price Case

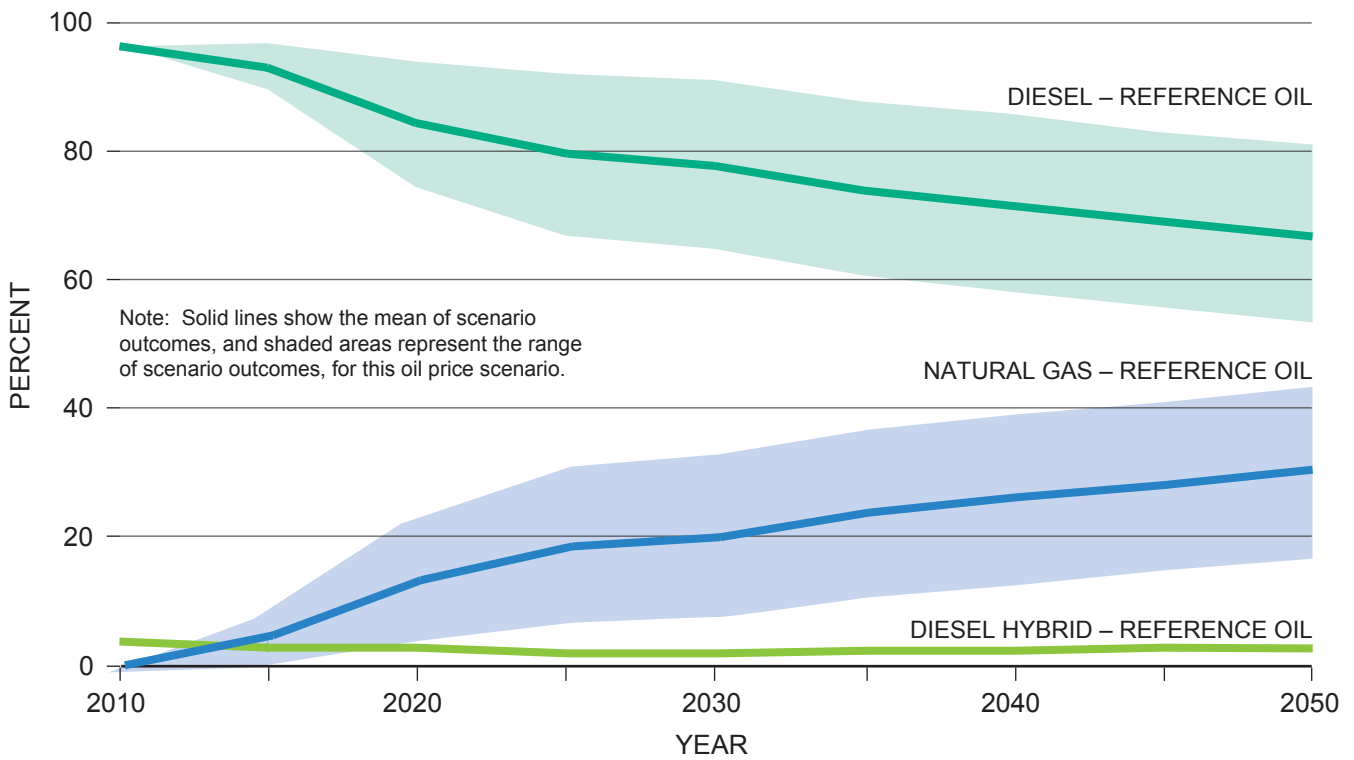


Figure 3-20. Class 7&8 Single-Unit Market Shares of New Diesel and Natural Gas Trucks – Reference Case

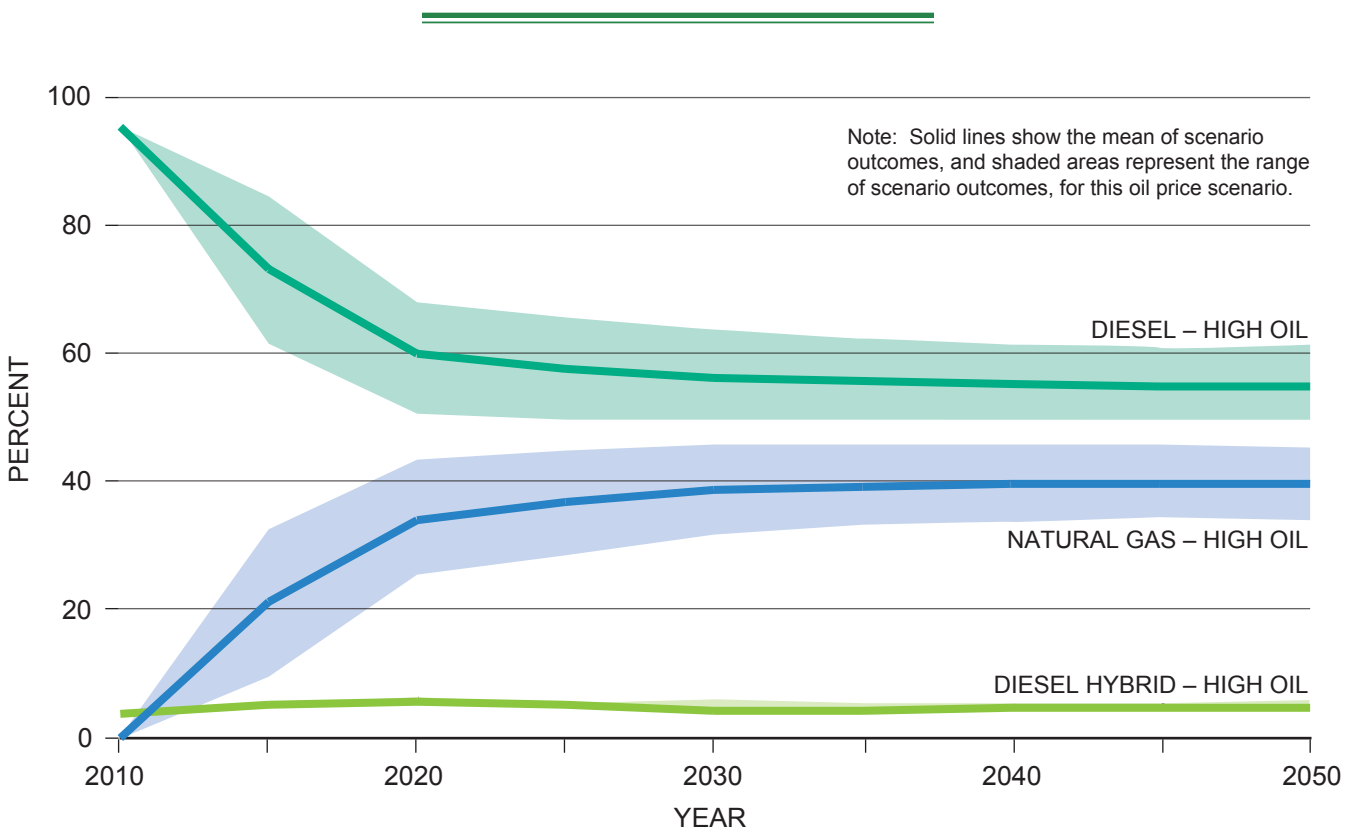


Figure 3-21. Class 7&8 Single-Unit Market Shares of New Diesel and Natural Gas Trucks – High Oil Price Case

Because of LNG's lower volumetric energy density, natural gas trucks must carry a greater volume of fuel to drive an equivalent distance compared to a diesel truck. Based on data from the U.S. Census Bureau's 2002 Vehicle Inventory and Use Survey (VIUS), the median annual mileage of Class 7&8 trucks is approximately 122,500 miles. In line with this, the modeling of natural gas trucks factored in fuel storage volumes sufficient for a 500-mile range, with a further 20% additional capacity (i.e., 600-mile total fuel capacity). At 6 miles per diesel equivalent gallon, this would be 100 diesel equivalent gallons of fuel or approximately 170 gallons of LNG. As fuel economy technology is adopted in the natural gas fleet, the quantity of fuel storage required would decrease, and the cost allocation for storage would likewise decrease. Although many diesel trucks carry sufficient fuel to drive longer distances between refueling, a distance of 500 miles at road speed limits is representative of a 9 to 10 hour driving shift, at which point it is not unreasonable to consider a vehicle refueling.

In the Class 7&8 single-unit truck segment, diesel-fueled hybrid trucks were included in the analysis with diesel and natural gas. The predicted market dynamics for this class of vehicle are similar to that of Class 7&8 combination trucks, with diesel-fueled vehicles retaining majority share, but with significant penetration of natural gas vehicles. Hybrid truck market share is minimal regardless of oil price due to the high system cost that is not easily offset by sufficient fuel savings, as shown in Figures 3-19, 3-20, and 3-21.

According to the National Academy of Sciences, Class 7&8 vocational trucks consume less fuel than Class 7&8 combination trucks or Class 3-6 trucks. However, their unique position in the market makes them meaningful as a starting point for alternative fuel expansion. For example, municipal fleets and centrally refueled "tethered" fleets are a natural starting point for natural gas adoption because infrastructure concerns are minimized. Such fleets tend to include Class 7&8 single-unit applications such as buses, refuse haulers, and heavy dump trucks that "return to base" for refueling.

Class 3-6 New Vehicle Attributes

The Class 3-6 truck market is very different from the Class 7&8 market. Class 3-6 trucks tend to drive shorter distances at lower speeds, often in stop-and-

go drive cycles. They cost less than their Class 7&8 counterparts and tend to be more cost constrained. A significant portion of Class 3-6 trucks are also powered by gasoline engines, which are cheaper to purchase than diesel but operate at lower fuel economy. Gasoline vehicles also generally deliver less torque than their diesel counterparts, making them less suitable for heavier load applications.

Class 3-6 New Vehicle Fuel Economy

In Class 3-6, there is potential for meaningful improvements in truck fuel economy but to a lesser extent than Class 7&8. Figures 3-22, 3-23, and 3-24 isolate the new Class 3-6 fuel economy for the years 2035 and 2050 for the three oil price cases.

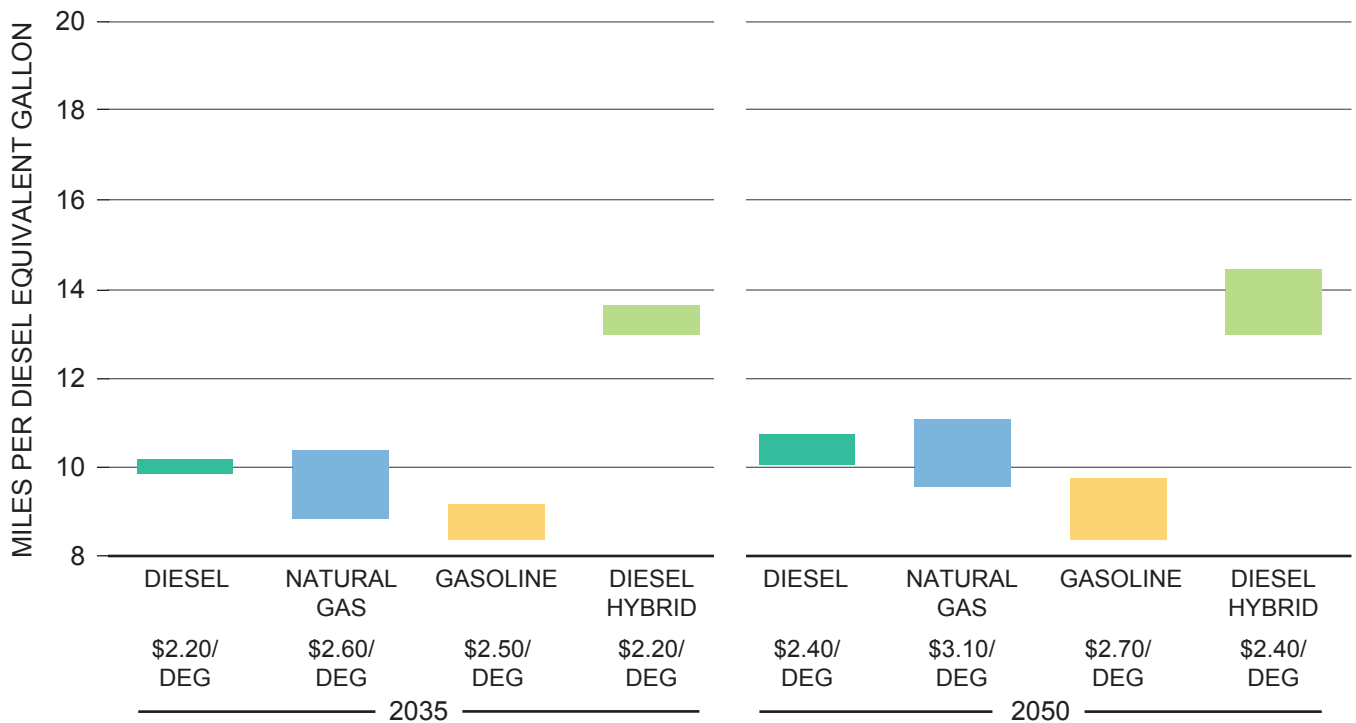
Class 3-6 2010 diesel truck fuel economy (from the AEO2010) is 9 miles per diesel equivalent gallon, and the maximum diesel fuel economy projected for 2050 under high oil price conditions is 14 miles per diesel equivalent gallon, as shown in Figure 3-24. This represents a 55% increase in fuel economy compared to 100% increases seen in high mileage Class 7&8 combination trucks. This is due to the trade-off between fuel saving and costly engine and transmission technology. Improvements in vehicle aerodynamics are less impactful in these classes of trucks since they tend to operate in more urban environments with lower average vehicle speeds.

Gasoline and natural gas trucks are projected to have similar fuel economy, consistent with the underlying assumption that both these vehicle types are spark ignited and throttled engines. In Class 3-6, natural gas trucks are assumed to be solely spark ignition using CNG as the fuel source.

Hybridization shows potential for fuel economy improvements over and above that of diesel in Class 3-6, with maximum fuel economies of approximately 16 to 18 miles per diesel equivalent gallon in 2050 under high oil price cases for diesel hybrid vehicles. Gasoline or natural gas hybrid vehicles were not modeled in this study but would provide similar fuel economy improvement.

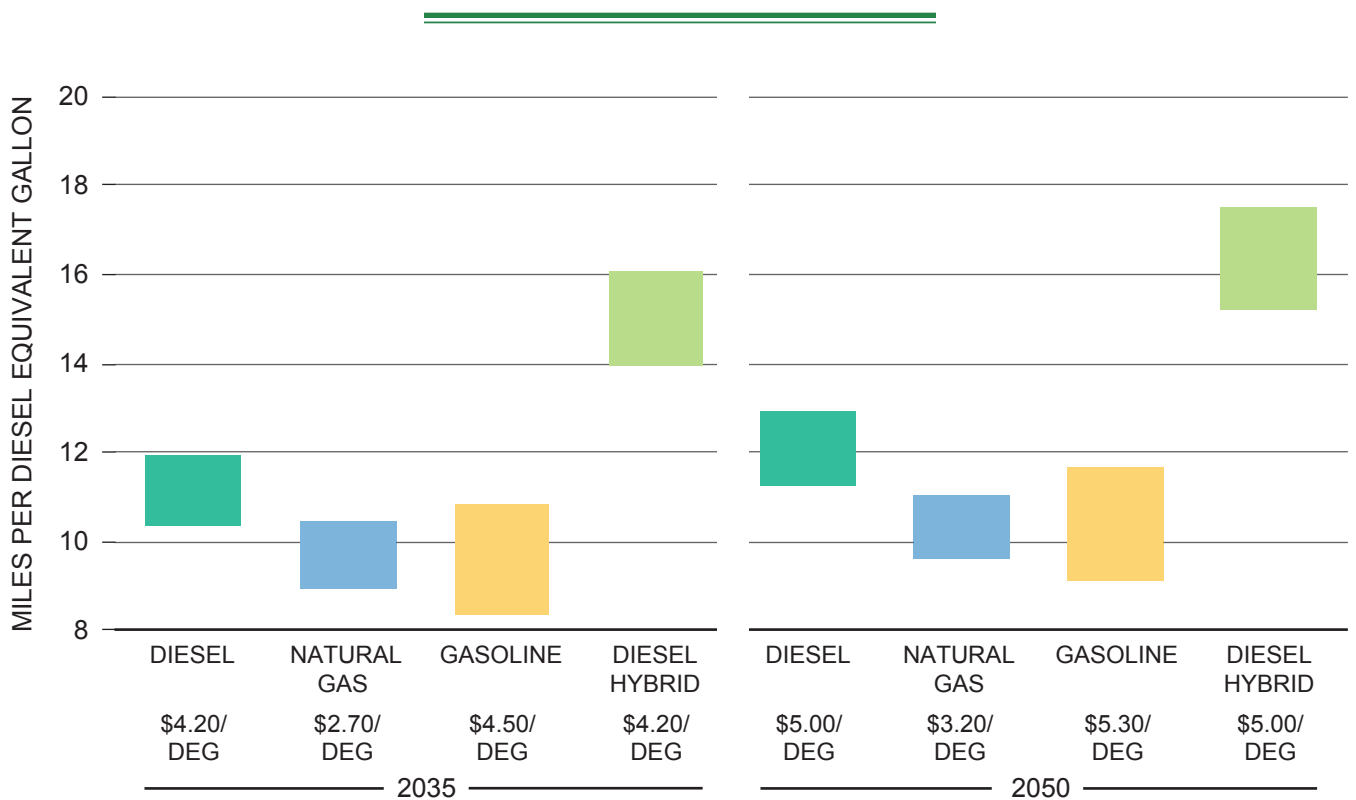
Class 3-6 New Vehicle Price

Class 3-6 has a greater variety of duty cycles and a greater variation in RPE of new trucks, as shown in Figures 3-25, 3-26, and 3-27.



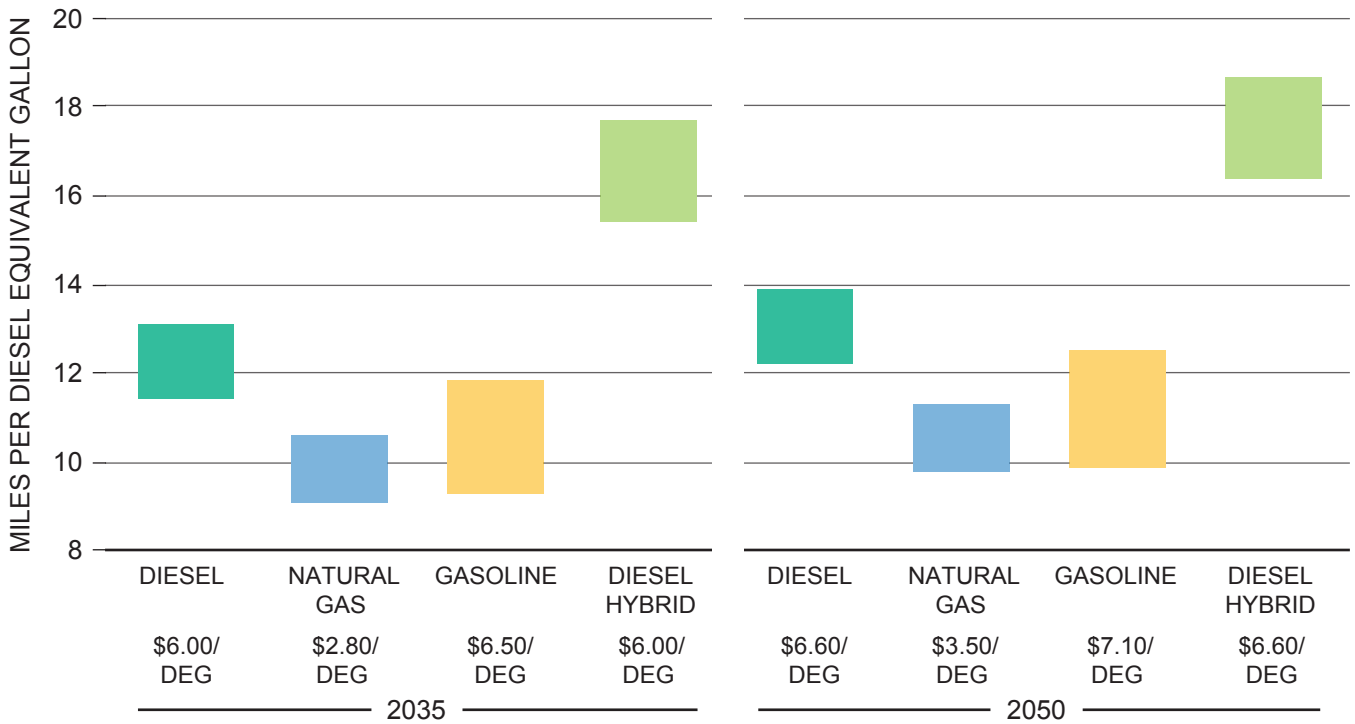
DEG = Diesel Equivalent Gallon.

Figure 3-22. Fuel Economy of New Class 3-6 Trucks in 2035 and 2050 – Low Oil Price Case



DEG = Diesel Equivalent Gallon.

Figure 3-23. Fuel Economy of New Class 3-6 Trucks in 2035 and 2050 – Reference Case



DEG = Diesel Equivalent Gallon.

Figure 3-24. Fuel Economy of New Class 3-6 Trucks in 2035 and 2050 - High Oil Price Case

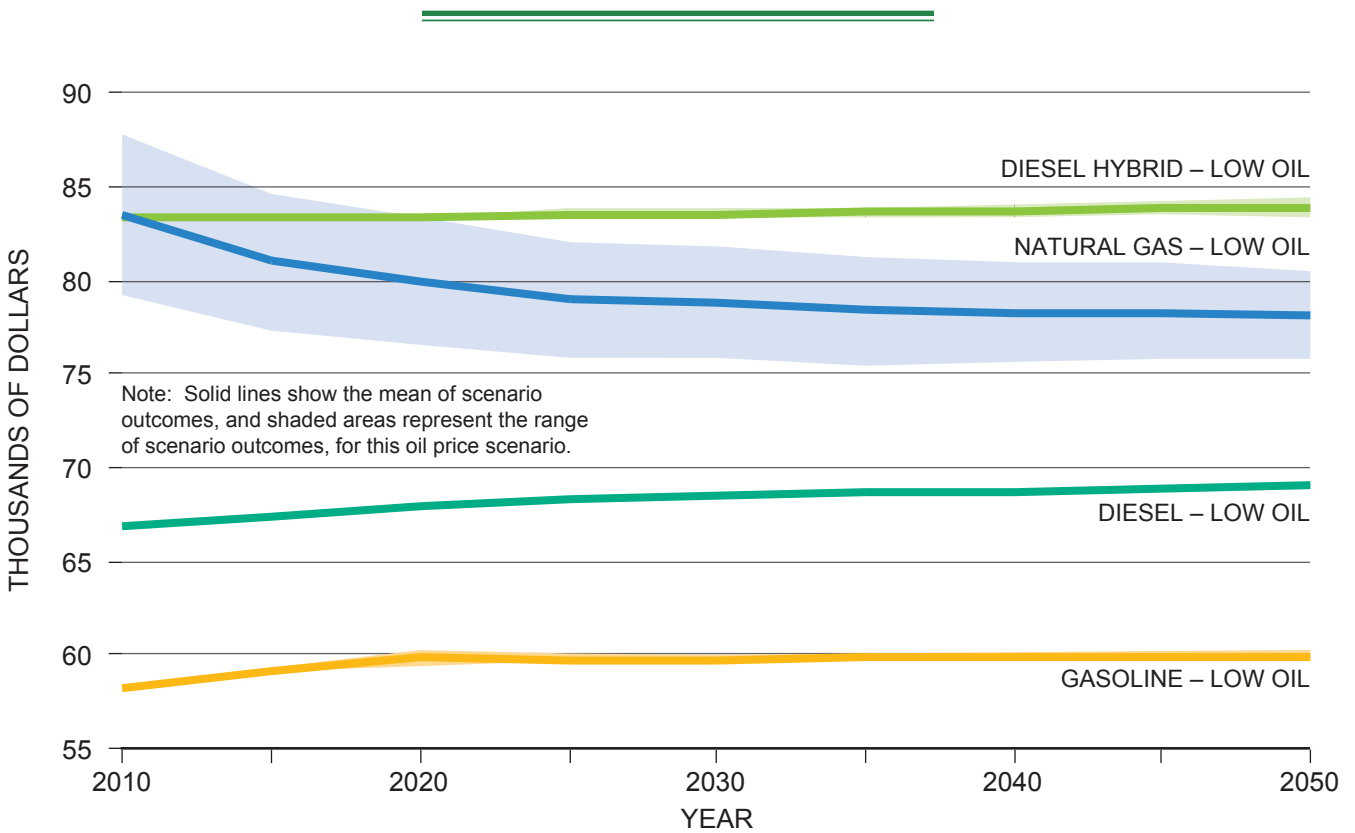


Figure 3-25. Retail Price Equivalent of Class 3-6 Trucks - Low Oil Price Case

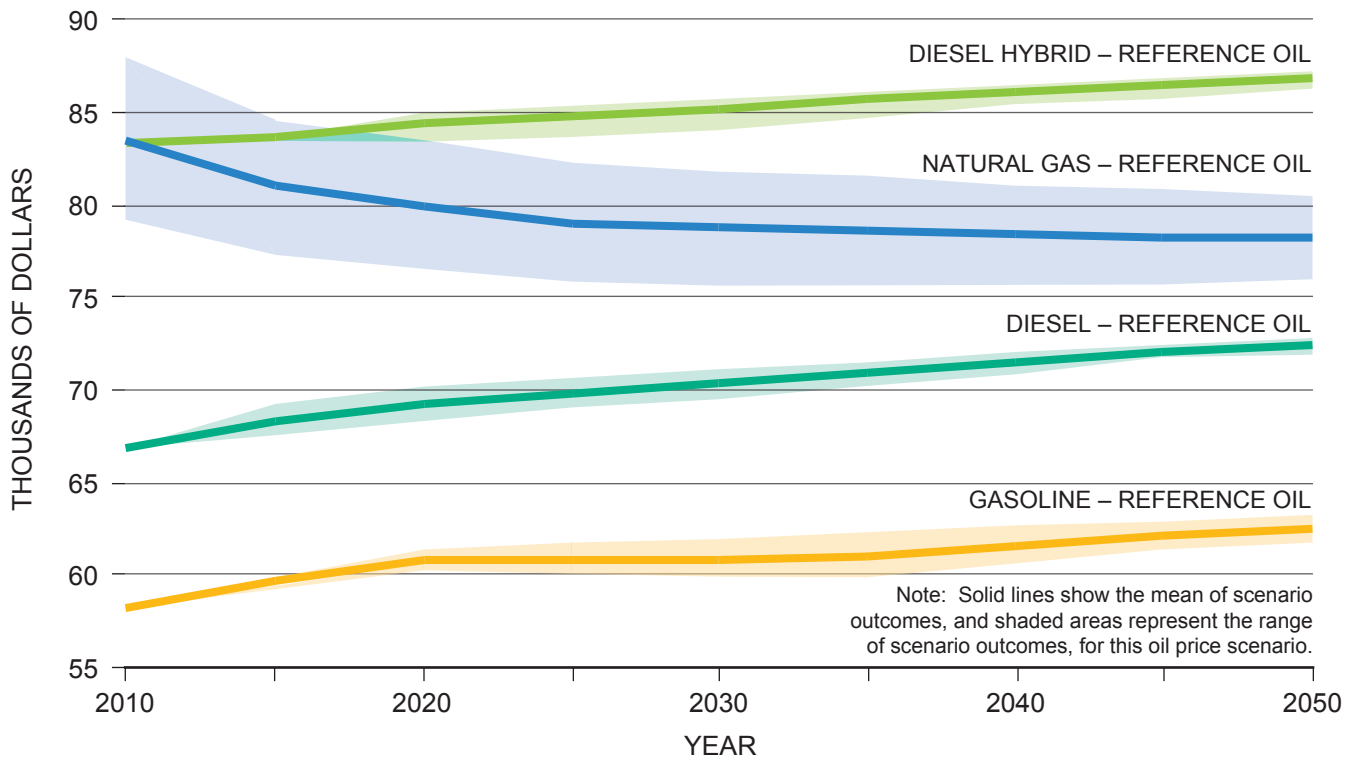


Figure 3-26. Retail Price Equivalent of Class 3-6 Trucks – Reference Case

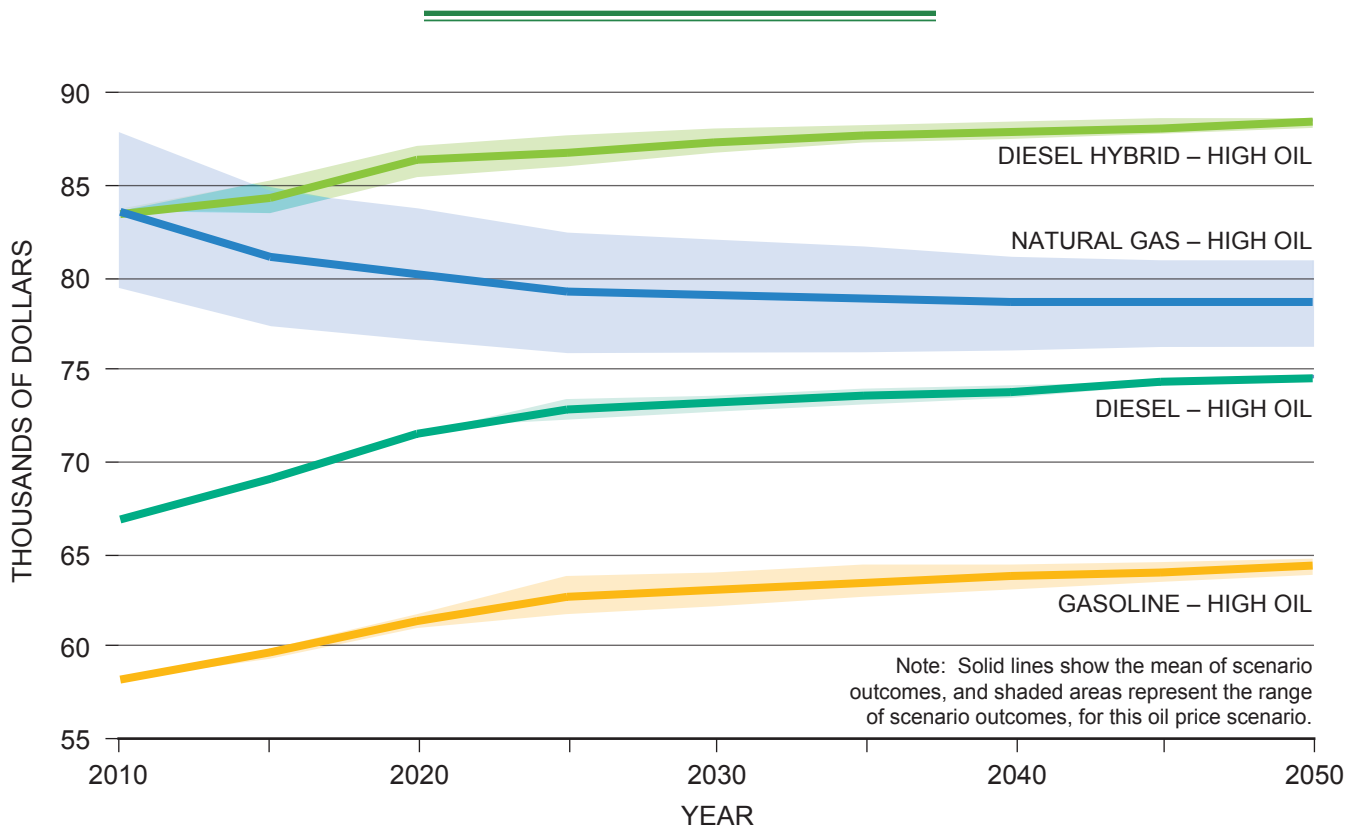


Figure 3-27. Retail Price Equivalent of Class 3-6 Trucks – High Oil Price Case

The RPE of diesel trucks increases modestly from about \$67,000 in 2010 to about \$75,000 in 2050 under the High Oil Price Case. Gasoline vehicles retain a cost advantage over diesel through the timeframe despite increasing fuel economy. This is a result of the lower cost of aftertreatment systems and the avoidance of costly diesel fuel injection systems. By 2035, the cost premium associated with spark ignited CNG trucks closes to within \$3,000 to \$8,000 of diesel, with the premium being largely associated with the cost of fuel storage. Hybrid truck premiums persist at approximately \$15,000 higher than diesel.

In Class 3-6, the sensitivity of oil price on fuel economy and vehicle price is less significant than in Class 7&8. Increasing levels of fuel economy technology have a diminishing return on fuel cost savings in this segment, due to the lower average operating mileage of these vehicles.

Class 3-6 New Vehicle Market Shares

Market share dynamics are more complex in the Class 3-6 segment with four different powertrain

technologies competing to varying degrees as shown in Figures 3-28, 3-29, and 3-30. Currently, diesel is the dominant fuel, but gasoline trucks hold as much as 35% market share today. In the Low Oil Price Case, the gasoline market share is projected to increase to as much as 50%, due to the lower vehicle cost as shown in Figure 3-28. Diesel market share drops to approximately 40% with diesel-hybrid vehicles making up the majority of the remainder. Under the Low Oil Price Case, natural gas penetration is low, as fuel cost savings are not sufficient to offset vehicle price premiums. As oil prices increase in the Reference Case, market share of natural gas trucks increases, taking share from both diesel and gasoline. While gasoline share remains relatively strong, in the range of 40 to 50%, the non-hybrid diesel share may drop as low as 25%. Note that some truck buyers will retain a strong preference for diesel power, due to the value of diesel's high-torque capabilities for higher-load operation on trucks of heavier weight. In the High Oil Price Case, the market is roughly equally split between diesel (including hybrids), gasoline, and natural gas vehicles.

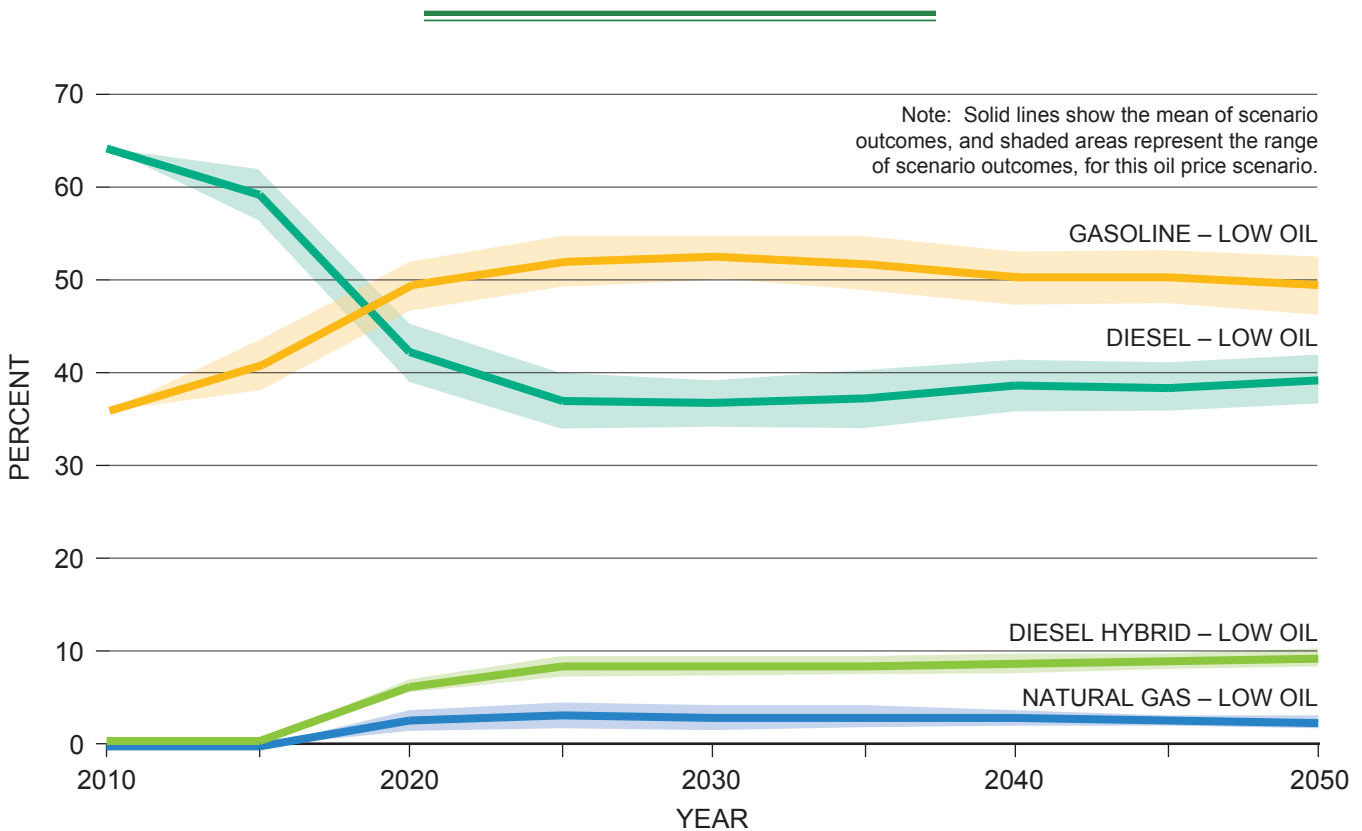


Figure 3-28. Class 3-6 Market Share of New Truck Sales – Low Oil Price Case

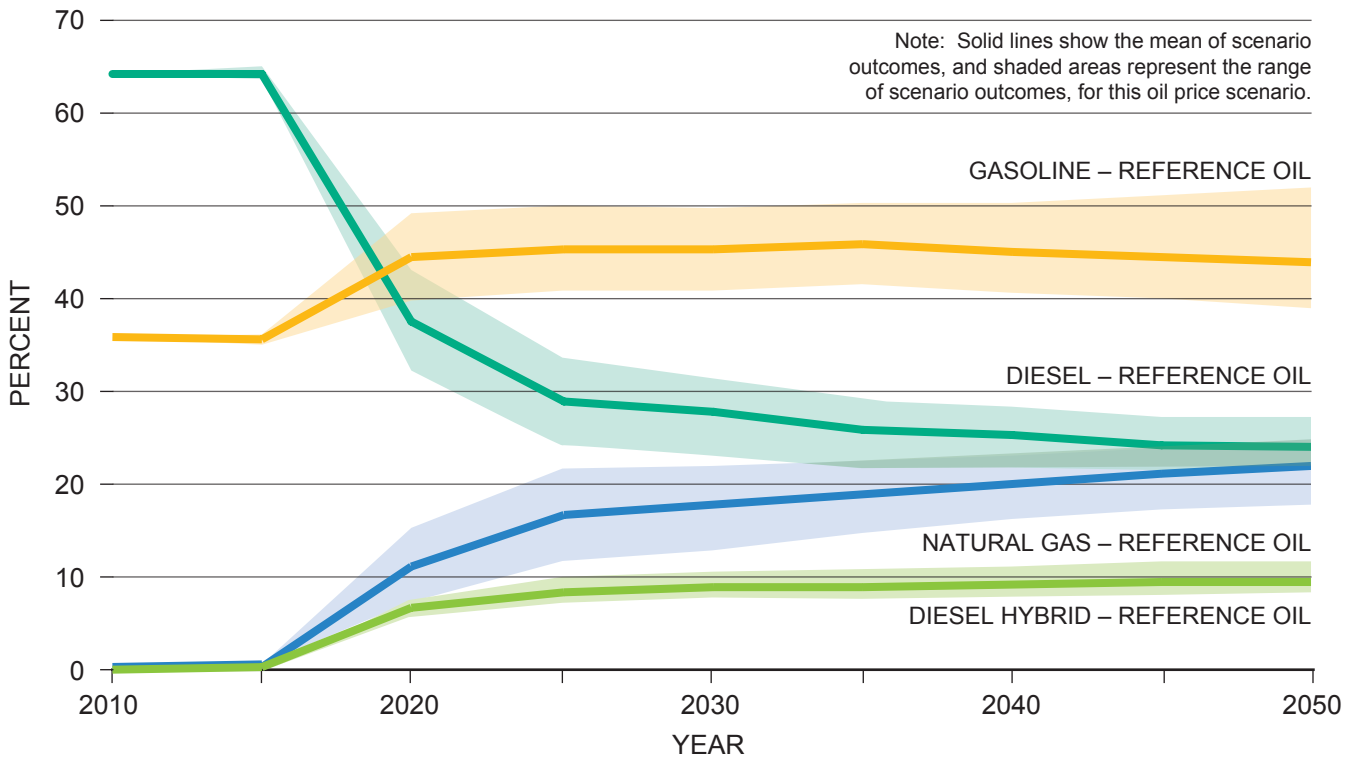


Figure 3-29. Class 3-6 Market Share of New Truck Sales - Reference Case

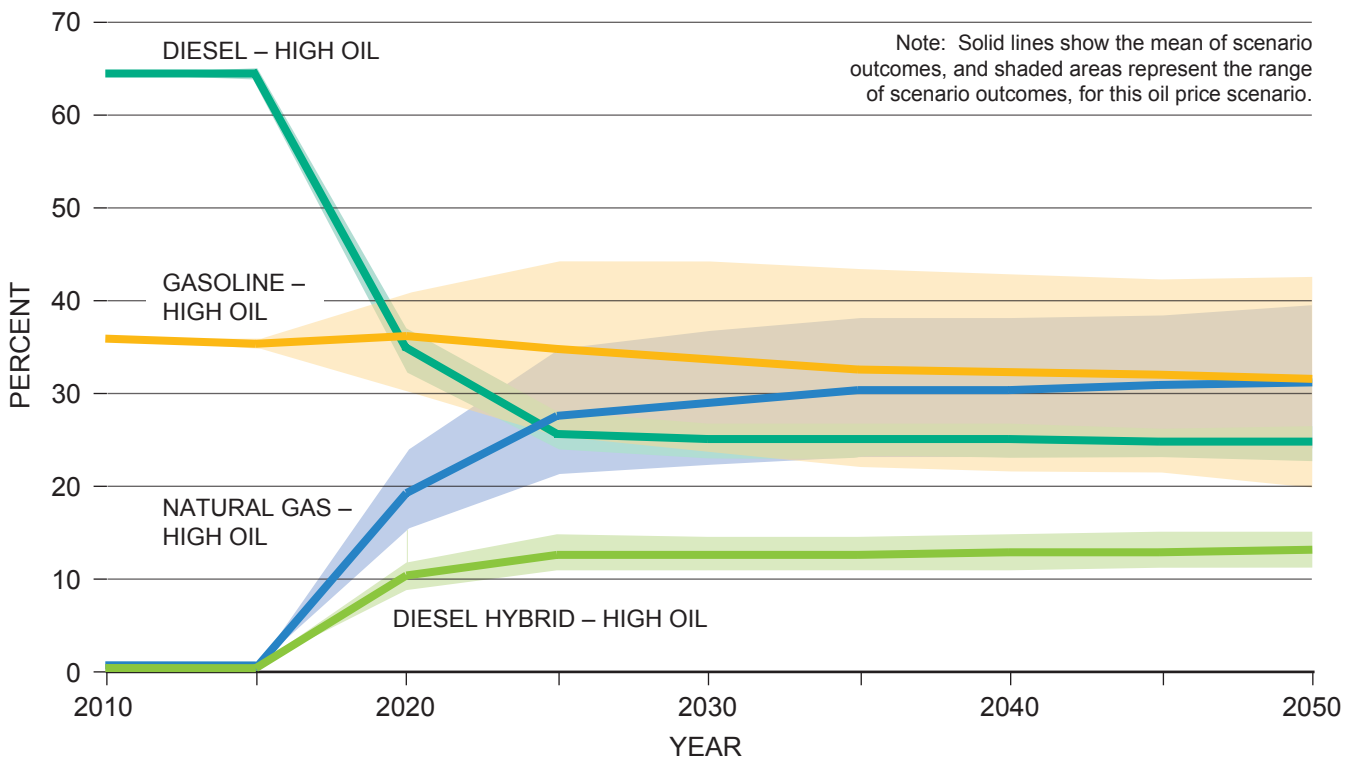


Figure 3-30. Class 3-6 Market Share of New Truck Sales - High Oil Price Case

Hybrid penetration is higher in Class 3-6 than for Class 7&8 single-unit trucks since the cost premium over conventional powertrains is lower due to the lower power and torque requirements in these classes. Hybrid truck shares are insensitive to oil price, stabilizing at around 10% of total sales. Hybrid trucks may see greater uptake for specific applications where duty cycles are characterized by regular stop-start operation. Some medium-duty trucks, such as “bucket” trucks for utility applications, are a natural fit for hybrids due to their pre-existing need for electric drive power onboard.

Future Truck Fleet Characteristics

The modeling framework considers new-truck characteristics and market shares for the entire truck fleet over time. The fleet consists of all trucks on the roads, including the new trucks added annually and older trucks that typically have lower mileage and drive for shorter distances as they age. Fleet-averaged results provide a picture of national fuel use and GHG emissions. By integrating the effects of industry behavior over time, the full fleet provides a perspective on national fuel economy, energy usage, and other economic considerations.

Fleet-Averaged Fuel Economy

The mileage of the full fleet of Class 7&8 trucks is shown in Figure 3-31. These trucks consume the largest share of fuel in the heavy-duty sector by a wide margin. Major advances in miles per gallon (mpg) for the Class 7&8 truck fleet are projected in 2035 and again in 2050. Improvements of almost doubled fuel economy are possible based on the most optimistic simulations in 2050. Improvements in fuel efficiency come from a range of improvements including engine and combustion technologies, aerodynamic improvements, and high-efficiency tires. As noted previously, many of these technologies are incremental and their combined effect is sizeable at the fleet level. These technologies tend to be adopted in the Class 7&8 combination sector. At high mileage levels, typical for line-haul trucks, marginal improvements in fuel economy can have a big impact on a truck purchaser’s bottom line.

Fleet-averaged fuel economy for Class 3-6 trucks is likely to improve as shown in Figure 3-32, though the model does not project as high an improvement

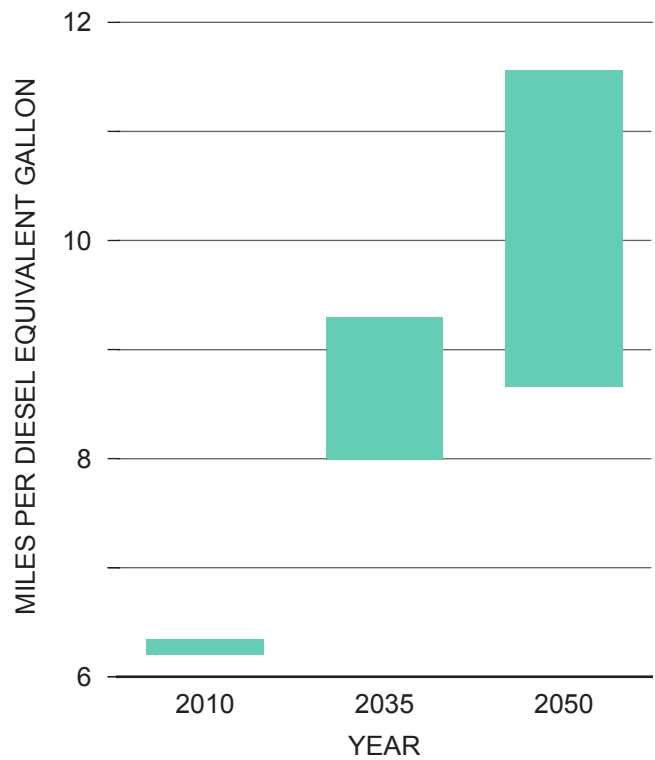


Figure 3-31. Fleet-Averaged Fuel Economy of Class 7&8 Trucks

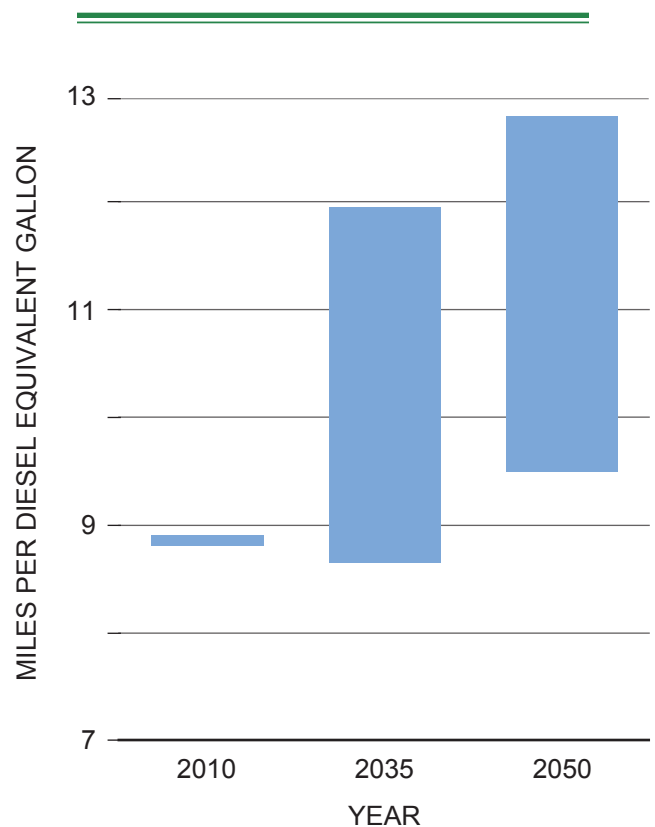


Figure 3-32. Fleet-Averaged Fuel Economy of Class 3-6 Trucks

rate as with Class 7&8. Improvements of 40–50% are possible in the best case for Class 3-6 trucks, due largely to incremental improvements from a variety of technologies. The annual mileage of a Class 3-6 truck is typically much less than that of a line-haul truck, which means investments in fuel economy do not pay off as quickly. Additionally, some technologies, including aerodynamic improvements and auxiliary-power units, are less effective under typical MD vehicle operating conditions, which are usually quite different from the Class 7&8 duty cycle.

The lower range of model outcomes for Class 3-6 trucks is essentially flat over the long-term even though new truck fuel economy is expected to improve over time in trucks of any fuel type, as shown in Figure 3-33. In Class 3-6, fuel economy improvements are countered by an ongoing shift away from diesel, and toward both gasoline and natural gas engines. Gasoline engines are fundamentally less efficient than diesel engines. As truck market share shifts away from diesel to gasoline and to natural gas in some cases, the shift puts downward pressure on fleet mpg.

Fleet Composition

New technologies penetrate the market over time, so the fleet composition lags the new-vehicle market share. As new technologies are taken up through new vehicle sales, older vehicles continue to haul freight, consume fuel, and contribute to overall energy consumption.

Figures 3-34, 3-35, and 3-36 and Figures 3-37, 3-38, and 3-39 show fleet composition for Classes 3-6 and Class 7&8, respectively, for the three oil-price scenarios. In the Class 3-6 segment, the role of traditional diesel and gasoline powertrains is eroded as oil prices increase, with a substantial share of the fleet shifting to both hybrid and natural gas in the High Oil Price Case. It must be noted that even with high oil price assumptions, traditional liquid-fueled internal combustion engine powertrains retain over 50% market share in 2050.

In the Class 7&8 market, natural gas trucks grow to a substantial number in both the Reference and the High Oil Price Cases. Natural gas has a cost advantage if there is a spread between diesel and

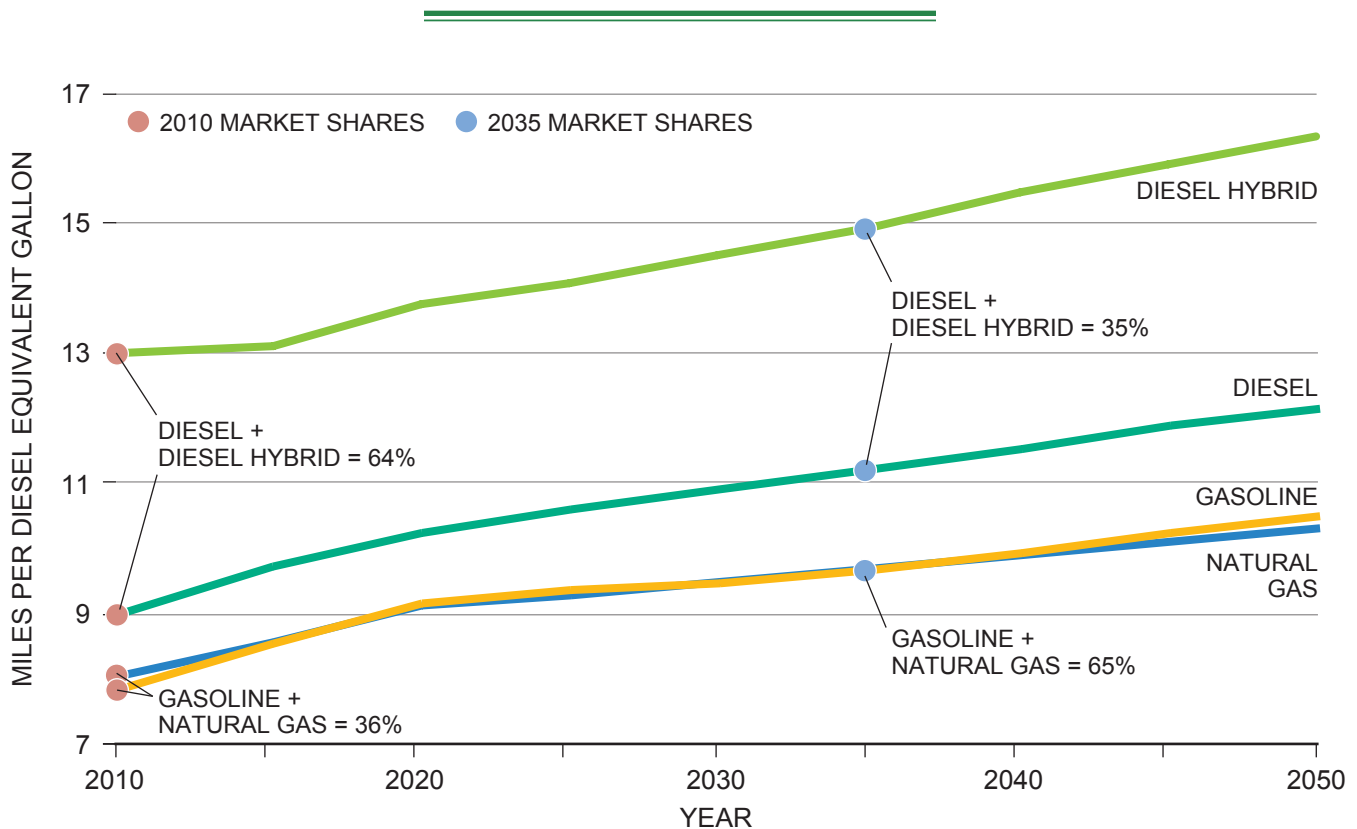


Figure 3-33. New Class 3-6 Truck Fuel Economy Over Time Using Reference Case Oil Price

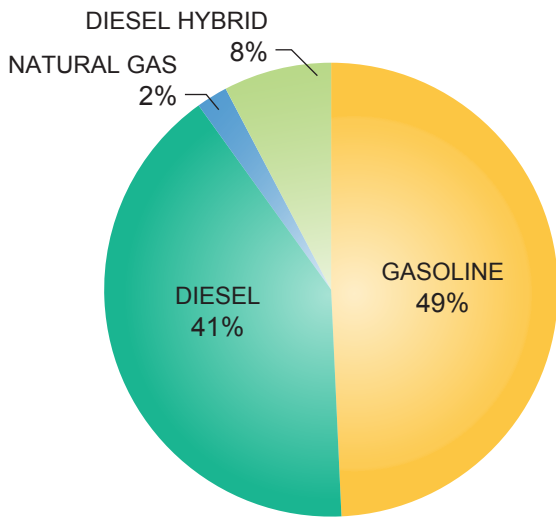


Figure 3-34. Fleet Composition Class 3-6 Vehicles in 2050 – Low Oil Price Case

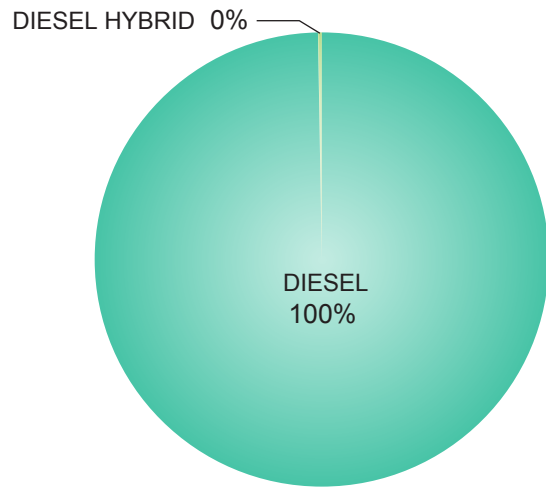


Figure 3-37. Fleet Composition Class 7&8 Vehicles in 2050 – Low Oil Price Case

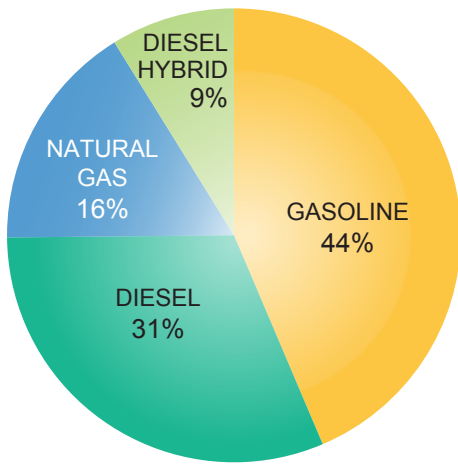


Figure 3-35. Fleet Composition Class 3-6 Vehicles in 2050 – Reference Case

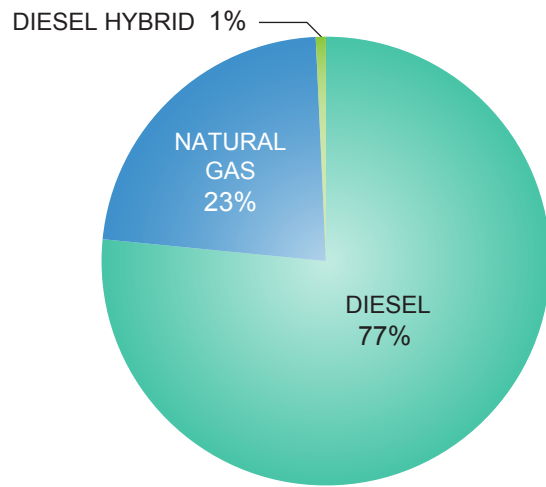


Figure 3-38. Fleet Composition Class 7&8 Vehicles in 2050 – Reference Case

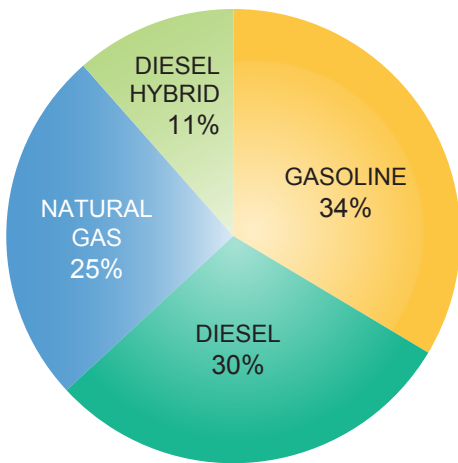


Figure 3-36. Fleet Composition Class 3-6 Vehicles in 2050 – High Oil Price Case

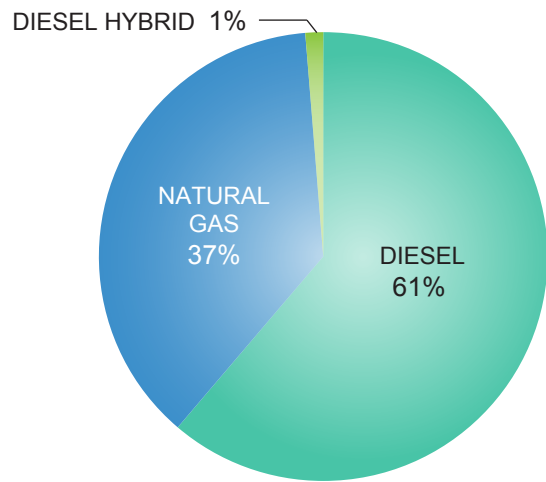


Figure 3-39. Fleet Composition Class 7&8 Vehicles in 2050 – High Oil Price Case

natural gas prices, and if that spread persists over time.

Hybrid trucks have the potential to gain a market share of between 10 and 15% in the MD market. Such trucks have an advantage in many applications but are still limited by the projected costs of the hybrid system even in the long term. In heavy truck markets, hybrid trucks are projected to play a smaller role. This is due to a combination of cost and complexity issues and a relatively less suitable duty cycle for the Class 7&8 market.

Fleet-Wide Energy Consumption

Fleet-wide energy consumption is shown in Figure 3-40 for 2010, 2035, and 2050. Note the bars in the figure present the range of modeling outcomes. Fleet-wide energy consumption grows between 2010 and 2035, and then again from 2035 to 2050.

As national truck VMT more than doubles from 2010 to 2050, truck fleet energy consumption grows by only approximately 50%. Growth in energy use is curtailed by substantial improvements in the

fuel economy of vehicles. The industry is growing much more efficient, but those efficiencies are overwhelmed by the projected rise in trucking demand and associated vehicle mileage.

Fuel expenditures increase in response to higher VMT demand and higher future fuel price assumptions, as shown in Figures 3-41, 3-42, and 3-43. In 2005, total fuel expenditures in the MD/HD fleet amounted to approximately \$88 billion, increasing to approximately \$270 billion, annually, by 2050 in the Reference Case. This study has identified technology options that could economically improve fuel economy and reduce fuel expenditures beyond the assumptions of the AEO2010, resulting in savings of between \$60 billion and \$100 billion per year.

Fleet-Wide Fuel Use Profiles

As noted in the market share discussion, diesel fuel remains the primary fuel for the trucking industry in the study time frame. However, in the Reference and High Oil Price Cases, most of the growth in fuel use between 2010 and 2050

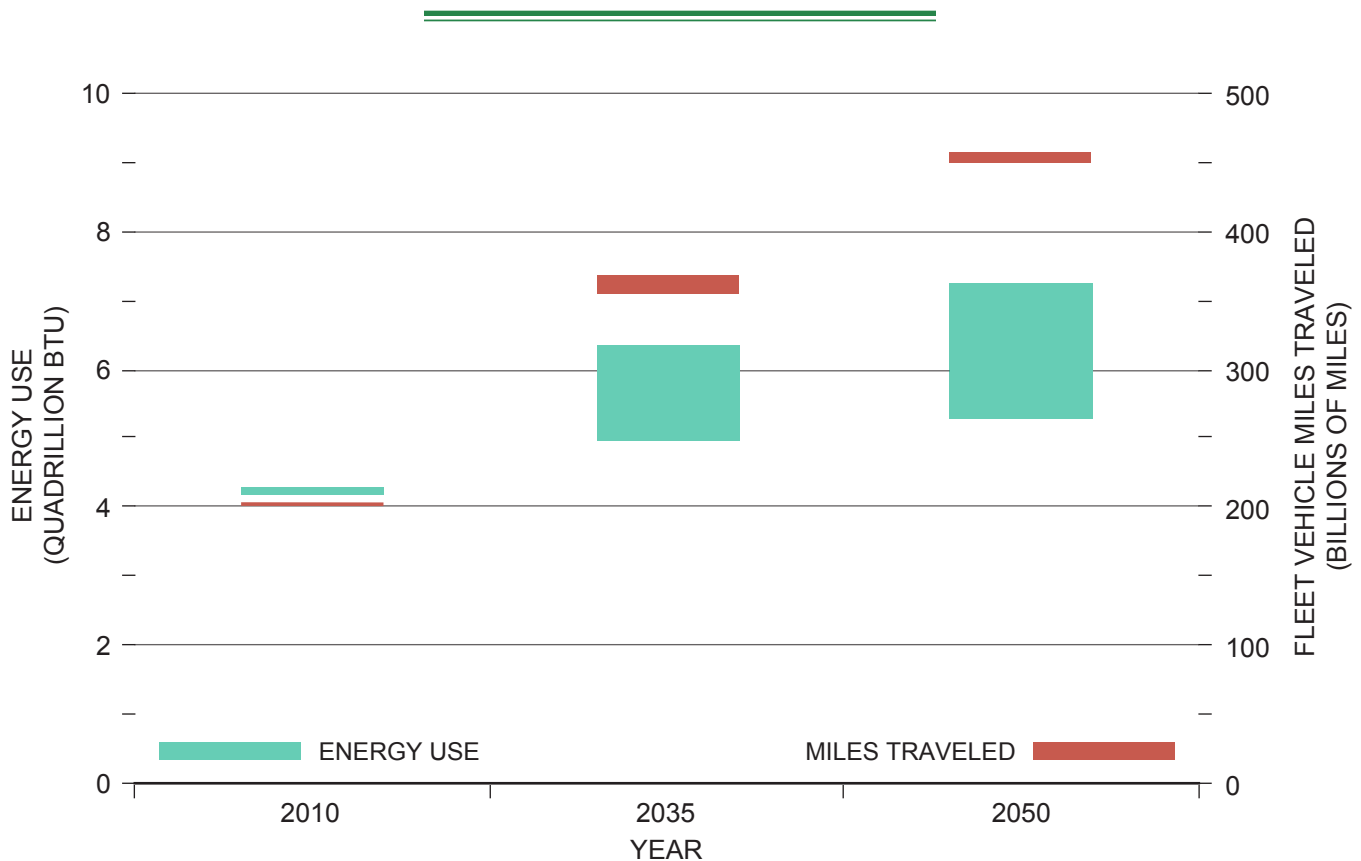


Figure 3-40. Heavy-Duty Energy Use and Vehicle Miles Traveled over Time

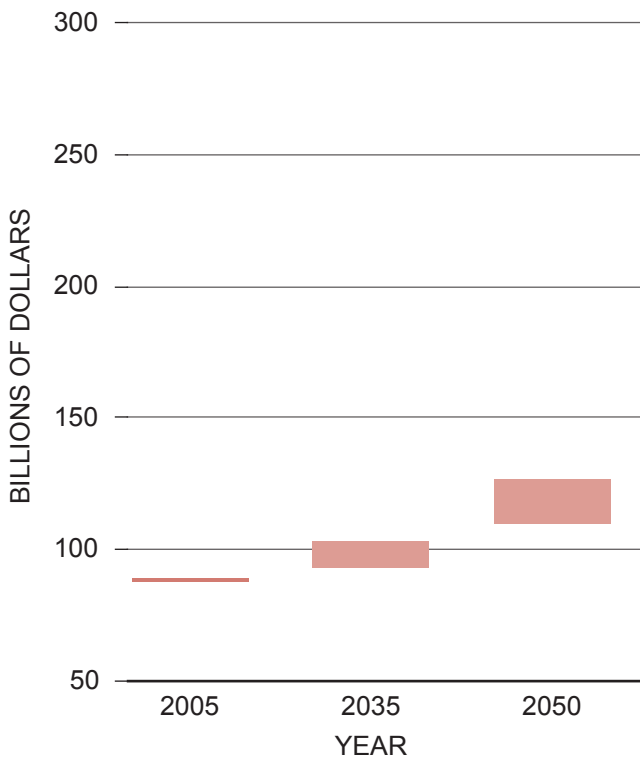


Figure 3-41. Annual Fuel Expenditures in Medium- and Heavy-Duty Trucks – Low Oil Price Case

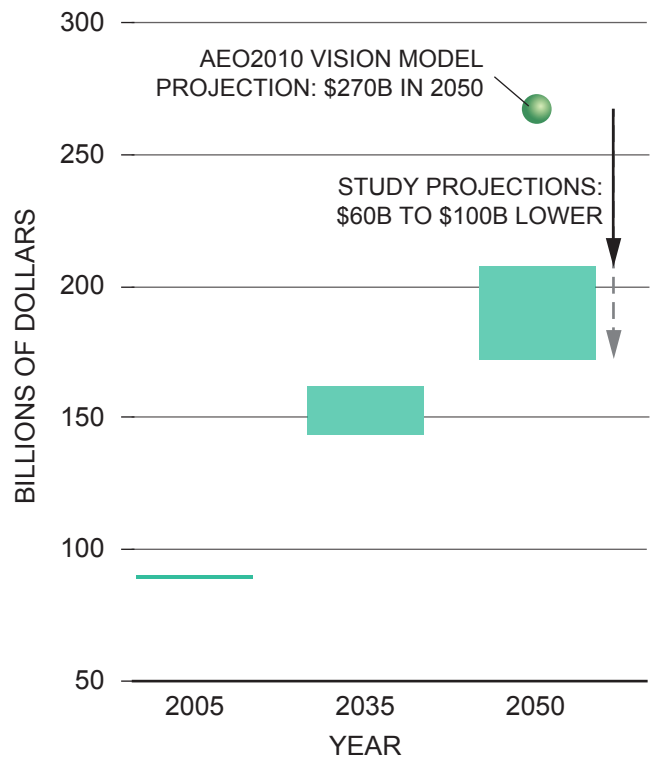


Figure 3-42. Annual Fuel Expenditures in Medium- and Heavy-Duty Trucks – Reference Case

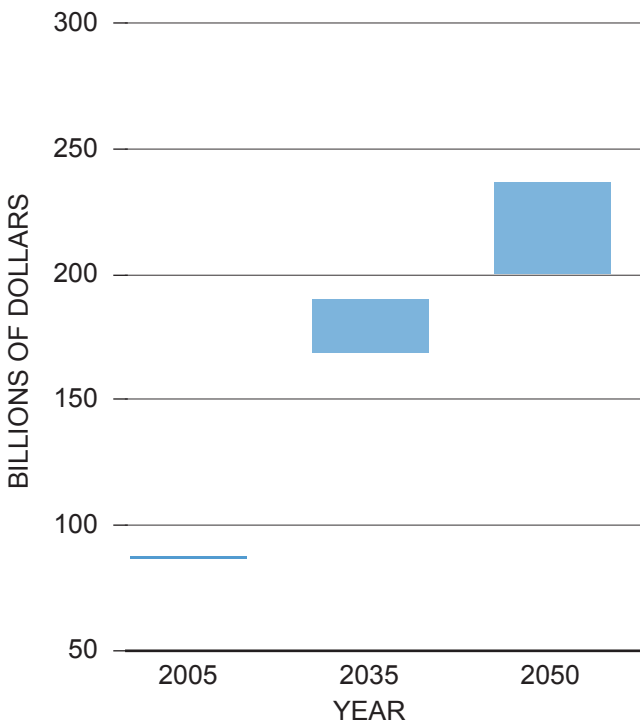


Figure 3-43. Annual Fuel Expenditures in Medium- and Heavy-Duty Trucks – High Oil Price Case

is accounted for by natural gas. Figure 3-44 shows the growth in fleet fuel consumption of the scenario-average broken down by fuel type. Higher oil prices produce a higher share of natural gas usage while natural gas use remains very low in the Low Oil Price Case.

Fuel use varies widely from one scenario to another for each type of fuel, depending on fuel price assumptions and cost-of-vehicle technology. In both the Reference and High Oil Price Cases, the model suggests a reduction in diesel fuel use. In these scenarios, the use of non-diesel alternatives may grow substantially. Conversely, in the Low Oil Price Case, diesel use may increase over time and retain its dominant role in truck transportation.

Biofuels are a relatively small component of fleet fuel use due to the assumed small supply of bio-derived diesel. If all the biofuel derived from fatty acid methyl esters was used in the HD truck industry's fuel stream, biodiesel content would be less than 10%. Note that no diesel produced by a low carbon biomass-to-liquid pathway was included in the modeling.

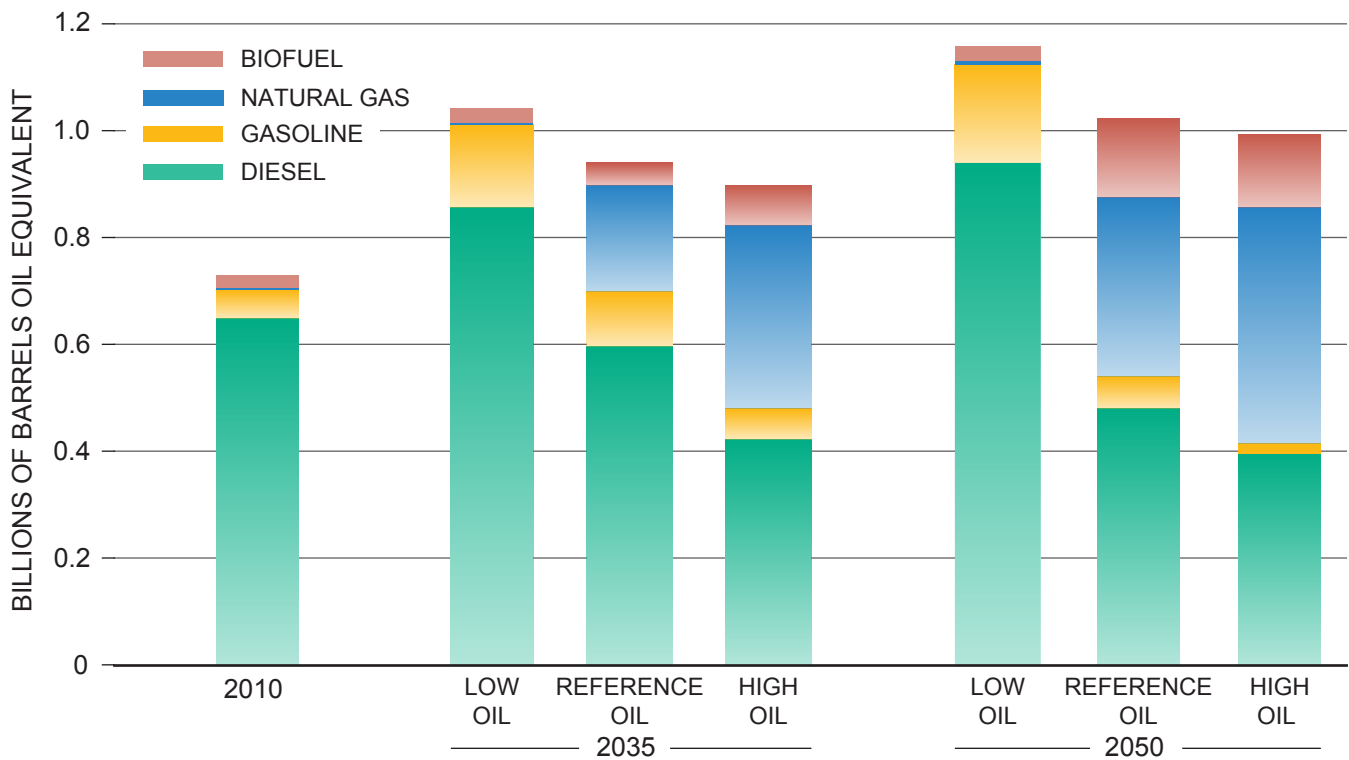


Figure 3-44. Heavy-Duty Truck Energy Use by Fuel Type

The modeling results show a far greater role on a percentage basis for ethanol with a larger assumed supply than bio-derived diesel. In some modeled scenarios, the heavy-truck consumption of ethanol in 2050 exceeds gasoline use in that same year. Note, however, that the model assumes fully flexible-fuel-capable engines, which can tolerate a variable mixture of ethanol and gasoline. Gasoline trucks are only a portion of the Class 3-6 segment, which itself is a small segment of the overall market. When viewed as a percentage of overall truck fleet fuel usage, the impact of ethanol and biodiesel is relatively small, as shown in Figure 3-45.

Transition Challenges and Strategies for Natural Gas Infrastructure

The natural gas fueling infrastructure is currently limited and would need to be expanded to support an increase in the market penetration of natural gas trucks. Expanding the infrastructure represents one of the largest obstacles to natural gas entering the HD truck market.

The analysis done in this study does not reflect transition hurdles to expanding the fueling infrastructure, such as economics, utilization, and fuel availability. One of the critical assumptions in the modeling was to eliminate concerns associated with refueling infrastructure. To illustrate this point, the model assumes that 30% of the incumbent, 10,000 heavy-truck refueling stations, would need to be fitted with natural gas capability. Over an economic life of 20 years, the stations were credited with 80% utilization from day one. However, if the 3,000 stations were built in the near term, utilization rates of much lower than 80% are calculated. Figure 3-46 illustrates the fuel demand for natural gas as market shares expand, along with station utilization based on these assumptions. It shows that if a refueling infrastructure of the size assumed was required and in place in the very near term, then infrastructure utilization levels would be very low for some time.

In summary, infrastructure transition is a major hurdle to natural gas market penetration. However, the characteristics of the trucking industry

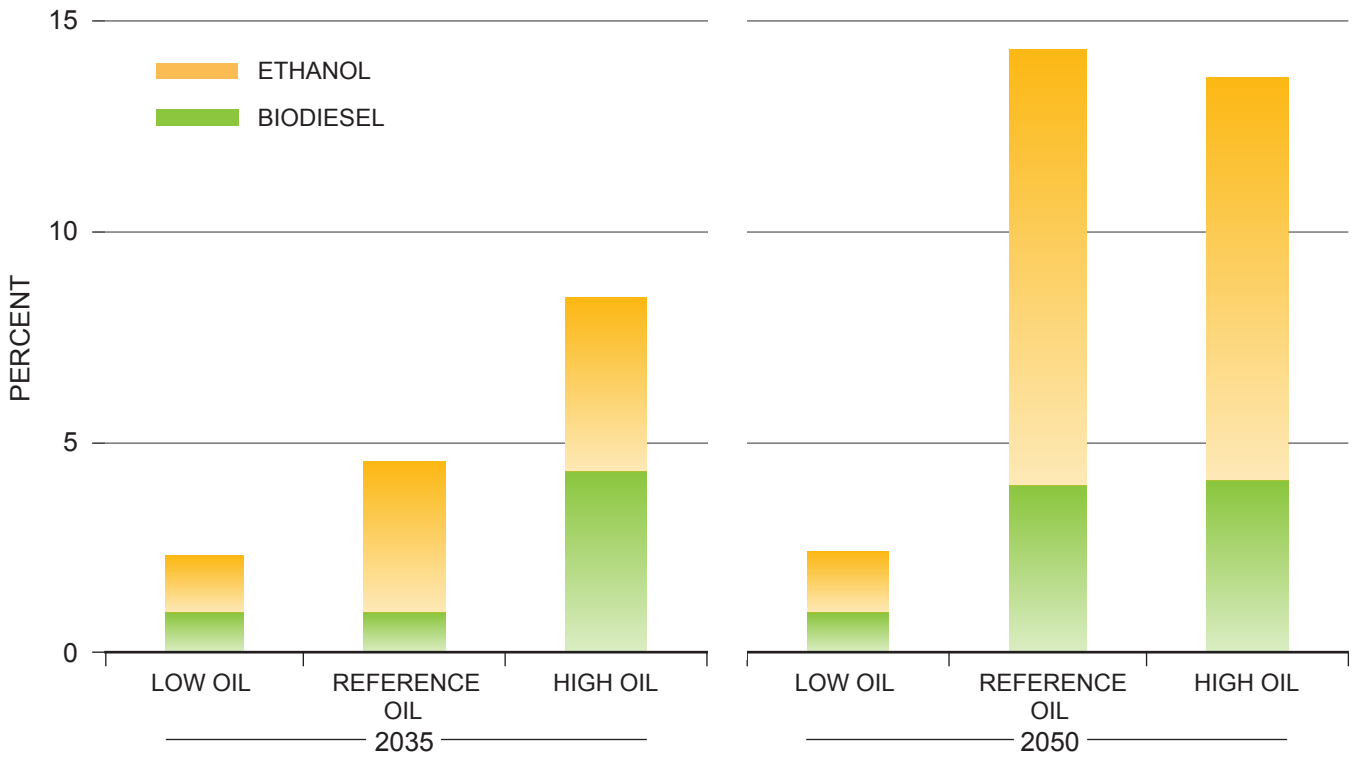


Figure 3-45. Biofuel Use as a Percentage of Overall Truck Industry Energy Use in 2035 and 2050

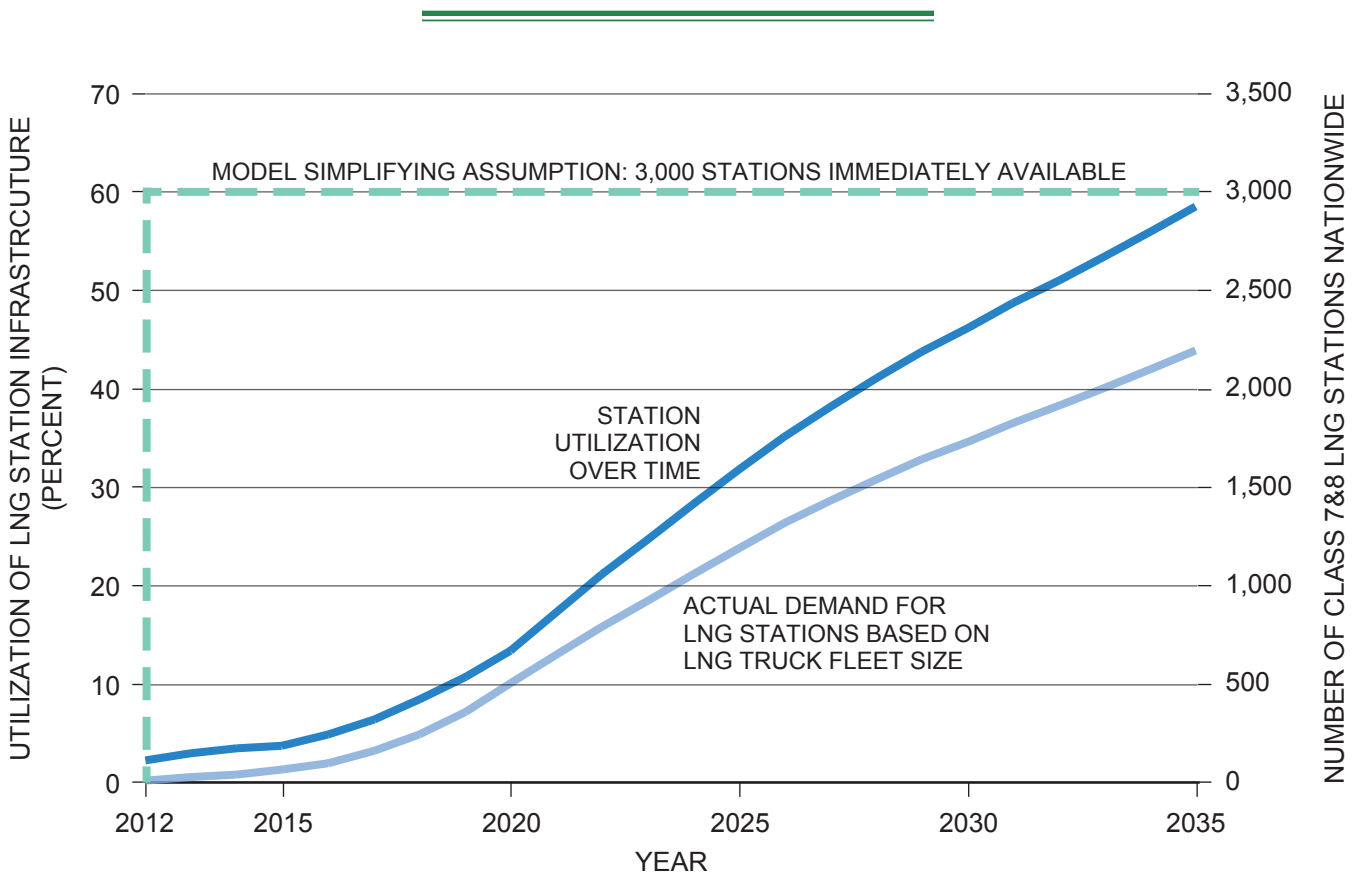


Figure 3-46. Natural Gas Station Utilization Based on Modeling Assumptions

allow for several incremental strategies for infrastructure transition; for example, using tethered return-to-base fleets, municipal fleets, etc. These strategies are considered in more detail in Chapter Five, “Infrastructure.”

FINDINGS

These findings provide a sound foundation for discussion of the potential for technology advancement in the medium- and heavy-duty truck industry. It should be noted that there is uncertainty in projecting future technology advancements. Additionally, transition costs and issues were not fully modeled.

1. There are opportunities for significant fuel economy improvements in diesel-powered trucks.

Public literature identifies approximately 20 technologies that, when bundled, can provide significant improvements in the fuel economy of heavy-duty trucks. Quantitative modeling indicates that up to 100% improvement in fuel economy for diesel powered trucks could be achieved under high oil price conditions. These improvements in fuel economy can be achieved through both engine and vehicle systems technologies.

In Class 7&8 trucks under low oil price conditions, fuel economy improved by almost 74% from 2010 until 2050. Under high oil price conditions, Class 7&8 truck markets were shown to favor more fuel economy technologies, and fuel economy for that segment increased up to 100%.

2. Diesel remains the dominant fuel used for trucking.

Diesel internal combustion engine powertrains provide high-torque, high-efficiency operation that is well matched to the demands of many truck applications. The extensive existing infrastructure, including a fueling infrastructure and a support and service infrastructure, creates a strong competitive advantage for diesels compared to alternate fuel technologies.

In Class 7&8, the combination of diesel fuel economy improvements and the high near-term cost of natural gas alternative powertrains suggests that under low oil price conditions there is little economic incentive for fleets to transition to alternative fuels. In Class 3-6, diesel share is challenged by gasoline spark ignition engines due to the lower cost of aftertreatment and fuel injection systems in gasoline engines, but diesel share remains substantial.

3. In Class 3-6 medium-duty trucks, advanced gasoline engines are strong competitors to diesel engines due to increased costs of recently mandated diesel emission controls.

Because gasoline trucks are less expensive than diesel trucks, gasoline trucks are generally more popular in low-mileage applications. Low-mileage vehicles have relatively low impact on overall fleet parameters such as GHG emissions and national fuel usage.

In many Class 3-6 applications, annual vehicle mileage is relatively low, which de-emphasizes fuel use in any overall cost-of-driving calculation. It also places greater emphasis on initial purchase price. In addition, diesel engine regulations now require emissions controls that increase the overall diesel vehicle cost by several thousand dollars per truck. The result of these effects has been a continuing trend toward gasoline engines. By 2050, it is possible for gasoline to comprise a greater share than diesel, independent of oil-price scenario. The market share of Class 3-6 trucks in 2050 is shown in Figure 3-47.

4. There is potential for natural gas trucks to gain significant market shares if a price spread between diesel and natural gas persists over time.

High initial price premiums for natural gas trucks must be overcome through fuel cost savings. Fuel cost savings for high-mileage vehicles that offset vehicle price premiums result in an economic motivation to switch from diesel to natural gas power when natural gas prices are lower than

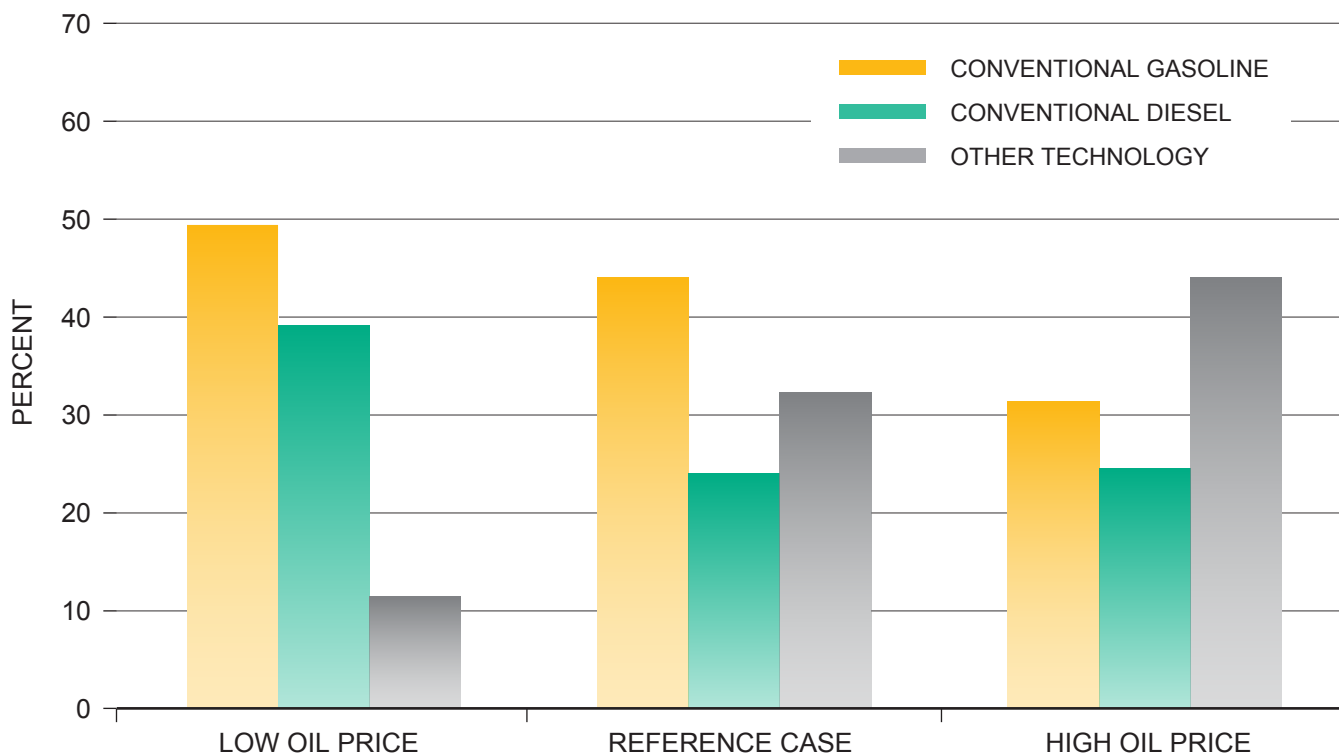


Figure 3-47. Market Share in 2050 for Powertrain Architectures in Class 3-6 Market Segment

diesel. See Figure 3-48 for the natural gas market share of new trucks in 2050.

Gasoline and diesel have much wider projected price variation, based on AEO2010 from High to Low Oil Price Cases, than natural gas. Modeled fuel costs are shown in Figure 3-49.

Natural gas fueling infrastructure availability may be the primary constraint on overall market potential. Initial market growth has been spurred by transit and refuse fleets. Regional hauling and other return-to-base fleets can be motivated to install or utilize infrastructure with higher sustained price spreads. As public-access infrastructure is expanded, the market would open for longer haul operation. Dual-fuel natural gas trucks would be advantageous in the transitional phase due to their ability to take advantage of available natural gas refueling infrastructure but continue operation on diesel for overall longer range. As fuel economy increases and infrastructure build-out expands, dedicated natural gas engines could also make the bridge from regional haul into long haul.

Additionally, streamlined and higher volume production of natural gas truck systems such as engines and fuel storage tanks can result in considerable reductions in the incremental price of such systems.

5. Market share of hybrid electric vehicles in medium- and heavy-duty truck markets may increase in specific market applications. However, faced with technology and cost barriers, projected market share is low.

The high cost of hybrids, and specifically the cost of batteries for long-life, high-power applications, is the major barrier to hybrid adoption in the commercial truck industry. Hybrids excel in low-duty cycle, stop-start applications, and also in niches where auxiliary electric power is required. In such applications, hybrids may have a key competitive advantage.

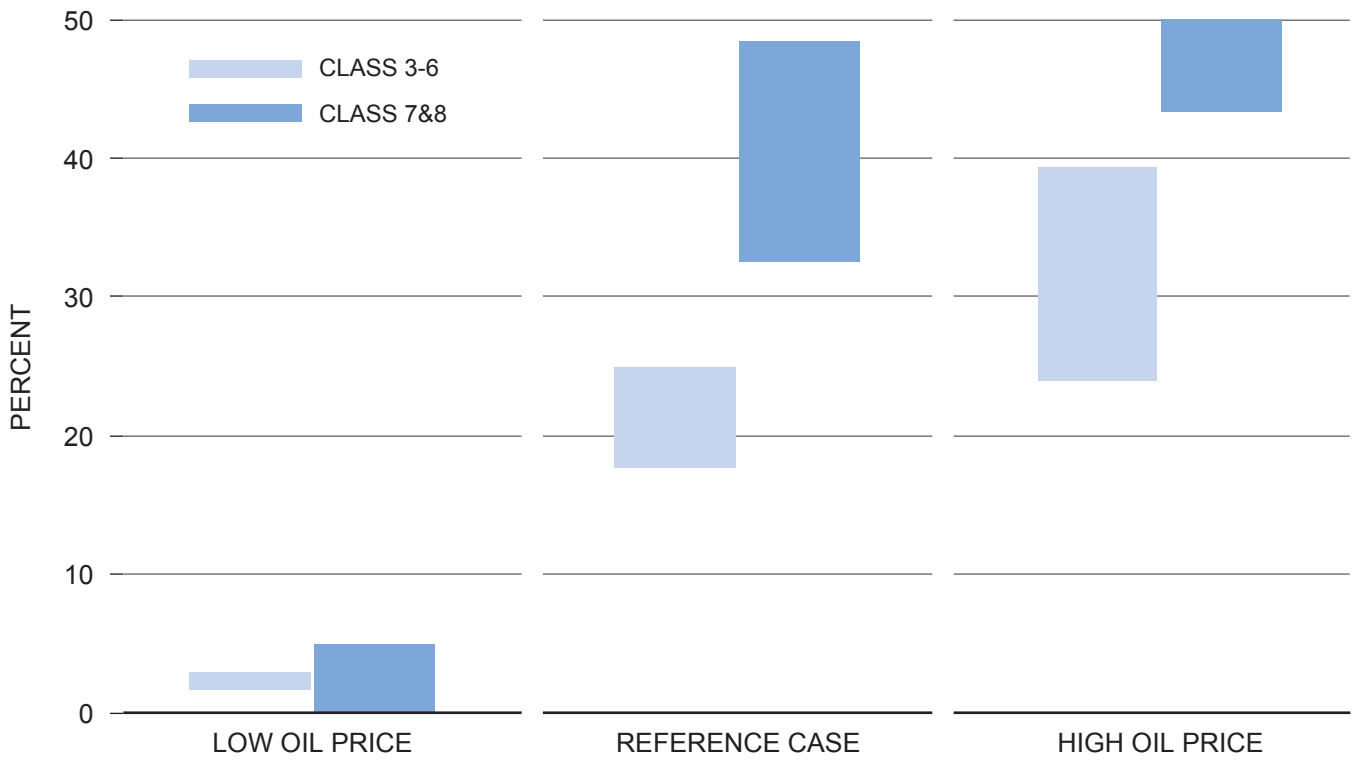


Figure 3-48. Natural Gas Market Share of New Trucks in 2050

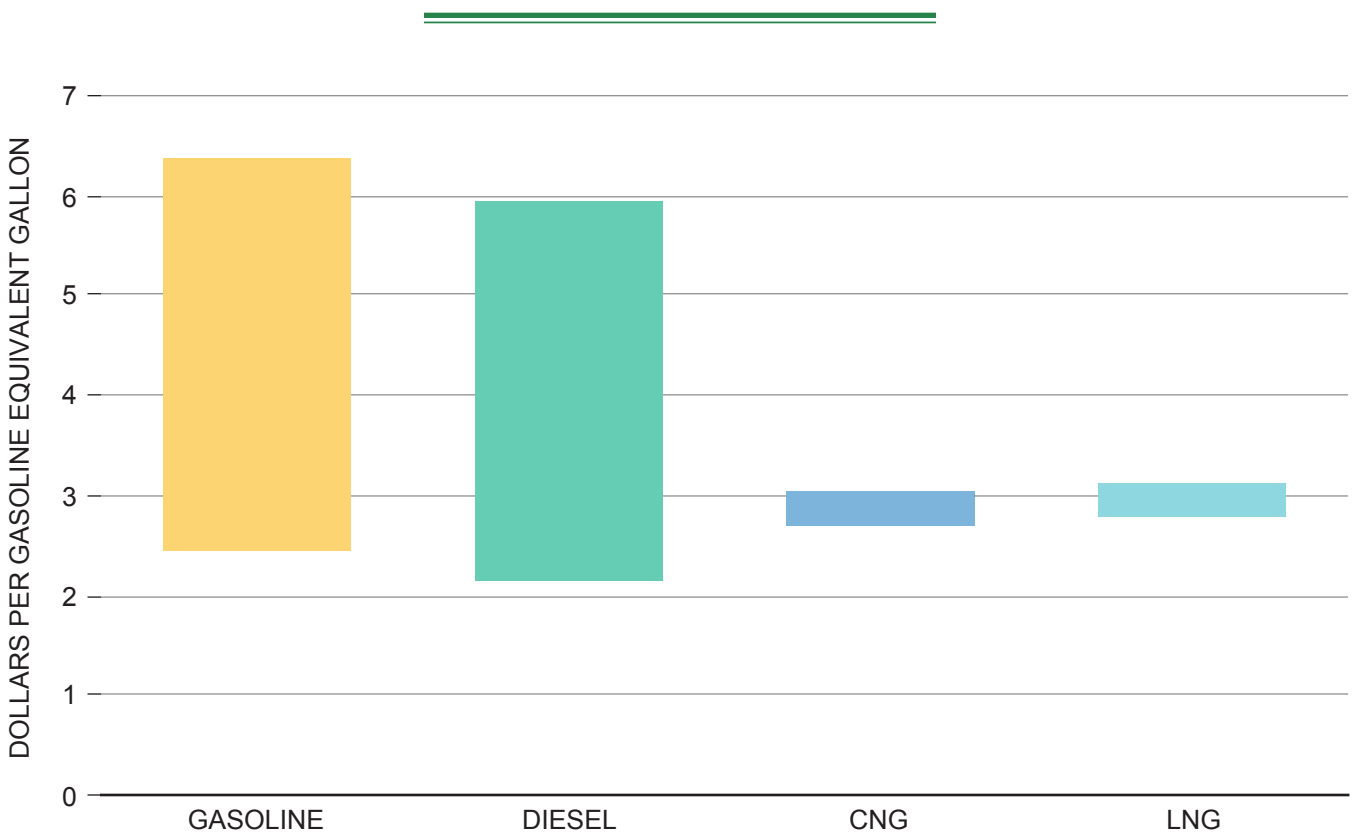


Figure 3-49. Range of Fuel Prices in 2050 Based on AEO2010, Adjusted for Infrastructure Costs

6. Biofuels are projected to play a limited role in overall truck energy use.

Medium- and heavy-duty engines can use ethanol and diesel-biofuels in gasoline and diesel engines. As gasoline engines gain share in Class 3-6, they

will be able to use ethanol and advanced cellulosic biofuels (refer to Chapter Twelve, “Biofuels,” for a comprehensive discussion). In the heavy-duty vehicle sector, traditional fatty acid methyl esters and renewable diesel will have little impact due to projected supply, cost, and availability as outlined in Chapter Twelve. In 2050, biofuels are projected to contribute less than 15% of total truck energy use.

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APPENDIX 3A: MODELING METHODS AND ASSUMPTIONS

Three tools are used in the heavy-duty vehicle modeling framework, as noted in Figure 3A-1. Each is described in brief below.

VEHICLE ATTRIBUTE CALCULATION

The attribute calculator determines the new-vehicle price and new-vehicle fuel economy over time, based on cost-of-fuel-economy as published in multiple sources, and using a simple economic optimization model. The economic optimization considers the design-point from a truck-buyers' perspective, optimizing the total cost of the vehicle, plus the cost of fuel, over a typical industry payback period currently set at three years. This optimized design-point sets the vehicle price and vehicle fuel economy level, for a given year and a given segment of trucks.

A critical input to the attribute calculation is the "cost of fuel economy" curve, which is built by combining the inputs of multiple sources. These curves

are shown in Figures 3A-2 through 3A-4. To build these curves, data from credible published sources are plotted on the same chart, building cumulatively from the "low-cost-per-mpg" technologies (e.g., those where the relative gain in miles per gallon is high compared to the investment cost to implement) to the relatively "high-cost-per-mpg" technologies. When these data are plotted from multiple sources, a pattern emerges as expected: higher fuel economy imposes higher vehicle costs. This trend is borne out in Figures 3A-2, 3A-3, and 3A-4. The curves shown on the figures are visual estimates of the high and low ranges of the data, which are used as bounding curves to represent high and low cost-of-fuel-economy in subsequent model runs. The equation for the curves, as well as other assumptions within the design-point model, are summarized in Table 3A-1.

Note that in some cases, the effect of a technology on price and fuel economy cannot be

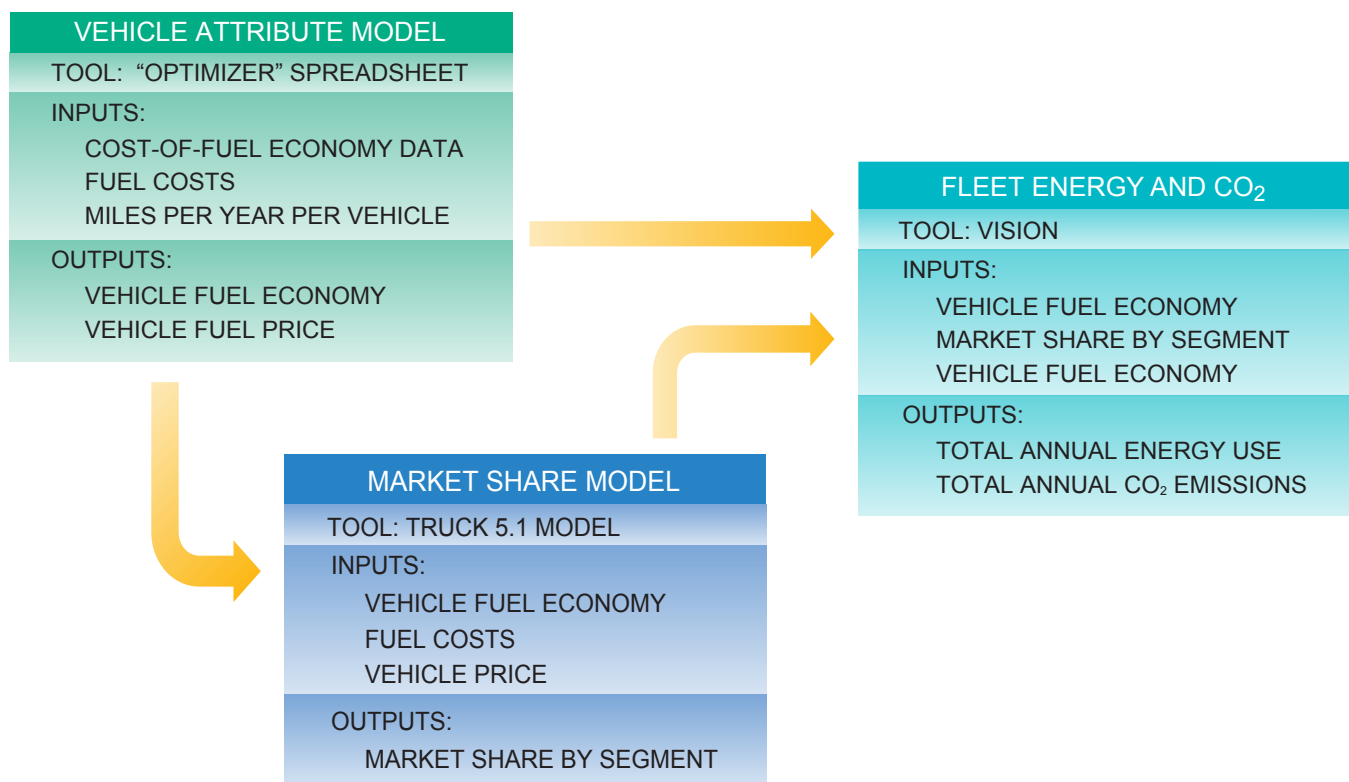


Figure 3A-1. Heavy-Duty Vehicle Modeling Framework

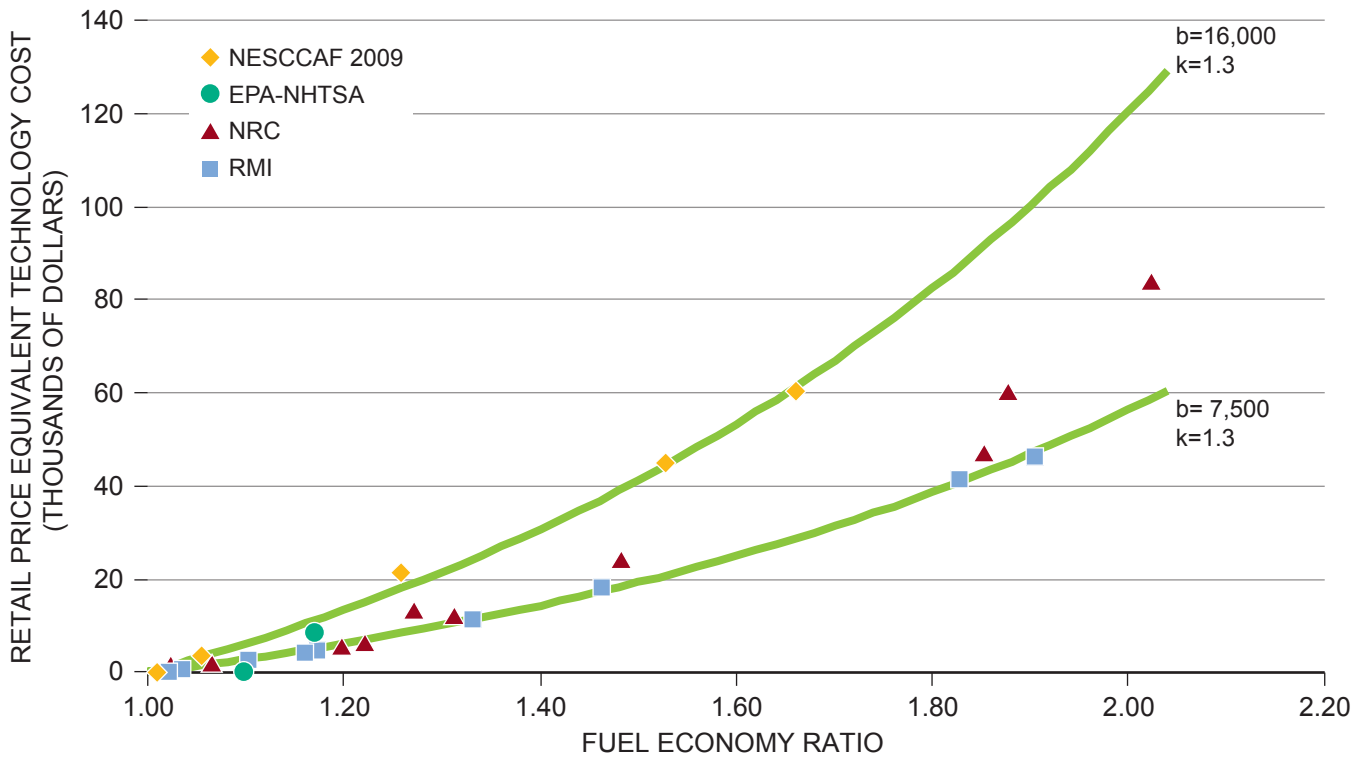


Figure 3A-2. Cost of Fuel Economy for Class 7&8 Combination Trucks

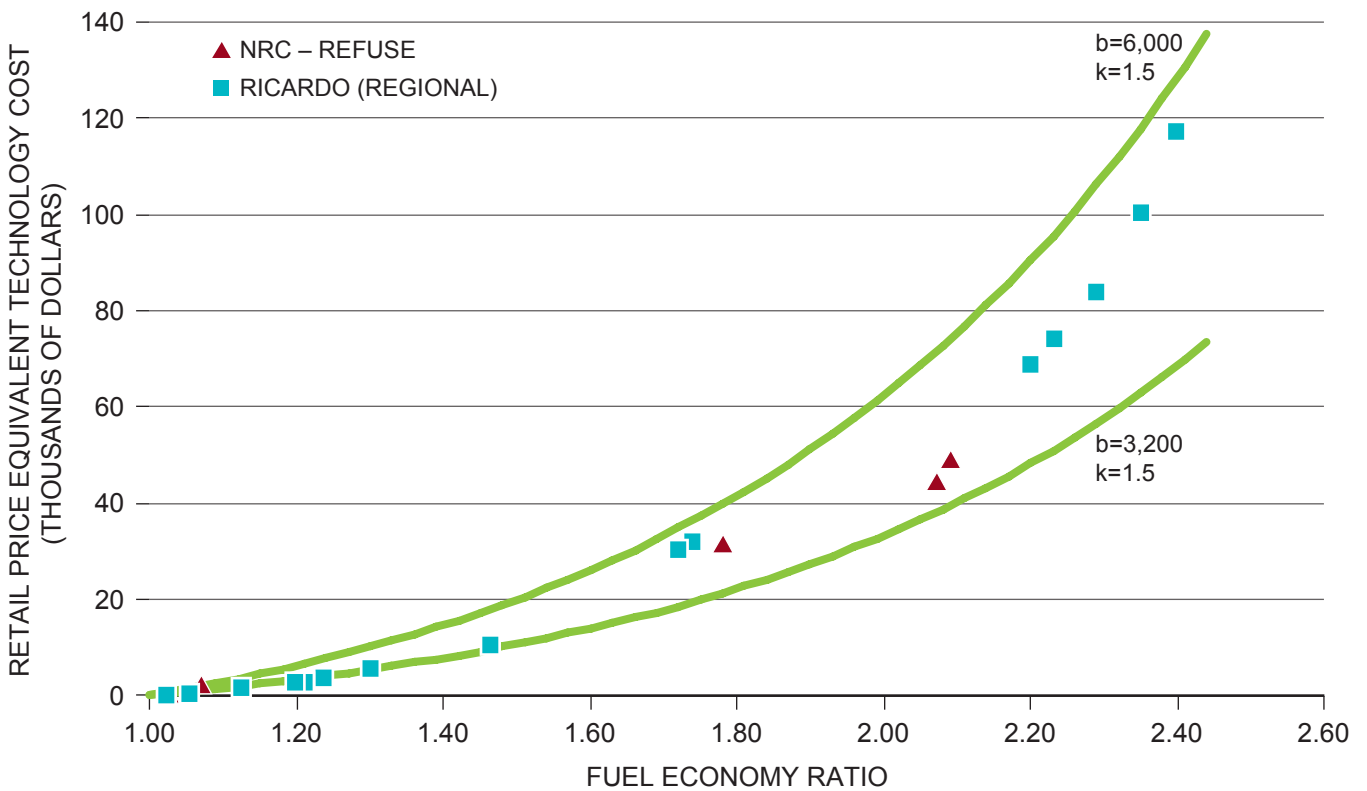


Figure 3A-3. Cost of Fuel Economy for Class 7&8 Single-Unit Trucks

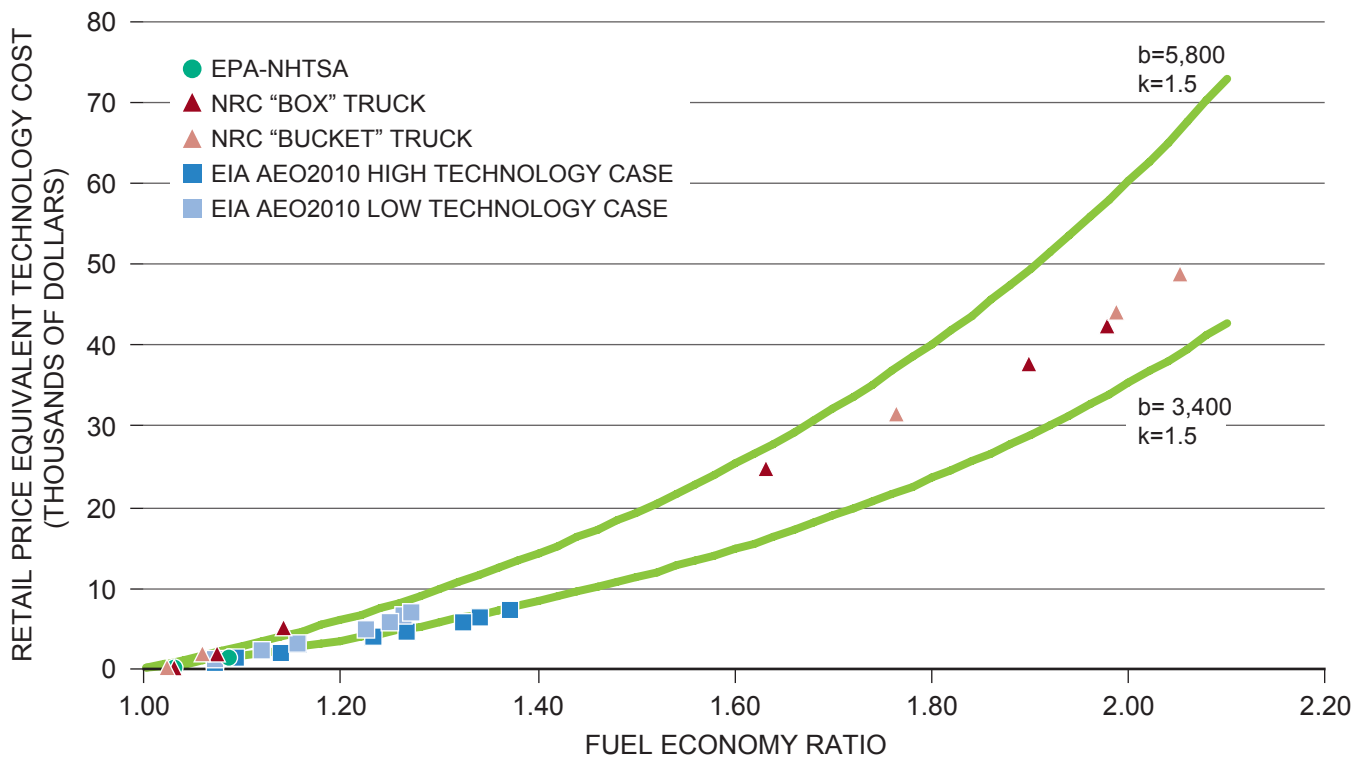


Figure 3A-4. Cost of Fuel Economy for Class 3-6 Trucks

“summed” cumulatively, due to technology overlaps. This is accounted for, whenever possible, by careful review and consideration in the literature. Fortunately many sources already consider such effects. For example, the National Research Council report listed in the bibliography provides summaries of individual engine technology impacts, and then an integrated total of those effects which is not identical to the sum of the parts. This is important, particularly in engine technologies, and also where a high degree of integration is required.

In several cases, the model predicted rapid shifts in the buying behavior of truck purchasers. This contradicts the industry reputation as conservative and adverse to rapid change. This reputation stems in part from a need for reliability, which can only be verified through years of on-road testing for new technologies. It is also related to the capital constraints of the industry, which limit the pace of adoption, particularly for high-investment/high-mpg technologies. To account for these realities, the attribute model was held to limits of change per

year, based on the outer limit of expectations from past data. Specifically:

- The rate of increase in fuel economy was limited to be no more than the highest rate seen in the last 30 years in any vehicle class, as calculated from fuel economy data contained in VISION. The resultant maximum rate of fuel economy increase was 2.35% per year.
- The rate of increase in truck prices was limited to no more than the average rate of inflation over the last 30 years, as calculated from the consumer price index. The resultant maximum rate of vehicle price increase was 2.60% per year. Note that, as all calculations are performed in real 2008 dollars, this implies nominal vehicle price growth of twice the historical rate of inflation.

MARKET SHARE CALCULATION

The TRUCK 5.1 model calculates the new-vehicle market share, based on a series of economic trade-offs as seen from the perspective of the new-truck-buying population. This population is

Parameter	Assumption	Source / Note
Timeframe for economic analysis from a truck-buyers perspective (design-point calculator): Mileage assumption for economic analysis:	3 years	Agreed by NPC heavy-duty vehicle working team and verified through results of the U.S. Census Bureau's 2002 Vehicle Inventory and Use Survey (VIUS 2002)
<i>Class 8 combination trucks</i>	122,500 miles per year	VIUS 2002
<i>Class 7&8 single-unit trucks</i>	28,098 miles	VIUS 2002
<i>Class 3-6 gasoline-powered trucks</i>	17,853 miles per year	VIUS 2002
<i>Class 3-6 diesel-powered trucks</i>	24,070 miles per year	VIUS 2002
Annual Ceiling on Fuel Economy Progress	2.35%	Historical average maximum, taken from the best 10 years on record in any vehicle class over the past 3 decades, as taken from AEO and VISION
Annual Floor on Fuel Economy Improvement	0%	Assumption: fuel economy never decreases over time
Annual Ceiling on Vehicle Price Increase	2.60%	Assumption based on historical maximum increase in general inflation; value is double the average consumer-price index between 1975 and 2005
Annual Floor on Vehicle Price Change	none	
Cost of Fuel Economy Technology	$(\text{cost}) = (b/k) [\exp(k/\text{mpgratio}) - \exp(k)]$	Where (cost) is the incremental cost of the technology; b and k are variables chosen by the modeler to match referenced data, mpg ratio is the vehicle fuel economy normalized by the initial fuel economy without improvements
<i>for Class 7&8 combination trucks, low range</i>	b=7,500, k=1.3	Based on published data from the Northeast States Center for a Clean Air Future (NESCCAF), the Environmental Protection Agency (EPA), the National Highway Traffic Safety Administration (NHTSA), the National Research Council of the National Academies (NRC), and the Rocky Mountain Institute (RMI)
<i>for Class 7&8 combination trucks, high range</i>	b=16,000, k=1.3	See above
<i>for Class 7&8 single-unit trucks, low range</i>	b=3,200, k=1.5	Based on published data from the National Research Council and Ricardo
<i>for Class 7&8 single-unit trucks, high range</i>	b=6,000, k=1.5	See above
<i>for Class 3-6 trucks, low range</i>	b=3,400, k=1.5	Based on published data from the EPA, NHTSA, National Research Council, and DOE-EIA
<i>for Class 3-6 trucks, high range</i>	b=5,800, k=1.5	See above

Table 3A-1. Model Assumptions

Parameter	Assumption	Source / Note
Medium-Duty Hybrid Trucks <i>retail price increase vs. conventional</i>	\$16,196	Average of values published by National Research Council and DOE-EIA (2008 dollars)
<i>fuel economy gain vs. conventional</i>	45%	Average of values published by National Research Council and DOE-EIA
Class 7&8 Single-Unit Hybrid Trucks <i>retail price increase vs. conventional</i>	\$26,895	Average of values published by National Research Council and Ricardo (2008 dollars)
<i>fuel economy gain vs. conventional</i>	22%	Average of values published by National Research Council and Ricardo (2008 dollars)
Natural Gas Truck Powertrains: Class 7&8	50-50 split spark ignition and compression ignition	Industry estimates
Natural Gas Truck Powertrains: Class 3-6	100% spark ignition	Industry estimates
Timeframe for economic analysis from a truck-buyers perspective (market-share modeling)	Distribution of allowable payback timeframes varying from 12 months to 4 years	Distribution taken from VIUS 2002
Mileage assumption for economic analysis (market-share modeling)	Taken based on transportation mileage survey results	Distribution taken from VIUS 2002
Preference Factor: <i>for Class 7&8 combination natural gas trucks</i>	0.25	Implies a long-term market share maximum of 50%
<i>for Class 7&8 single-unit natural gas trucks</i>	0.25	Implies a long-term market share maximum of 50%
<i>for Class 7&8 hybrid trucks</i>	0.25	Implies a long-term market share maximum of 50%
<i>for Class 7&8 diesel trucks</i>	Ramp from 1.0 (2007) to 0.5 via 16-year sigmoid curve	Implies near-term benefit for diesel; matches near-term data
Fuel Prices	Low, medium, and high fuel price assumptions as documented in the heavy-duty appendix and infrastructure chapter	Based on AEO2010 fuel price scenarios with NPC calculation updates as documented in Chapter Five, "Infrastructure"
Discount Rate	5%	
Long-term cost reduction rate: all technologies	3% per year from 2015–2020; 2% per year from 2020–2025; 1% per year beyond 2025	Based on EPA estimates
Short-term cost reduction rate for hybrid technologies	9% per year from 2015–2020; 3% per year; 3% per year from 2020–2025, 2% per year from 2025–2030, 1% per year beyond 2030	Based on light-duty battery price projections from multiple sources

Table 3A-1. Model Assumptions (continued)

defined by a distribution of new-vehicle miles taken from the U.S. Census Bureau's 2002 Vehicle Inventory and Use Survey (VIUS), and a distribution of allowable payback for new-technology adoption taken from 1997 American Trucking Association (ATA) survey data. The TRUCK 5.1 model calculates the market shares of individual technologies within a given miles-per-year cohort or "bin." The calculation is repeated for the "zero to 5,000 mile" bin, the "5,000 to 10,000 mile" bin, the "10,000 to 15,000 mile" bin, etc., up to a maximum of 200,000 miles per year. The results are summed to obtain overall market shares. The mileage distribution is shown in Figure 3A-5 (an economic comparison is made between technologies within each mileage bin).

A second key concept of the market share modeling is a distribution of buyers' opinion regarding the acceptable payback time associated with fuel economy investment. These data were developed in a study by the ATA (1997 Investment Survey), where participants were asked what payback time frame was acceptable to them. That is, how quickly must a technology investment pay for itself before

it would be considered for purchase? The results varied between one and four years, as shown in Figure 3A-6. Conceptually, the TRUCK 5.1 model overlays the distributions of Figure 3A-5 and Figure 3A-6, calculating the degree of investment in fuel-saving technology for a multitude of mileage and payback expectations, and integrating those many results into overall market shares.

NATIONAL FLEET ENERGY USE AND CO₂

The national vehicle "fleet" of trucks in use, including its shifting and growing composition over time, is modeled using the VISION tool from the U.S. Department of Energy. The model takes, as inputs, the outputs from the other two model components: vehicle price, fuel economy, and technology market shares. With VISION as the target calculator, several assumptions were necessary within the overall modeling framework, including the following:

- The overall market is divided into three segments, to align to the appropriate VISION

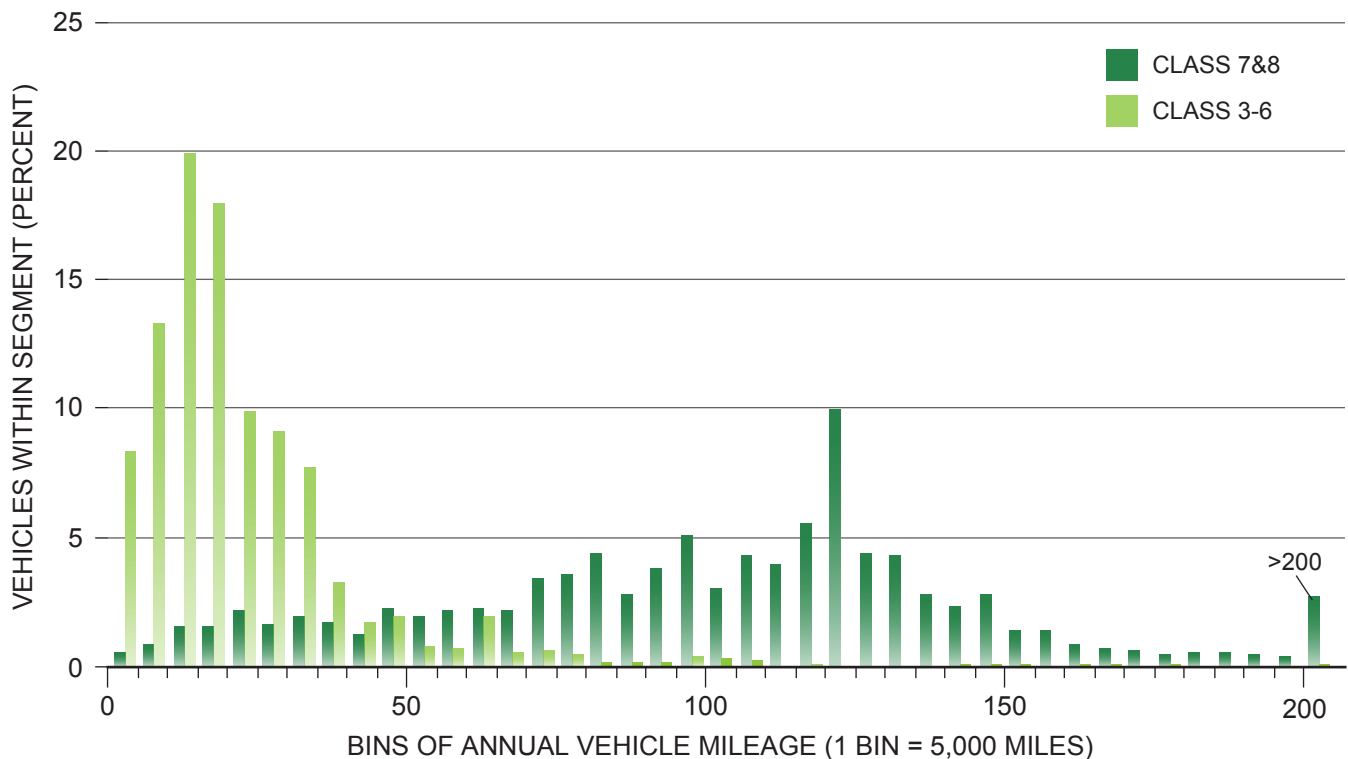
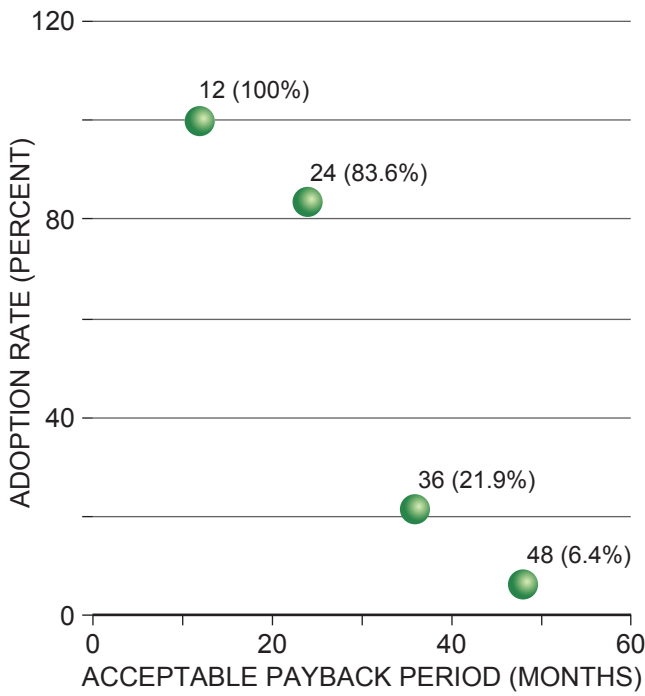


Figure 3A-5. Example of Mileage Distribution as Used in the TRUCK 5.1 Market Share Modeling Framework



Source: 1997 American Truck Association Survey.

Figure 3A-6. Truck Buyers' Acceptable Payback Timeframe for Investments in New-Truck Fuel Economy Technology

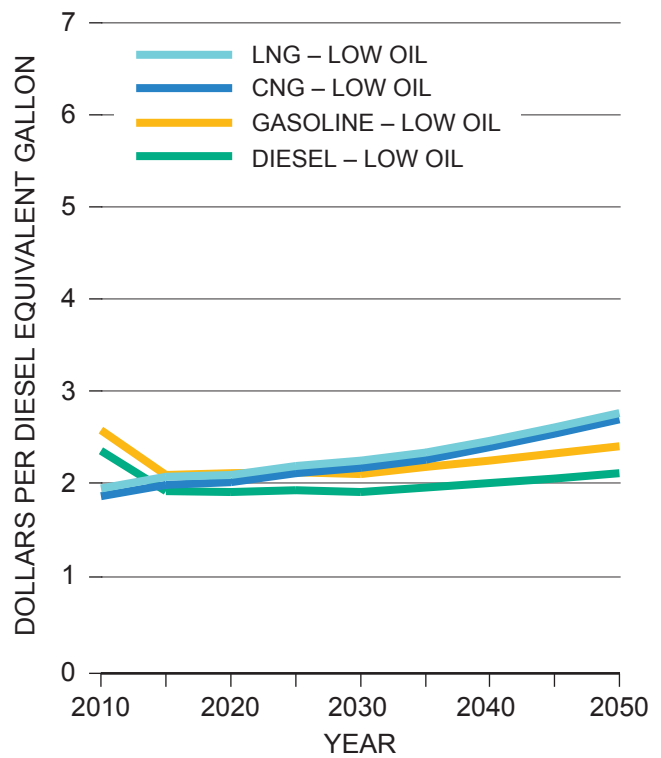


Figure 3A-7. Fuel Price Assumptions for the Low Oil Price Case

categories available: Class 3-6 trucks, Class 7&8 single-unit trucks, and Class 7&8 combination trucks.

- Class 7&8 combination trucks may be powered by conventional diesel or natural gas powertrains.
- Class 7&8 single-unit trucks may be powered by conventional diesel, natural gas, or hybridized diesel powertrains, inclusive of both electric and hydraulic hybrids.
- Class 3-6 trucks may be powered by conventional gasoline powertrains, conventional diesel powertrains, natural gas powertrains, or hybridized-diesel powertrains.

Fuel prices are an input to the VISION model as well as the other modeling components, and are determined based on the published scenarios of the Department of Energy's Energy Information Administration, with minor updates to reflect the cost of alternate fuel infrastructure, as published elsewhere in this study. The resultant fuel prices are shown in Figures 3A-7, 3A-8, and 3A-9.

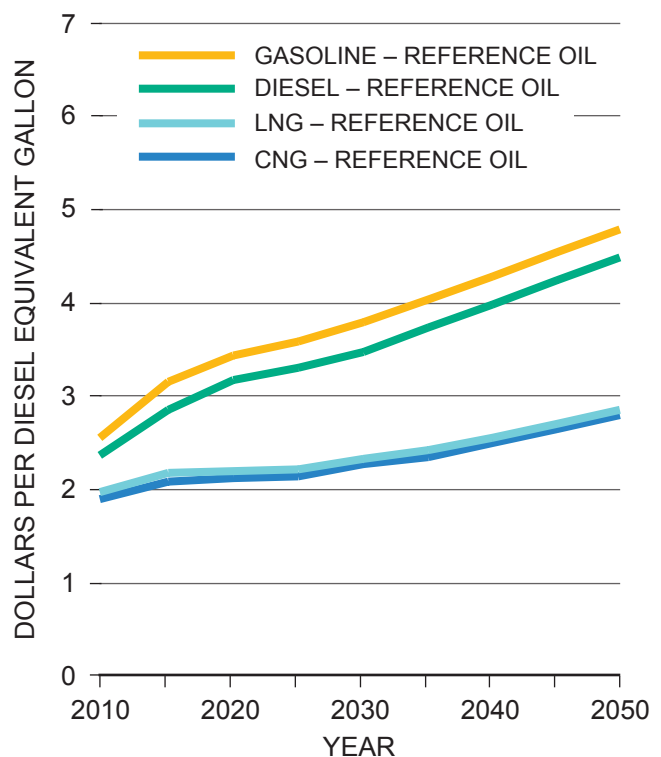


Figure 3A-8. Fuel Price Assumptions for the Reference Oil Price Case

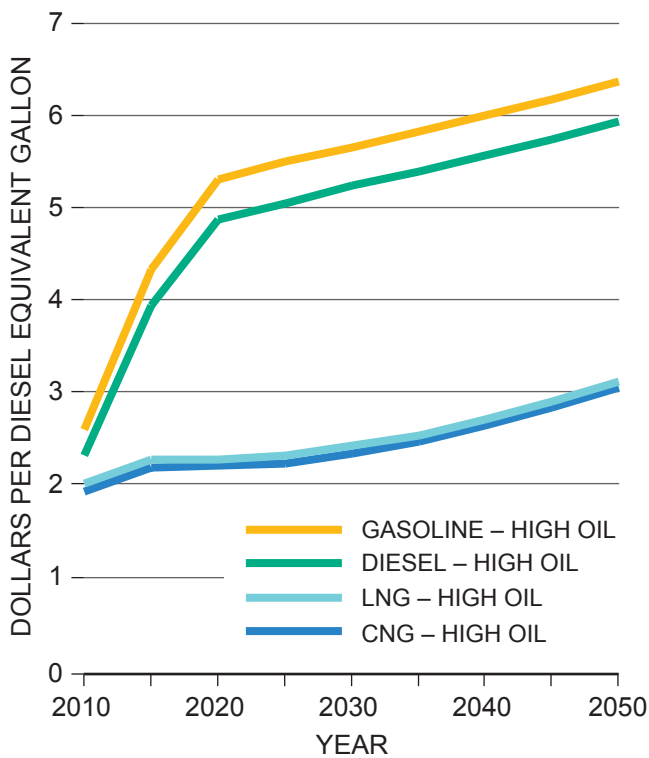


Figure 3A-9. Fuel Price Assumptions for the High Oil Price Case

NATURAL GAS ASSUMPTIONS

The natural gas vehicles included in the model assumptions are described in Table 3A-2.

In Class 3-6, the analysis assumed that the natural gas vehicle options were constrained to spark-

ignited engines utilizing three-way catalyst after-treatment and CNG fuel supply only.

In Class 7&8, the analysis assumptions of fuel economy and system costs cover the range of spark ignition (SI) and compression ignition (CI) technologies. Within compression ignition both dual fuel and direct injection engine types were considered in the range of inputs. A mix of CNG and LNG systems costs were included within the ranges and fuel storage capacity was varied by range expectations in each segment as well as with fuel economy as that increased.

In terms of cost, the lowest engine cost is represented by SI engines because they have low-cost, passive aftertreatment and lower cost fuel injection systems than diesel. The highest cost systems are represented by dedicated direct injection CI systems since their fuel injection systems are more complex and they currently rely on both diesel particulate filter and urea-SCR after treatment systems. Dual-fuel compression ignition engines have cost structures that are likely to be closer to that of SI systems since their gaseous fuel injection system is similar in complexity. The range of cost assumptions employed in the analysis covers the full range of technologies considered.

With fuel cost savings being central to the value proposition for natural gas trucks, the natural gas fleet was modeled using attributes indicative of the range of performance of the different technologies. SI engines have the lowest fuel economy

Market Segment	Engine Type	Fuel Source
Class 3-6	Spark Ignition	CNG only
Class 7&8 Single Unit	Dedicated Spark Ignition Dual-Fuel Compression Ignition Dedicated Direct Injection Compression Ignition	CNG and LNG
Class 7&8 Combination	Dedicated Spark Ignition Dual-Fuel Compression Ignition Dedicated Direct Injection Compression Ignition	CNG and LNG

Table 3A-2. Natural Gas Vehicle Assumptions

as a result of throttling, while CI engines have fuel economy similar to diesel. Dedicated direct injection engines would have the lowest cost of fuel since they use natural gas for approximately 95% of their required fuel energy. Dual fuel engines, while having similar fuel economy, would have slightly higher total cost of fuel since they use perhaps 70–80% natural gas, with the remainder being diesel.

When reviewing natural gas specific findings, it should be noted that the model inputs were based on the following assumptions:

- Class 3-6 – 100% spark ignition with CNG fuel storage
- Class 7&8 Single Unit – 80-20 mix of SI and CI engines, with 50-50 mix of CNG and LNG
- Class 7&8 Combination – 50-50 SI and CI engines, with 50-50 mix of CNG and LNG.

