CHAPTER FOURTEEN

NATURAL GAS

EXECUTIVE SUMMARY

Natural gas has primarily fueled power generation, industrial processes, and residential and commercial heating, namely every sector of the American economy except for transportation. Its use as a transportation fuel has grown over the last decade in a number of international markets, but until recently its use in the United States has been limited. The potential for a long-term and low-cost domestic supply of natural gas, supported by significant economically recoverable shale gas resources, presents an opportunity for the increased use of natural gas as a transportation fuel, replacing some part of the current requirements for oil in transportation: gasoline in light-duty (LD) applications and diesel fuel in heavy-duty (HD) vehicles.

The Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2010 estimates natural gas resources at 2,575 trillion cubic feet (tcf) with technically recoverable shale gas resources estimated at 368 tcf and annual production rates of approximately 23 tcf. In the AEO2011 outlook, technically recoverable shale reserves increased to 827 tcf.

If this expansion in reserve base evidenced in recent years continues to result in sustainable long-term and stable price advantages relative to petroleum fuels, there are economic incentives for increased use of natural gas in the transportation sector. The natural gas fuel price differential advantage over gasoline and diesel is already significant. The EIA suggests that this gap between gasoline/diesel and natural gas may widen further through 2035.

- With a sustained significant fuel price differential between oil and natural gas, driven by relatively low natural gas prices in the United States, the benefits from natural gas may be larger, earlier, and faster than alternative technologies. Volatility in fuel prices and fuel price differential, on the other hand, may cause consumers to be conservative and lead to slower natural gas adoption in transportation.
- The current economics of both HD and LD natural gas vehicles (NGVs) are encouraged by the lower price of natural gas versus oil, and they are discouraged by higher vehicle costs and infrastructure availability.
- As higher vehicle purchase price premiums are a primary barrier to market expansions, creating sufficient demand to migrate to fully original equipment manufacturer (OEM) produced vehicles would be expected to result in cost improvements from today's low volume "final vehicle modifier" approach.
- NGVs are already a product of choice in some HD markets, particularly transit buses and refuse haulers, with HD commercial trucks now also beginning to emerge. Internationally, LD NGVs have a growing market share, but adoption in the United States has been limited and fragmented to date.
- The opportunity for bi-fuel NGVs in both LD and HD markets may be a factor in easing issues around refueling availability in transitional time frames and markets.

Heavy-Duty Trucks

HD compressed natural gas (CNG) and liquefied natural gas (LNG) vehicles are already making inroads in the market and offer opportunity for early adoption of natural gas for transportation in the United States due to their high annual fuel use and fleet base and the local/regional nature of a large element of the freight industry.

- Assuming a sustained price advantage for natural gas over diesel, high annual fuel use in HD vehicles helps recover the incremental vehicle price premium, which has been a major market barrier.
- Natural gas engines have large architectural and technical synergy with their diesel counterparts, meaning that many of the advancements in diesel powertrains can be applicable to natural gas engines.
- The primary natural gas HD market hurdles that need to be overcome include:
  - High vehicle costs due to limited volumes of factory finished vehicles and engines, and low volume of demand for natural gas systems.
  - Limited refueling infrastructure currently in place.
  - A broader range of engine options is required to meet the wide variety of HD vehicle applications. Recent new product announcements from major HD engine manufacturers indicate that this is being addressed for HD vehicles, but still remains an issue for medium-duty (MD) vehicles.

Light-Duty Vehicles

LD vehicle CNG markets have the opportunity for growth initially in private fleet segments using light trucks and vans. Improved technology has addressed initial hurdles associated with performance, fuel economy, and range. The re-entry of the major OEMs is starting to increase the initial range of product offering in the United States and in Europe.

- Globally the number of LD CNG vehicles has increased about tenfold in the last decade, but this growth has been almost entirely outside the United States.
- The recent increases in natural gas fuel price differential versus gasoline provide an economic incentive for consumers to choose NGVs.
- The primary LD market hurdles that need to be overcome include:
  - Higher vehicle costs due to non-factory finished vehicles and low volume production scale of CNG systems.
  - Fuel storage system costs and higher energy storage density.
  - Limited make-model availability impacts consumer options. The majority of the vehicles offered in the United States are pickups and vans.
  - Limited refueling infrastructure.
  - Minimal inclusion of CNG in the OEMs' current long-term product architecture plans regarding powertrain and chassis.
  - Limited availability of public information on quantified long-term performance potential.

Natural Gas Refueling Infrastructure

The United States has an extensive, well established production, transmission, and distribution network to transport natural gas to key markets. Since direct use of natural gas as a transport fuel can exploit this network there are few barriers to fuel availability. Little of this current infrastructure, however, is dedicated to retail vehicle refueling.

Natural gas retail refueling infrastructure is in early stage development and will require major expansion and investment to meet the growing demands for natural gas transportation fuel as the industry commercializes. As of March 2012, there were 988 CNG stations compared to ~160,000 retail gasoline stations, and 47 LNG stations serving HD vehicles.[1] The transition to a fully scaled and mature retail infrastructure system to serve the LD and HD markets will take time and investment.

The technology opportunities for infrastructure include:

- Improvements in modular CNG dispensing systems to improve the cost effectiveness of retail station upgrades.
- Cost and performance of CNG compressor systems.
- Small-scale LNG technology to support localized HD fleets.
- Home refueling systems that can mitigate the need for widespread retail infrastructure

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[1] U.S. Department of Energy, Alternative Fuels and Advanced Vehicles Data Center (website), "Alternative Fueling Station Total Counts by State and Fuel Type," 2012, http://www.afdc.energy.gov/afdc/fuels/stations_counts.html.

systems, which require improvements in low-cost compressor systems, or a migration to low-pressure, high-density fuel storage systems.

Although infrastructure expansion may be challenging, particularly for LD consumer markets, expansion could be more manageably achieved by targeting regional markets first, before full nationwide infrastructure is deployed. This is the way HD natural gas fleets and infrastructure has developed, where a large number of vehicles operate on regional hub and spoke routes, and these regional networks are connected by high-traffic-density freight corridors.

Capital investments in infrastructure can be absorbed assuming sustained fuel price advantages of natural gas and high utilization of stations.

Technology

There are few technical barriers that prevent NGVs entering the market. Market entry barriers are largely logistical and commercial and involve matters of timing and pace around the introduction of a new fuel and infrastructure into the transportation mix.

Further R&D would be beneficial to improving the performance of NGVs in a number of areas:

- Direct injection turbocharged CNG engines: Turbocharging increases torque/power output due to improved air mass flow and knock resistance. Downsized, direct injection natural gas engines can approach the torque output of diesel engines.
- On-board fuel storage: Improvements in energy storage density are similarly beneficial; however, it is critical to understand the full extent of tradeoffs between storage volume, ease of vehicle packaging, mass (both direct and compounded), storage pressure, and fuel dispensing pressure.
- HD cryogenic fuel handling systems: Material or system developments can improve static and dynamic seals, non-intrusive fuel level sensing, and vapor pressure management.
- Greater OEM engagement in engine and vehicle production to reduce costs. The combined effect of higher volumes and streamlined manufacturing will bring cost reductions through reduced material costs, higher degrees of automation, and longer-term supply chain contracting.

Environmental Attributes of Natural Gas

Although natural gas has relatively modest greenhouse gas (GHG) emission benefits over petroleum fuels, typically in the range of 11 to 25%, it supports the overall reduction of transport sector emissions and can do so while displacing diesel and gasoline consumption. As with other alternative fuels, the long-term potential of natural gas for reducing absolute GHG emissions compared to a 2005 baseline is challenged by the projected large growth in vehicle miles traveled associated with increased passenger and freight movement.

The Potential of Renewable Natural Gas

Renewable natural gas (RNG) is pipeline quality gas obtainable from renewable sources that is interchangeable with fossil natural gas for use in vehicles. It is produced from a variety of biomass and/or biogas sources including landfill gas, solid waste, municipal wastewater, and agricultural manure via purpose-built anaerobic digesters. It can also be produced from larger lignocellulosic sources such as forestry and agricultural waste through the processes of thermal gasification and methanation.

RNG has the potential to offer significantly lower GHG emissions (typically 70 to 100%) than that of petroleum and fossil natural gas. Its ability to have a material impact on the overall fleet emissions is contingent on an increase in the number of NGVs on the road, and whether material amounts of RNG can enter the fuel distribution system.

While modest amounts can be produced at a relatively small incremental fuel cost, a more substantive use of RNG is likely to require economic conditions with a large price differential between natural gas and petroleum based fuels. A topic paper produced in parallel with this study (Topic Paper #22, "Renewable Natural Gas for Transportation," on the NPC website) determined that there are significant RNG resources available if they can be developed economically.

In contrast to the demand for renewable electricity, a similarly robust market for transportation use of RNG does not currently exist. Each state faces a different mix of regulatory barriers, making it difficult to generalize opportunities and constraints from a national perspective. While RNG could support de-carbonization of fuel for use in transportation, its use will be in competition with other sectors such as power generation.

The technology barriers for RNG are modest as it makes use of existing technology for natural gas engines and infrastructure. There is currently no common gas specification standard for RNG as a transport fuel including composition analysis and allowable levels of trace compounds. However, there are pipeline specifications that RNG will need to meet in order to enter the existing pipeline networks.

INTRODUCTION

This chapter discusses the use of natural gas as a direct fuel for internal combustion engines in both LD and HD vehicles. LNG can also fuel the rail and marine sectors; however, these applications are beyond the scope of this chapter. Natural gas can be used as a feedstock for other transportation fuels such as hydrogen and methanol and these pathways are addressed within other chapters as appropriate.

Natural gas has a long history of use for power generation, industrial processes, and residential heating. Due to a number of economic, technical, and regulatory conditions and factors, it has had only an intermittent history of use as a fuel source for transportation in the United States despite broader international use. The development of unconventional North American natural gas resources or "shale plays" has generated renewed interest in the use of natural gas as a vehicle fuel for both on- and off-highway applications. This chapter will look at the issues and opportunities surrounding NGVs and their ability to move beyond niche markets to have a material impact on improved economic, environmental, and energy security aspects of the U.S. transportation sector.

Infrastructure requirements including domestic natural gas production, distribution, and dispensing for CNG and LNG are discussed in the context of the fuel supply chain.

As the markets, technologies, production/supply chains, and opportunities for LD and HD NGVs differ significantly, these vehicle types are addressed within separate sections of the chapter.

Hurdle diagrams illustrating the barriers to deployment are included to highlight the necessary logistical, commercial, or technological breakthroughs needed to achieve commercial scale.

The environmental attributes of natural gas and the potential for RNG are introduced to understand how NGVs may contribute to a lower carbon fuel mix.

As NGVs for both LD and HD vehicles are built off of internal combustion engines with substantive commonality to those fueled with gasoline and diesel, this chapter expands on several key issues addressed in the chapters on conventional LD and HD vehicles. The reader is referred to these chapters for specific details of technology advancements that are shared with liquid hydrocarbon fueled vehicles.

Figure 14-1 outlines the vehicle and infrastructure pathways that are within the scope of this chapter.

INDUSTRY OVERVIEW

Global Natural Gas Vehicle Market Perspective

There are almost 14 million NGVs of all classes on the road globally.[2] The largest regional markets are Latin America and Asia-Pacific, which combined account for 71% of the total number of NGVs. More than 95% of the total are LD vehicles including passenger cars and LD trucks and vans. Natural gas buses, HD trucks, and other vehicles such as auto rickshaws comprise the remaining 5%. Figure 14-2 depicts the growth in global NGV populations.

The global NGV market is highly stratified by region and further so by country. As shown in Figure 14-3, nearly 95% of the total number of NGVs is found within just 15 countries.[3] Only 20 countries maintain NGV fleets with at least a 1% market share of the national vehicle fleet.

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[2] Natural & bio Gas Vehicle Association (NGVA) Europe (website), "Worldwide NGV Statistics," accessed November 9, 2011, http://www.ngvaeurope.eu/worldwide-ngv-statistics.

[3] International Association for Natural Gas Vehicles (website), "Natural Gas Vehicle Statistics," updated April 2011.

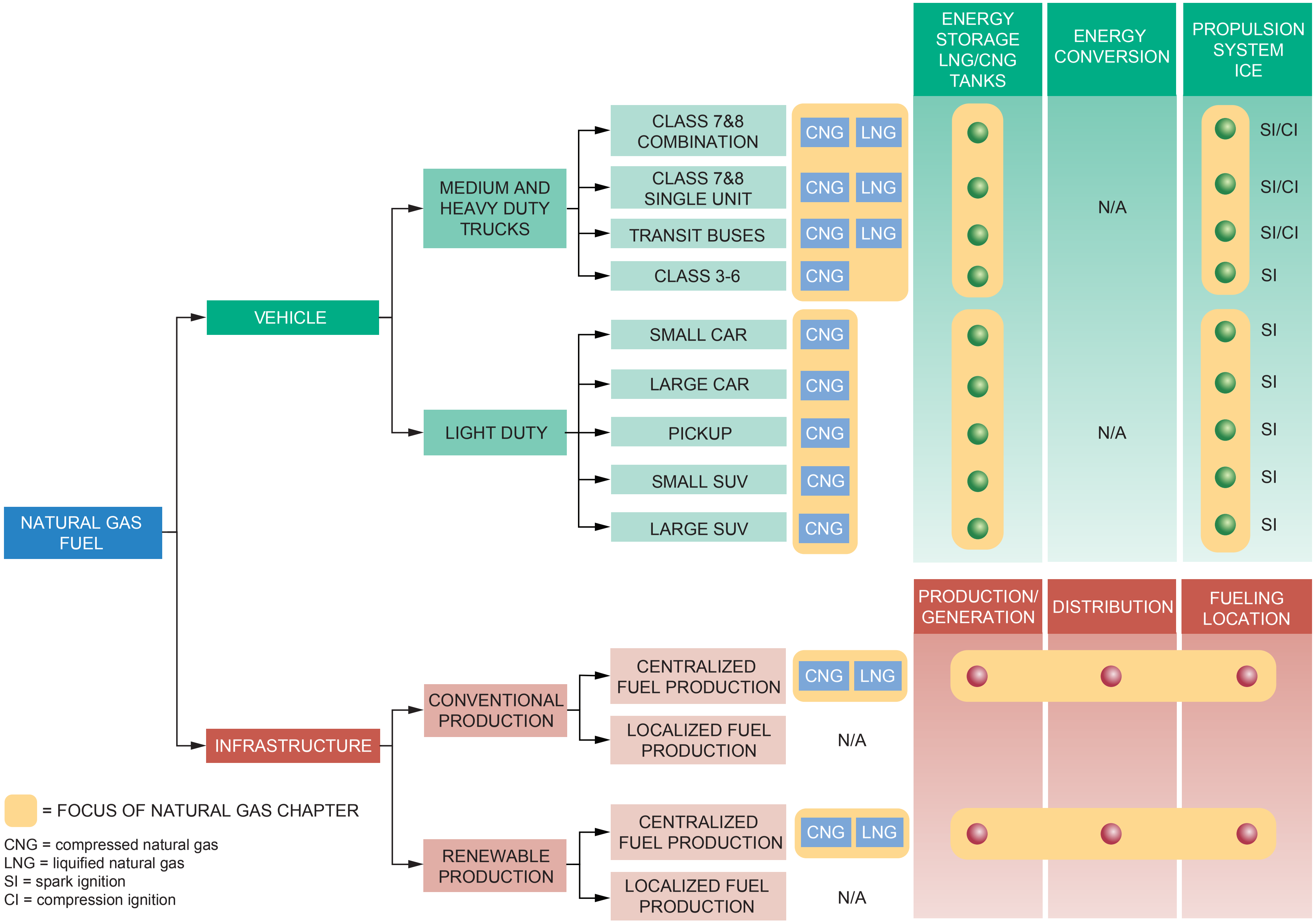

Figure 14-1. *Natural Gas Supply Chain – Scope of Discussion*

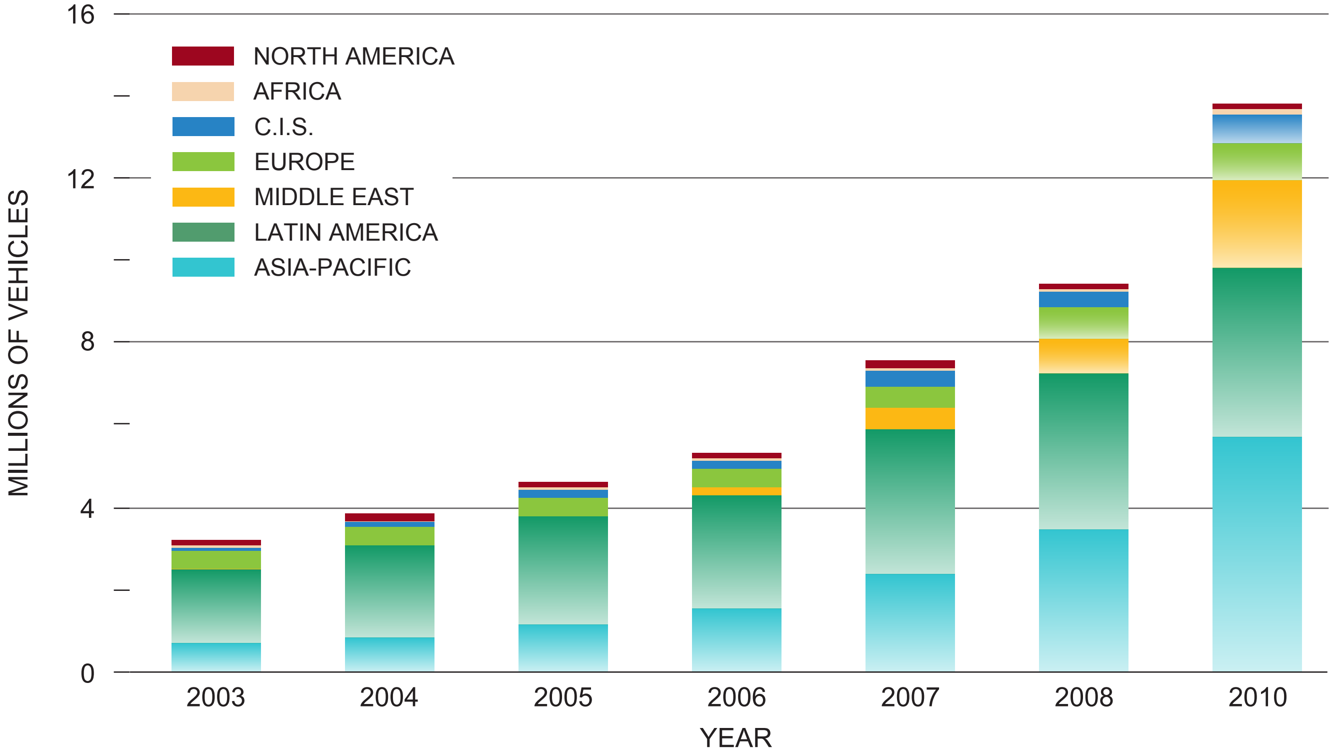

Figure 14-2. Growth of Global NGV Populations by Region

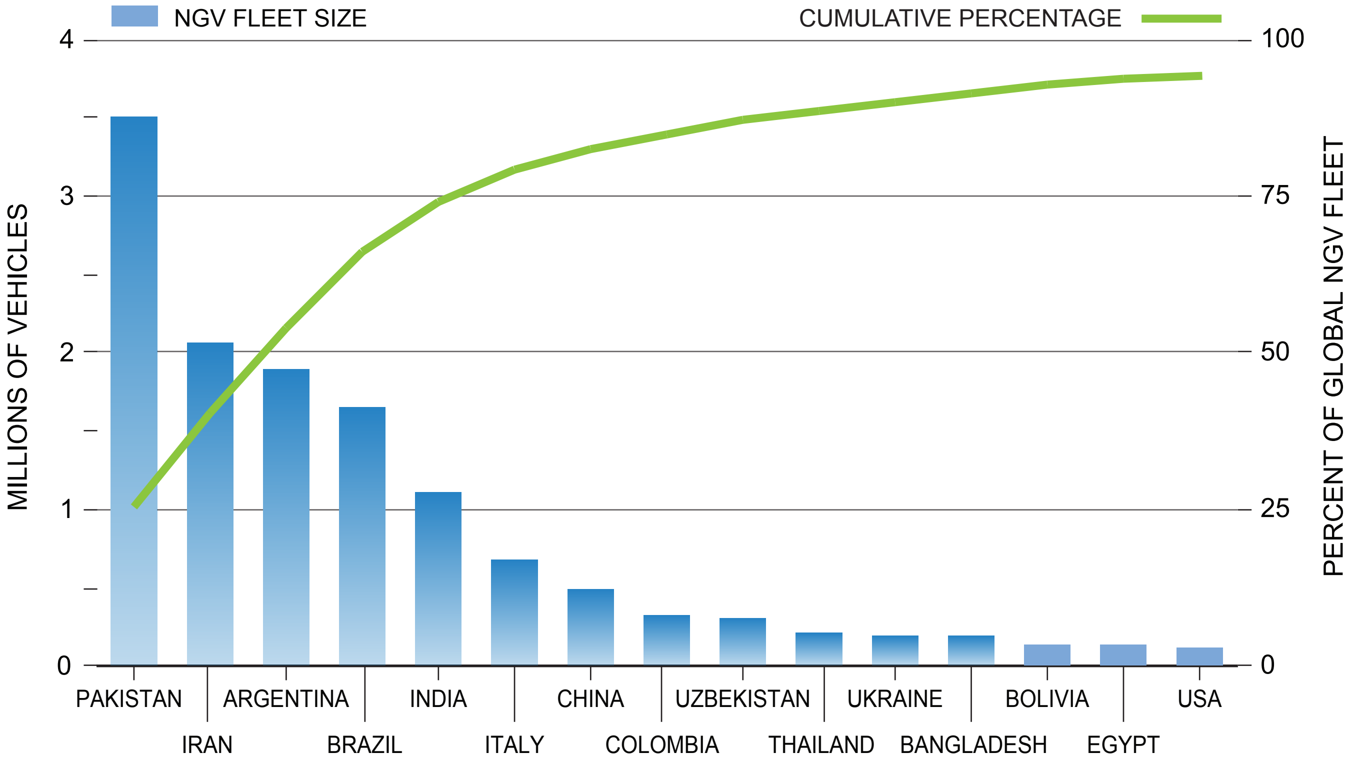

Figure 14-3. NGV Fleet Populations by Country

These countries generally share at least one of the following common and even contradictory attributes that serve to promote the shift to natural gas for transportation. This is a reflection of the very diverse economic, environmental, and regulatory factors that have supported the deployment of NGVs in different regions:

- Lack of domestic oil reserves or insufficient refining capacity to meet transportation demands with petroleum fuels only
- Domestically available and cost advantageous natural gas resources
- Favorable natural gas fuel price differentials compared to petroleum fuels[4]
- Well-established gas transmission and distribution networks coincident with major transport routes
- Urban air quality concerns
- Lack of stringent emissions standards, resulting in a low adoption of advanced vehicle emissions controls
- Regulations and policies for either GHG mitigation or energy security purposes that either mandate alternative fuels or incentivize their use.

While these global statistics are dominated by LD vehicles, an early groundswell for the use of natural gas in HD trucks, particularly in transit and refuse applications has been seen over the last decade. This has been spurred by new technology to enable the use of natural gas as a supplemental or replacement fuel in diesel engines, coupled with the continued growth of its use in public transit fleets. Table 14-1 compares the geographic distribution of the MD and HD vehicle populations segmented by bus and truck applications.

The vast majority of NGVs currently on the road have been produced as either retrofit or aftermarket conversions, with a wide variety of conversion kits of disparate complexity, functionality, and quality. In some markets, this philosophy is likely to remain the dominant approach for the near term. As global OEMs enter the market with more sophisticated, integrated, higher quality systems that are capable of achieving the strictest emissions standards with improved fuel economy compared to historical NGV technologies, the performance comparisons to gasoline and diesel vehicles have improved.

Although the total number of NGVs represents a small fraction of the global on-highway vehicle fleet (the International Energy Agency estimates that in 2006 there were 800 million LD vehicles), the global NGV market growth trend represents a compounded annual growth rate of 23.2% over the period of 2003 to 2010.[5]

Region	MD/HD Natural Gas Buses	MD/HD Natural Gas Trucks	Total HD Natural Gas Vehicles
Africa	1,237	713	1,950
Asia-Pacific	237,274	88,275	325,549
Europe	12,717	5,572	18,289
Middle East	5,364	0	5,364
North America	11,240	2,500	13,740
Latin America	13,820	9,660	23,480
C.I.S.	131,231	102,026	233,527

Table 14-1. *Heavy-Duty NGV Populations by Region*

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[4] Collantes and Melaina (2011) argue that the price difference between fuels needed to accept alternative fuels are a function of affluence in the society. The less affluent a country, the lower the price difference between fuels is required for consumer acceptance of the alternative fuel such as CNG.

[5] These 800 million light-duty vehicles accounted for approximately 47% of total global transportation energy use according to the International Energy Agency's *Transport, Energy and* CO_2 study. Further, IEA forecast that the light-duty vehicle fleet could reach 2 billion vehicles by 2050.

North American NGV Market Overview

The North American NGV market took significant hold in the 1970s during the Middle East Oil Crisis. NGV sales grew with an emphasis on fleet customers, taxis, and private retail customers. Transit fleets, recognizing the potential cost savings in high-use applications, began to adopt natural gas with spark ignition engines based on diesel engine platforms. The NGV fleet today remains dominated by LD vehicles but a shift is occurring towards HD vehicles in terms of total gas consumption and petroleum displacement.

The Energy Policy Act of 2005 boosted the alternative fuel vehicle industry in the United States with provision of incentives and some mandates. According to the Department of Energy, of the alternative fueled vehicles in use in 2009, approximately 120,000 were NGVs (Figure 14-4), almost entirely fueled by CNG.[6] While the vast majority of these vehicles remain LD car and light trucks such as utility vehicles, taxis, shuttle buses, and vans, the use of natural gas in high-fuel-use HD fleets has been growing.

The transit bus fleet demonstrates the sustained and expanding deployment of natural gas in HD applications (see Figure 14-5). As of 2009, 12,300 natural gas transit buses were in operation, accounting for 19.5% of the fuel use in the total transit sector.[7] The EIA forecasts this to increase to 65% of total transit bus fuel usage by 2035 in its AEO2010 Reference Case.

The Los Angeles Metropolitan Transit Authority (LAMTA) is a high profile example of natural gas vehicle deployment. LAMTA retired its last diesel bus in January 2011 and now operates an entirely CNG fleet of 2,200 buses. LAMTA announced that it has compiled over 1 billion miles on CNG, saving 300,000 pounds of greenhouse gas per day, and doing so economically.[8] This level of success in transit has been supported by a number of state and federal programs including the DOE Clean Cities program.

Similar market acceptance has been witnessed for refuse collection vehicles. As of January 2009, an estimated 3,500 refuse haulers were operating on natural gas, still a relatively small but growing portion of the total U.S. collection fleet of approximately 135,000 vehicles.[9] While the total CNG refuse fleet may currently be small at ~2.5% of the total refuse fleet, the portion of new vehicle sales in this application is growing through new sales. The time taken to transition a large portion of the total fleet is dictated by the long life and ownership cycles of these vehicles.

Recognition of the fuel cost savings in high fuel use fleets, acting in tandem with incentives and local mandates, has led to a growing awareness of the potential for natural gas in HD fleets encompassing both freight and vocational applications.[10] With new technologies based on both spark ignition and compression ignition combustion cycles, many of the major truck OEMs now offer factory built CNG and LNG trucks with all of the features expected in a modern diesel truck, and with engines that meet or exceed all emissions requirements.[11]

NGV Industry – Challenges and Opportunities

NGVs have primarily made an impact in U.S. and global niche markets based on geography or application.

The primary challenges for NGVs can be summarized by the following:

- Vehicle economics
  - Reduction in the incremental cost of natural gas systems
  - Total cost of ownership, covering cost of vehicle and fuel

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[6] U.S. Department of Energy, Alternative Fuels and Advanced Vehicles Data Center (website), "Data Analysis and Trends: AFVs in Use," accessed November 9, 2011, http://www.afdc.energy.gov/afdc/data/vehicles.html.

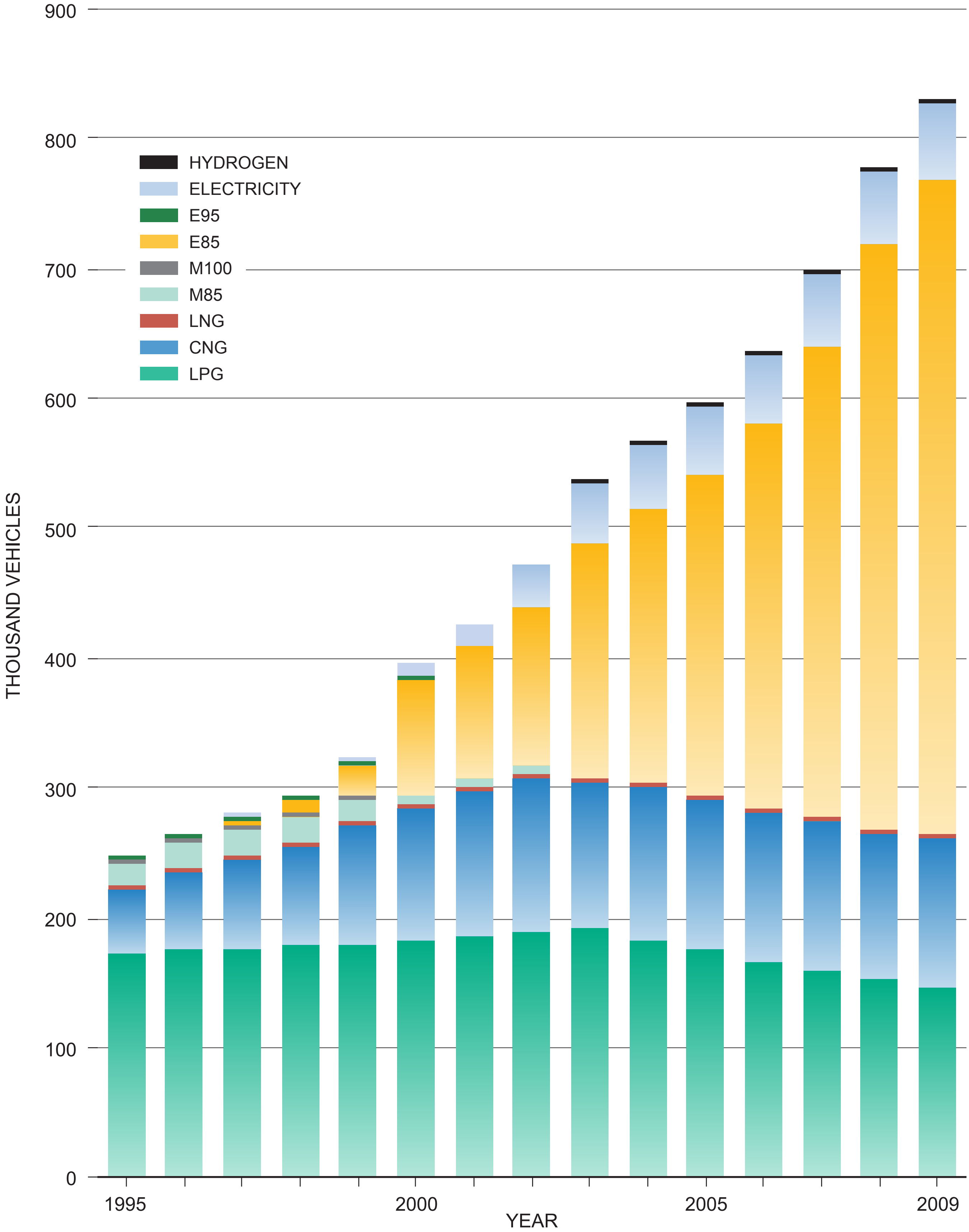
[7] Ibid.

[8] Natural Gas Vehicle Global News, "LA Metro Retires Last Diesel; Now Operates 2221 CNG Buses," press release, January 13, 2011, http://www.ngvglobal.com/la-metro-retires-last-diesel-now-operates-2221-cng-buses-0113#more-12244.

[9] Natural Gas Vehicle Global News, "Natural Gas Fuel for Refuse Trucks – The Right Choice," press release, September 24, 2009, http://www.ngvglobal.com/natural-gas-fuel-for-refuse-trucks-the-right-choice-0924.

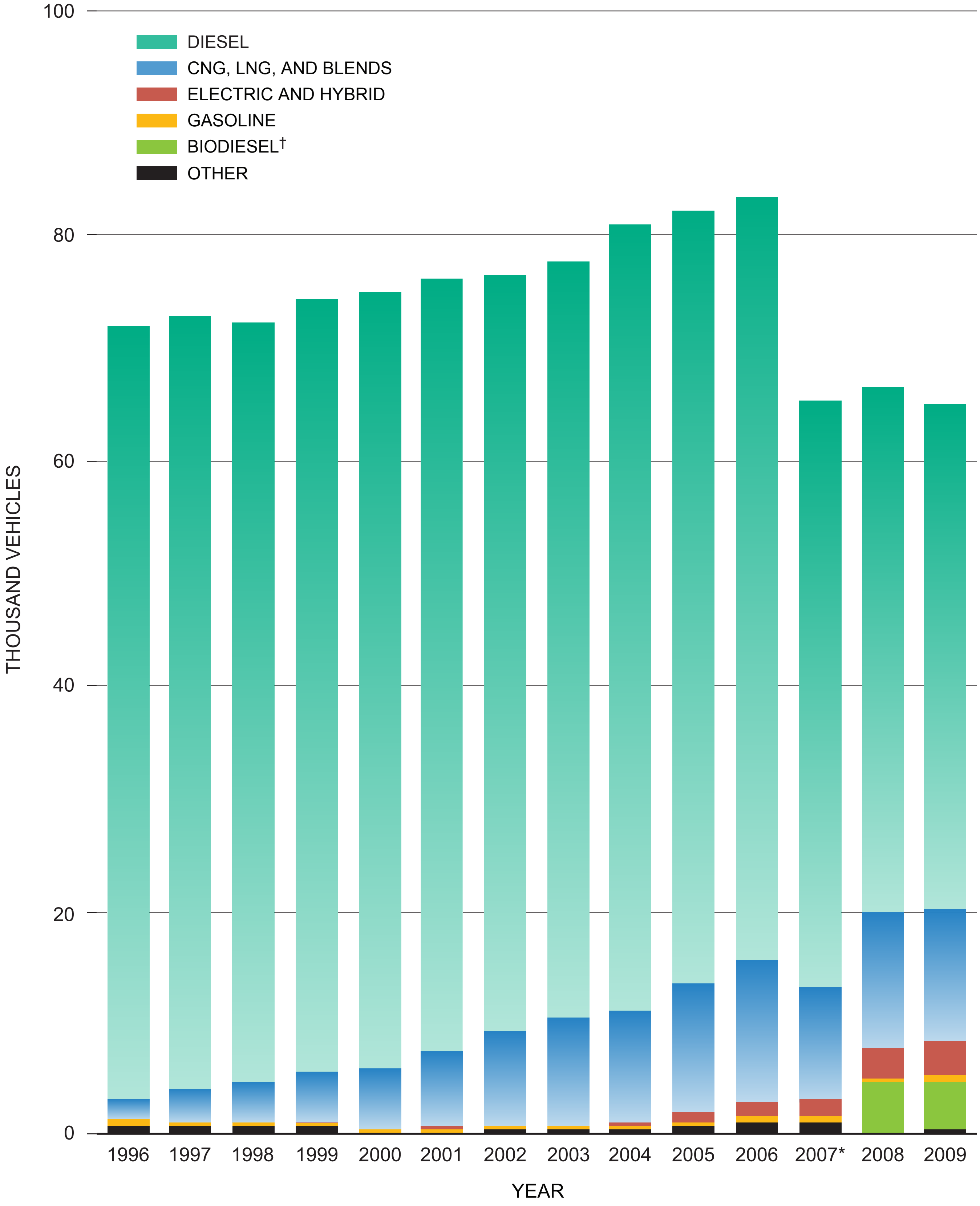
[10] Vocational applications include cement trucks, water trucks, refuse collection, etc.

[11] These OEMs include Kenworth, Peterbilt, Mack, Freightliner, Navistar, and McNeilus.



Source: U.S. Department of Energy, Alternative Fuels and Advanced Vehicles Data Center.

Figure 14-4. *U.S. Alternative Fueled Vehicle Populations*



* Data is not continuous between 2006 and 2007, due to the availability of new data sources.
† Biodiesel was counted in the "Other" category until 2008.
Source: U.S. Department of Energy, Alternative Fuels and Advanced Vehicles Data Center.

Figure 14-5. *U.S. Transit Buses by Fuel Type, 1996–2009*

- Fuel availability and economics
  - Infrastructure for CNG and LNG to serve both fleet and consumer vehicles
  - Cost of dispensed fuel in relation to liquid hydrocarbon fuels
- Technology
  - Ability to comply with modern emission regulations
  - Ability to produce vehicles with comparable performance and utility to those of gasoline or diesel fuel vehicles.

Recent developments in shale gas resources have led to the potential for a significant increase in the domestic production capacity of natural gas. If this expansion in capacity results in long-term and stable price advantages relative to petroleum fuels, then its use in transportation is likely to gain further attention.

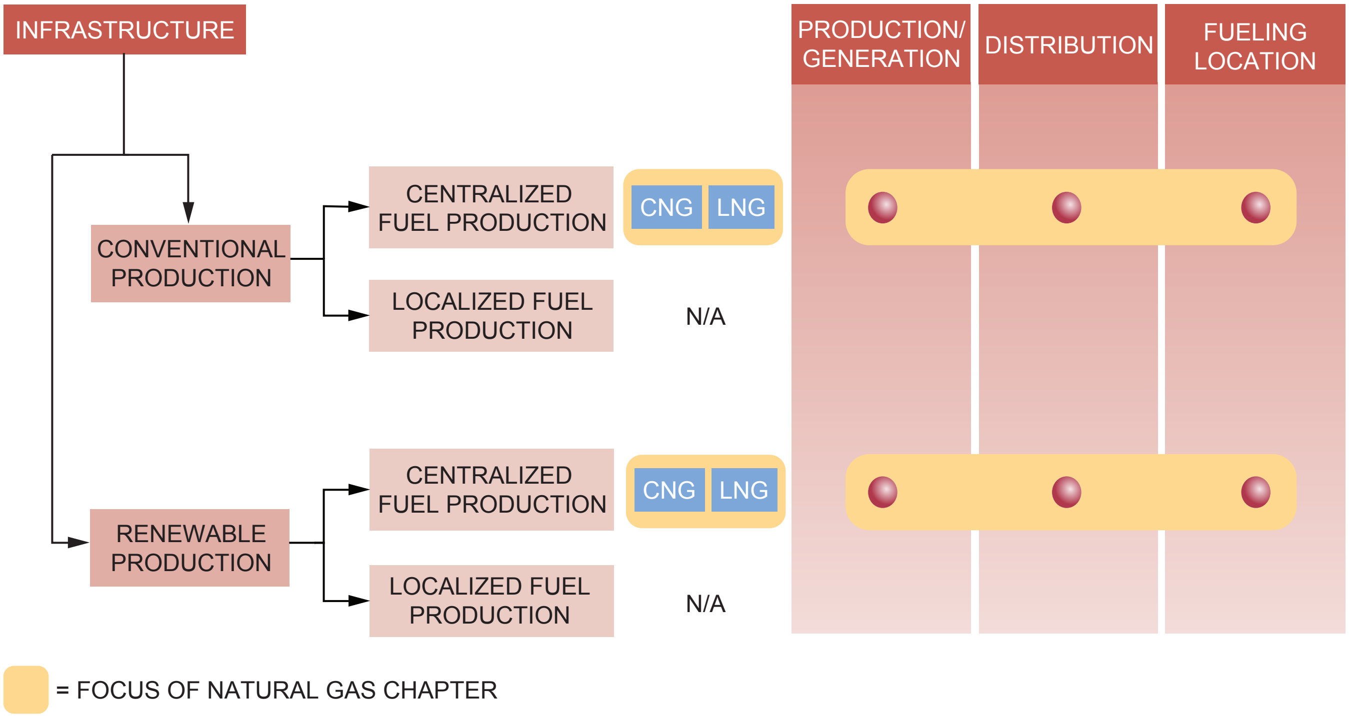
Refueling infrastructure build-out is underway and growing, particularly in support of HD NGVs with associated expansion to support localized LD fleet customers. Continued and accelerated infrastructure development is required to position natural gas as a wide-scale commercial fuel alternative.

Advances in natural gas engine and vehicle technology, coupled with increasing product availability from recognized OEMs, are forming a foundation for expanded model availability for both consumer and fleet customers.

NATURAL GAS SUPPLY CHAIN

This section discusses aspects of the natural gas fuel supply chain as they pertain to use as a transportation fuel, culminating in estimates of fuel costs for use in LD and HD vehicles. Figure 14-6 shows the scope of the natural gas supply chain. A more detailed discussion of RNG is provided in a separate section of this chapter.

Methane is a colorless, odorless gas, and is the major component of natural gas. It can be derived from oil fields, traditional gas fields, shale deposits, or from renewable sources such as landfill gas,



CNG = compressed natural gas

LNG = liquefied natural gas

Figure 14-6. Scope of Natural Gas Supply Chain though some differences may arise due to the existence of secondary components. Methane exists in gaseous form at ambient temperature and pressure. An extensive system of interconnected pipelines and storage systems allow for the efficient use of natural gas for a wide array of energy demands. The system supplies both domestic and imported gas and is owned by private and public entities who work to safely deliver energy to meet an expanding need.

The National Petroleum Council's 2011 study *Prudent Development: Realizing the Potential of North America's Abundant Natural Gas and Oil Resources* examines the wide range of studies and data from public sources and aggregated proprietary data collected via confidential survey. An analysis of the factors that affect long-term natural gas demand across sectors is beyond the scope of this chapter and the reader is referred to the *Prudent Development* report for further investigation. A consistent finding common to recent studies is that the demand for natural gas is expected to increase within the study time frame.

Technological advancements have dramatically changed the outlook for North American natural gas supply and created an opportunity for natural gas in the transition to a lower carbon fuel mix. As late as 2007, domestic natural gas supplies were constrained and it was expected that the United States would become increasingly reliant on LNG imports. New applications of technologies including horizontal drilling and hydraulic fracturing have unlocked previously unavailable deposits and expanded economically recoverable volumes. The United States is now the number one natural gas producer in the world and together with Canada accounts for over 25% of global natural gas production.[12]

Natural Gas for Transportation Fuel Supply Chain

Figure 14-7 illustrates the supply chain for bringing domestic natural gas to market through the three primary phases of production, transmission, and distribution. This infrastructure is critical to enable the fueling of NGVs.

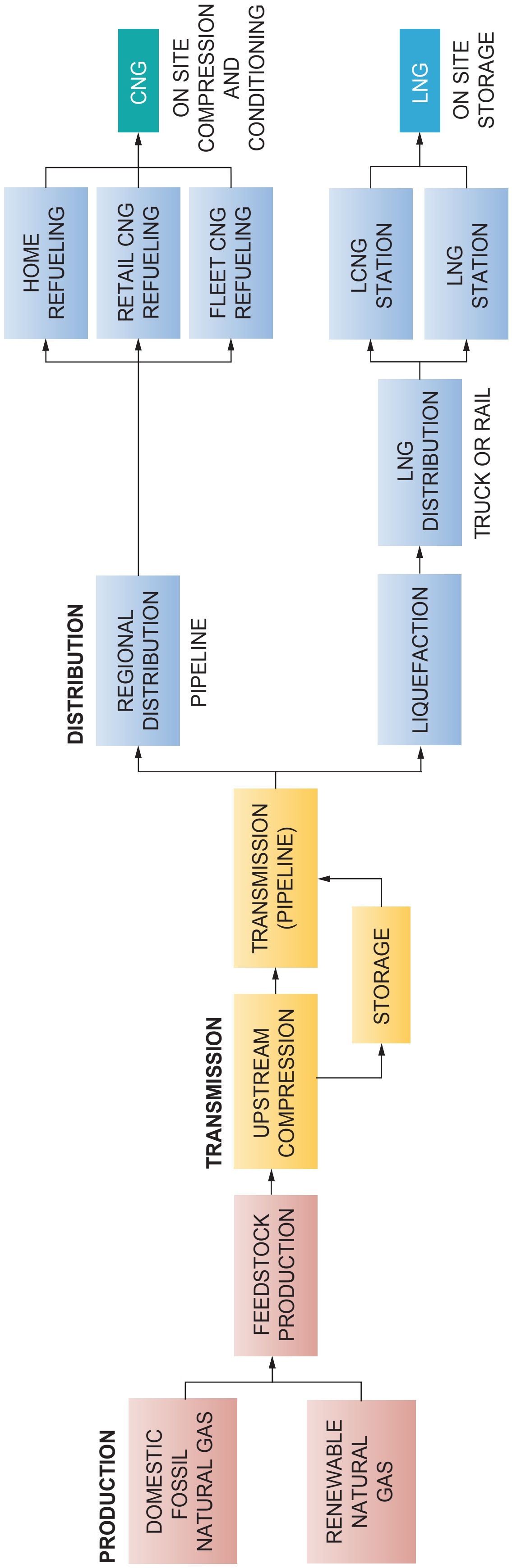


Figure 14-7. *Natural Gas for Transportation Supply Chain*

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[12] National Petroleum Council, *Prudent Development: Realizing the Potential of North America's Abundant Natural Gas and Oil Resources*, 2011, http://www.npc.org/NARD-ExecSummVol.pdf.

Production

Natural gas resources are available from conventional and unconventional geological gas reserves. Conventional gas reserves can be associated or unassociated with a crude oil reserve deposit. Unconventional gas reservoirs include tight gas, coalbed methane, gas hydrates, and shale gas.

Over the past decade, the deployment of new technologies in horizontal drilling and hydraulic fracturing has allowed the extraction of large volumes of gas from unconventional sources such as shale gas. This discovery has transformed the potential for the North American gas market as projections indicate an ample supply.[13]

Natural gas resources and production estimates increased materially between EIA's 2010 and 2011 Annual Energy Outlook, primarily as a result of shale gas resources. AEO2011 forecast 827 tcf of shale gas and total U.S. natural gas reserves are 2,543 tcf or 110 times the annual consumption in 2009. Shale gas and coalbed methane are forecast to account for 57% of U.S. production by 2030.[14]

Natural gas withdrawn from a well may contain liquid hydrocarbons and non-hydrocarbon gases such as carbon dioxide, helium, nitrogen, hydrogen sulfide, water vapor, and other gases. Gas conditioning, processing, and liquid fractionation remove the hydrocarbon liquids and the majority of non-hydrocarbon impurities resulting in pipeline quality natural gas.

Transmission

With over 300,000 miles of gas pipelines regulated by the Federal Energy Regulatory Commission, the transmission system is responsible for the safe and efficient delivery of natural gas from source points to demand points. Natural gas pipelines are constructed of carbon steel, varying in size from 2 to 60 inches in diameter depending on type. Gas is compressed to provide for efficient flow.

The ability to transport natural gas from production regions to consumption regions also affects the availability of supplies to the marketplace. The current pipeline infrastructure as illustrated in Figure 14-8 has a daily delivery capacity of 119 billion cubic feet (bcf).[15] It is expected that a growing industrial and residential demand may necessitate the expansion of the national pipeline infrastructure.

Traditionally, natural gas has been a seasonal fuel due to the high demand for residential and commercial heat in the winter. Natural gas storage is essential to balance between demand cycles. Underground storage is usually in large reservoirs such as depleted gas reservoirs, aquifers, and salt caverns. Above-ground storage is lower volume and comprised primarily of peaking LNG facilities or excess pipeline fill.

Distribution

The distribution of CNG or LNG is the most visible phase of the supply chain. CNG is produced on demand by conventional multi-stage compression equipment at CNG stations that are connected to natural gas transmission or distribution systems. A nominal amount of CNG is stored on-site to help facilitate the pressure transfer of fuel from the station to the vehicle but in general the natural gas distribution system is the buffer capacity for a CNG network.

In comparison, LNG can be manufactured using mature cryogenic technology. Since the 1950s, utility companies have been manufacturing and storing LNG to ensure they have adequate supplies of natural gas to supply their peak demand. There are 59 LNG peaking facilities in the lower-48 states that manufacture and transfer LNG to substations.[16] These small scale liquefaction systems produce from 10,000 to 500,000 gallons per day with the economies of scale favoring the larger plants. This production capacity is smaller than world scale facilities that liquefy and ship LNG between international markets.

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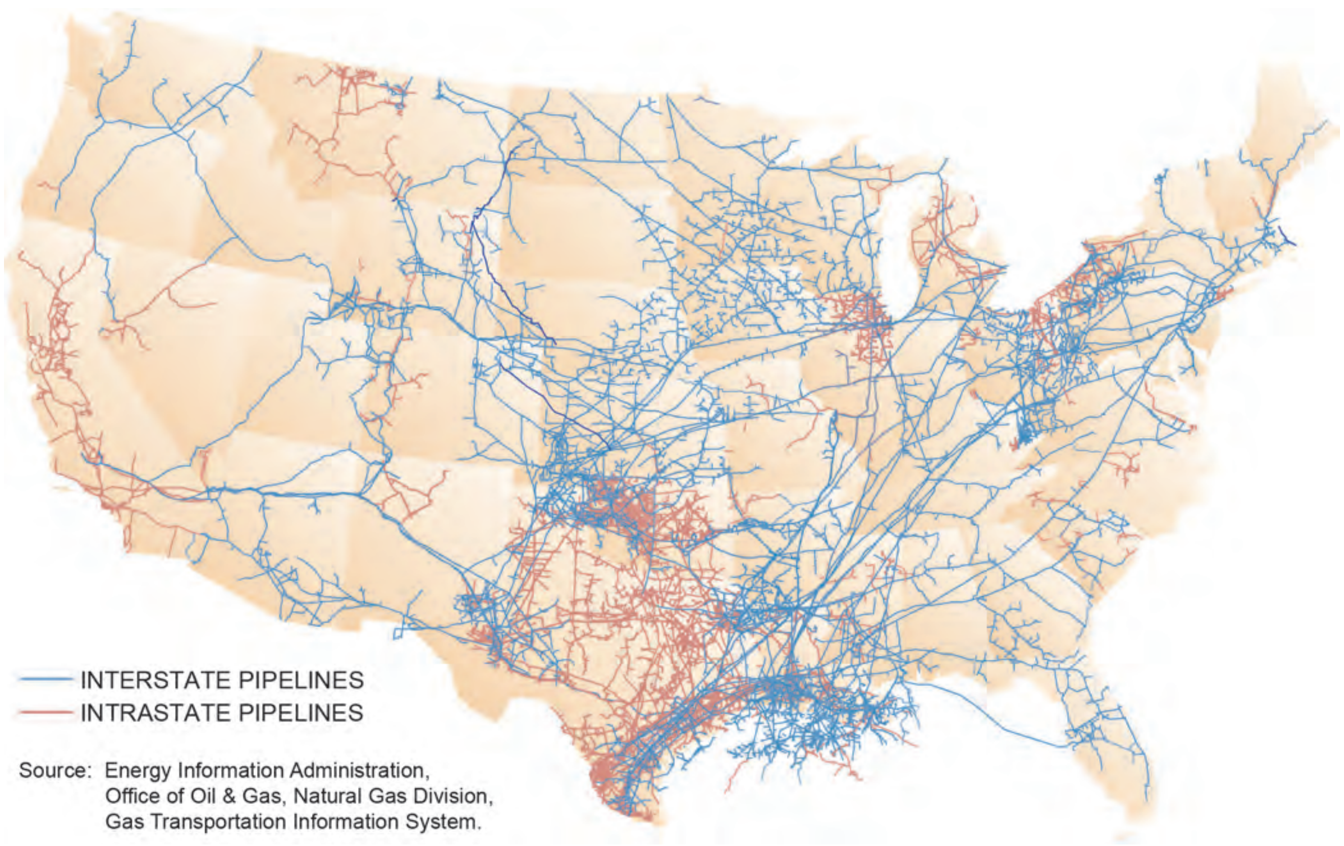
[13] Ibid.

[14] BP Statistical Review, Slide 54 in "BP Energy Outlook 2030," Powerpoint presentation, London, January 2011, http://www.bp.com/liveassets/bp_internet/spain/STAGING/home_assets/downloads_pdfs/e/energy_outlook_2030.pdf.

[15] U.S. Energy Information Administration (website), "Natural Gas: About U.S. Natural Gas Pipelines – Transporting Natural Gas (based on data through 2007/2008): *Underground Natural Gas Storage*," accessed November 10, 2011, http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/undrgrnd_storage.html.

[16] U.S. Energy Information Administration (website), "Natural Gas: About U.S. Natural Gas Pipelines – Transporting Natural Gas (based on data through 2007/2008): *U.S. LNG Peak Shaving and Import Facilities, 2008*," http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/lngpeakshaving_map.html.



Source: Energy Information Administration, Office of Oil & Gas, Natural Gas Division, Gas Transportation Information System.

Figure 14-8. *U.S. Natural Gas Pipeline Infrastructure*

There are approximately 500 trucks distributing LNG through specific cryogenic tank trailers. Major LNG tanker firms move the product for two markets: peak shaving facilities in the Northeast and the HD transportation market in the Southwest.[17] The economics of LNG distribution have a disadvantage over diesel as typical trailers carry 10,000 gallons of LNG or 6,700 diesel equivalent gallons (DEG) compared to 9,000 gallons of diesel. Other countries where the downstream LNG market has been further developed have adopted methods to transport LNG such as rail or intermodal LNG tanks that can be transported and dropped at the market location.

Dispensing Technology

Station designs vary depending on whether they are configured to dispense CNG, LNG, or a combination of both fuels.

CNG stations are designed to accept incoming fuel from the distribution system, and then compress that incoming gas to the dispensing pressures of approximately 3,600 pounds per square inch (psi). On-site equipment typically includes dryers to remove moisture from the natural gas, multistage compressors to boost natural gas from distribution/transmission pressures to 4,500 to 5,000 psi, high-pressure storage cylinders to act as pressure buffers for pressure filling vehicles, and dispensers to transfer fuel to vehicles. CNG is pressure transferred from storage to the lower pressure of the vehicle, which is typically 3,600 psi at full fill. Incremental land requirements for CNG stations are minimal when compared to gasoline stations since large volumes of fuel are not required to be stored due to the interconnection with the distribution system.

Provision of CNG could be through new build dedicated stations, or via the addition of new technology encompassing modular CNG dispensing units that can be added incrementally to existing gasoline

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[17] Zeus Energy Library, *LNG Downstream Distribution Growing at Twice the Pace of World Trade,* White Paper Report, Houston, Texas, December 9, 2010, http://archive.zeuslibrary.com/DLMD2011/white-paper.asp.

station islands (see Figure 14-9), provided access to the gas distribution system is available. Further development of this technology to reduce cost and footprint will allow the expansion of CNG into the existing retail gasoline station network. Recent announcements by a major gasoline retailer include a CNG island in their gas stations of the future.[18]

With approximately 56% of U.S. homes having access to natural gas, home refueling systems could be an option for increasing fuel availability to the retail consumer LD market via the domestic gas supply.[19] Home refueling systems have been available since 1989 but a sustainable industry to provide this service has not yet developed, due in part to the challenging economics of current technology. In home refueling units, a wall or floor mounted unit takes domestic pipeline gas and compresses it to dispensing pressure required for the vehicle. Because of the low incoming feed pressure and the capacity of compressors, dispensing rates are typically low, between 0.5 and 1 gallon gasoline equivalent (GGE) per hour. As a result, refueling is intended to take place primarily overnight, giving the typical consumer enough fuel for the average vehicle's daily travel, which is approximately 32.7 miles.[20] This approach may work well for bi-fuel LD vehicles which do not need to provide full driving range on CNG, having a secondary gasoline

Figure 14-9. *Modular CNG Dispensing Unit*

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[18] Geoffrey Styles, "The Future Energy Station Arrives," Energy Outlook blog, May 3, 2011, http://energyoutlook.blogspot.com/2011/05/future-energy-station-arrives.html.

[19] NaturalGas.org (website), "Residential Uses," http://www.naturalgas.org/overview/uses_residential.asp.

[20] M. Rood Werpy et al., *Natural Gas Vehicles: Status, Barriers, and Opportunities,* ANL/ESD/10-4, Argonne National Laboratory, August 2010, http://www.afdc.energy.gov/afdc/pdfs/anl_esd_10-4.pdf.

fuel tank. Systems retail at approximately $3,000–$4,000, with an installation fee of $1,000–$2,000.[21] Federal income tax credits are currently available to partially offset these costs. Many states and air quality districts offer incentives, and some utilities offer preferential gas rates to home refueling customers.

Although customers have access to residential rates of gas for use in vehicles, the amortized cost of home refueling systems and their maintenance may result in a total cost of dispensed fuel higher than gasoline equivalent cost. Reductions in home refueling system costs may be attainable, particularly if dispensing pressures could be reduced. Current CNG fuel systems operate at a rated pressure of 3,600 psi, and filling to a lower pressure results in reduced fuel energy stored and lower vehicle range. Advancements in fuel storage systems, such as metal organic frameworks that allow high density gas storage at low pressure could be an enabler of more cost effective home refueling systems.

LNG stations are more analogous to diesel fuel stations. The fuel is stored in an insulated tank generally 15,000 gallons or larger. A tank of this size allows for a full tanker load of LNG to be delivered at one time. Stations can have much greater fuel storage on hand depending upon the fueling requirements of the station and local permitting regulations. A cryogenic pump transfers fuel from the storage tank to the fuel dispenser and into the vehicle. (See Figure 14-10 for a typical LNG station configuration.)

The smallest LNG station, which consists of one storage tank and one dispenser, costs approximately $1 million or about the same as a commercial CNG

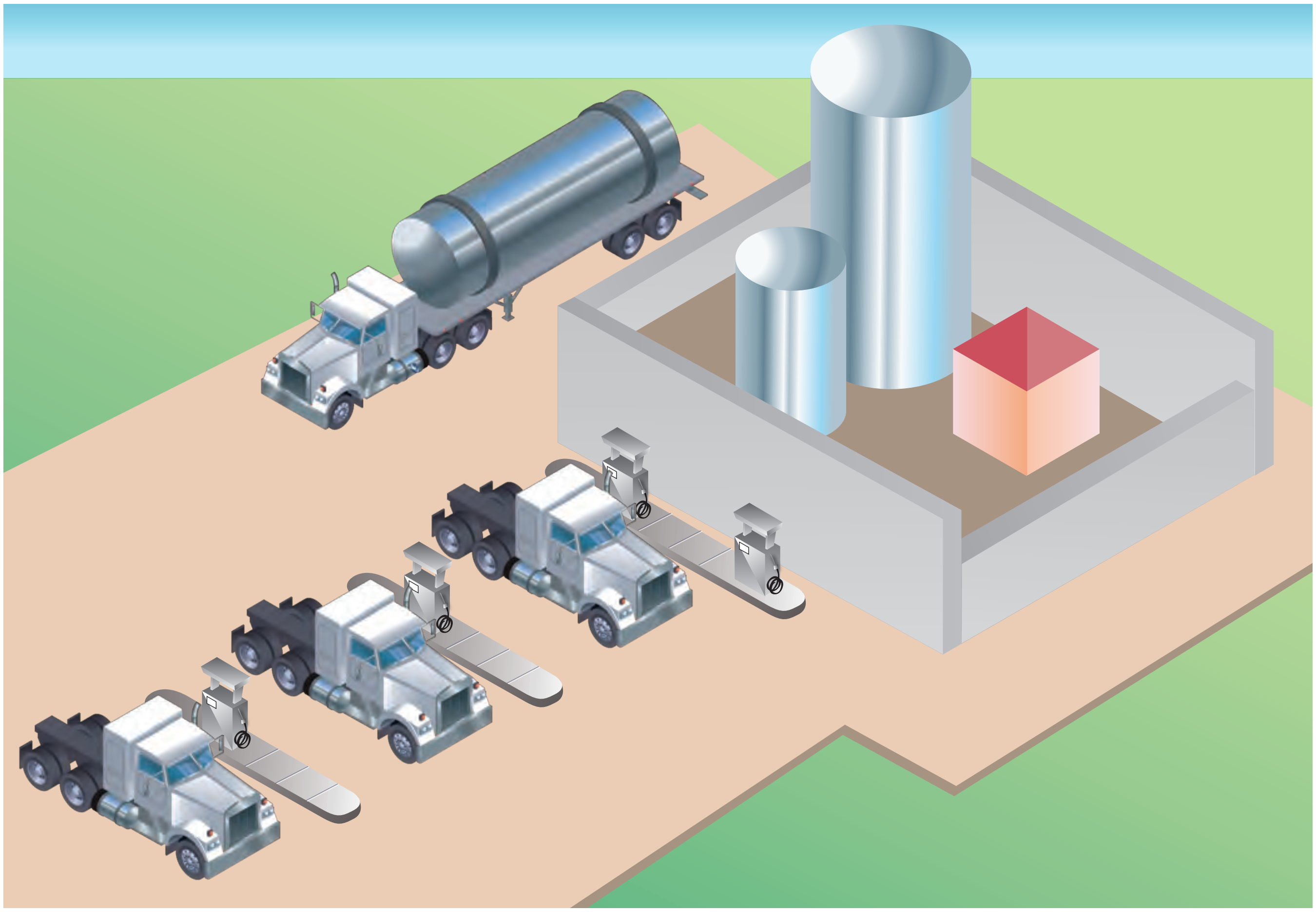

Figure 14-10. *Typical LNG Station Configuration*

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[21] BRC FuelMaker (website), Phill Product Information: "Fill up your CNG car right at home!" accessed February 20, 2012, http://www.brcfuelmaker.it/eng/casa/phill.asp?click=no.

fuel station.[22] Larger LNG stations could cost up to five times that amount but offer much better scale of efficiency.

Station operators can provide both LNG and CNG through a liquefied compressed natural gas (LCNG) configuration. An LCNG station that stores LNG but also dispenses CNG is an economical way to increase LNG throughput and satisfy latent CNG demand without the cost of CNG compression. CNG is produced by decanting some of the LNG from storage at higher pressures. This type of facility is very efficient in dispensing CNG and improves the scale of existing LNG operations. LCNG also provides CNG to areas that are not served by a traditional gas line. Depending on the regional nature of the service station, LCNG can be an effective transition to the use of natural gas for transportation.

Fuel Economics

Natural gas transportation fuel costs are comprised of feedstock expense, and capital and operating expenses within the value chain described above, as well as taxes. CNG and LNG fuels are treated separately due the differing market requirements associated with LD and HD markets.

CNG Fuel Economics for Light-Duty Market

The methodology used to estimate CNG fuel costs for the LD market is shown in Figure 14-11. Many of the inputs were developed during discussions with a number of fuel companies.[23]

Feedstock costs were based on Industrial Gas prices, taken from the AEO2010 through to 2035 and extrapolated to 2050. Fees for connecting to the distribution system and for metering were estimated, based approximately on utility tariff rates.[24]

Capital costs were modeled through two pathways: (1) dedicated new high capacity CNG stations and (2) modular upgrades to existing retail gasoline sites. To be consistent with methodologies used for other fuel streams, capital costs were amortized over a 20-year life with an assumed 10% weighted average cost of capital. Acknowledging the uncertainty in how the infrastructure could ultimately be developed, a simplifying assumption was made that 60% of fuel dispensed would be via dedicated high capacity CNG stations.

For new dedicated stations, station capital was assumed to be $1.5 million for a designed dispensing capacity of 1.25 million GGE per year, scaled down to 80% utilization of 1 million GGE per year. CNG compression is one of the largest cost elements for larger stations and is generally rated by SCFM (standard cubic feet per minute) of compressor capacity. A gasoline equivalent gallon (GGE) of CNG is about 125 standard cubic feet of natural gas based on higher heating value. Current gas stations pump gasoline at 5–10 gallons per minute (gpm), which is equivalent to a natural gas delivery rate of 625–1,250 SCFM.[25] Compressor stations with 500–2,000 SCFM of compressor capacity (4.0–15.8 GGE per minute) can be installed for an estimated cost of $600,000.[26] Land estimates were included assuming a 0.5 acre lot and $2 million per acre although it is acknowledged that regional land costs may vary significantly. For dedicated stations, the amortized cost of capital was $0.29 per GGE. Variable costs covering operation and maintenance, electricity costs (1 kilowatt-hour per GGE at $0.10 per kilowatt-hour) and margin were included for a total of $0.32 to $0.40 per GGE.

Modular dispensing system costs were estimated at $400,000 with no land requirement. Because of the lower dispensing capacity of these systems (approximately 100,000 GGE per year), the amortized cost of capital and variable costs is much higher on GGE basis than dedicated high capacity stations.

Currently CNG is taxed on an energy basis of 126.67 cubic feet (1.0 GGE) at rate of 18.3¢ by the Internal Revenue Service. In comparison, gasoline is taxed at 18.4¢ per gallon for highway use.[27] Local taxes can vary by state. In California, CNG is taxed at 10.5¢ per GGE and gasoline is 35.3¢ per gallon

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[22] California Energy Commission, *California Alternative Fuels Market Assessment 2006,* Report # CEC-600-2006-105-D, prepared by TIAX LLC, October 2006, http://www.energy.ca.gov/2006publications/CEC-600-2006-015/CEC-600-2006-015-D.PDF.

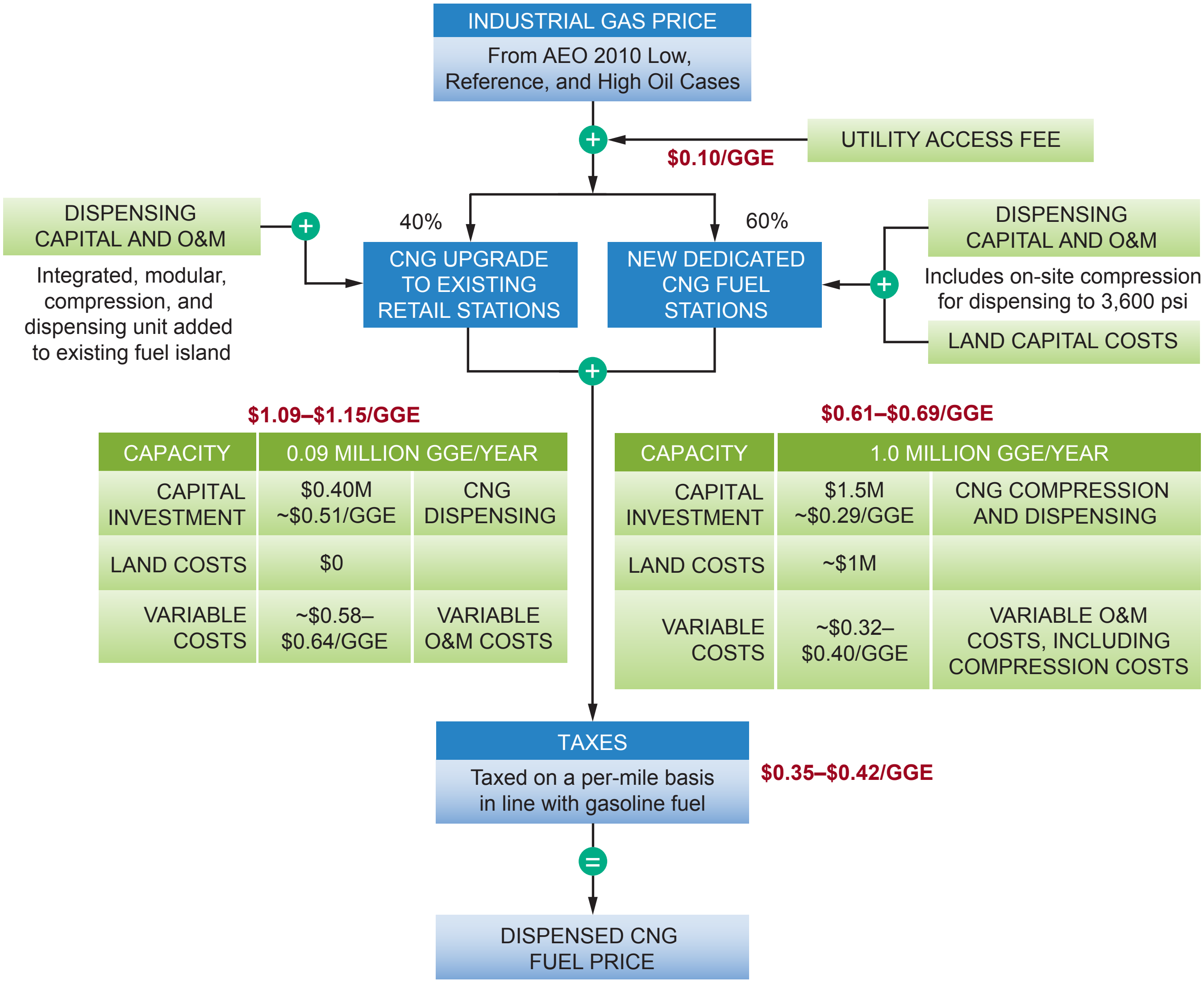
[23] Discussions with Clean Energy Fuels, Chevron, and Exxon Mobil.

[24] Southern California Gas Company (website), "Rate Schedules," accessed 2012, http://www.socalgas.com/regulatory/tariffs/tariffs-rates.shtml.

[25] An average rate is usually eight gallons per minute.

[26] G. A. Whyatt, *Issues Affecting the Adoption of Natural Gas Fuel in Light- and Heavy-Duty Vehicles,* PNNL-19745, Pacific Northwest National Laboratory, September 2010.

[27] U.S. Internal Revenue Service, "Quarterly Federal Excise Tax Return," IRS Form #720, Rev. January 2012, OMB No. 1545-0023, http://www.irs.gov/pub/irs-pdf/f720.pdf.



CNG PRICE	2010	2015	2025	2035	2050
LOW OIL PRICE CASE ($/GGE)	$1.92	$2.04	$2.16	$2.29	$2.71
REFERENCE CASE ($/GGE)	$1.92	$2.12	$2.17	$2.38	$2.82
HIGH OIL PRICE CASE ($/GGE)	$1.92	$2.19	$2.23	$2.47	$3.05

Figure 14-11. *CNG Fuel Economics for Light-Duty Market*

(effective July 1, 2010). For the purposes of this analysis, federal and state tax rates taken from the AEO2010, for a total tax rate of $0.35 to $0.42 per GGE.

Natural Gas Fuel Economics for Heavy-Duty Market

The methodology used to estimate LNG fuel costs for the LD market is shown in Figure 14-12. Fuel for the HD market was modeled primarily as LNG derived from LCNG stations capable of dispensing 3.9 million GGE per year. In addition, each station was assumed to have up to 400,000 GGE per year dispensing capacity of CNG.[28]

Feedstock prices were taken from the AEO2010 Industrial Gas price estimates. The first step in the supply chain is a dedicated liquefaction plant with

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[28] Discussions with Clean Energy Fuels, Chevron, and Exxon Mobil also provided context for this analysis.

transmission and distribution connection charges based on utility tariffs for larger consumption customers. Capital for liquefaction and dispensing was again assumed to have a 20-year life at a 10% weighted average cost of capital. Liquefaction costs were assumed to be $70 million for a 180,000 LNG gallon per day facility operating at 80% capacity, equal to $0.25 per GGE.[29] Liquefaction costs were estimated based on electric costs of 1.25 kilowatt-hours per gallon and $0.10 per kilowatt-hour ($0.19 per GGE) plus a further $0.06 per GGE of operating costs.

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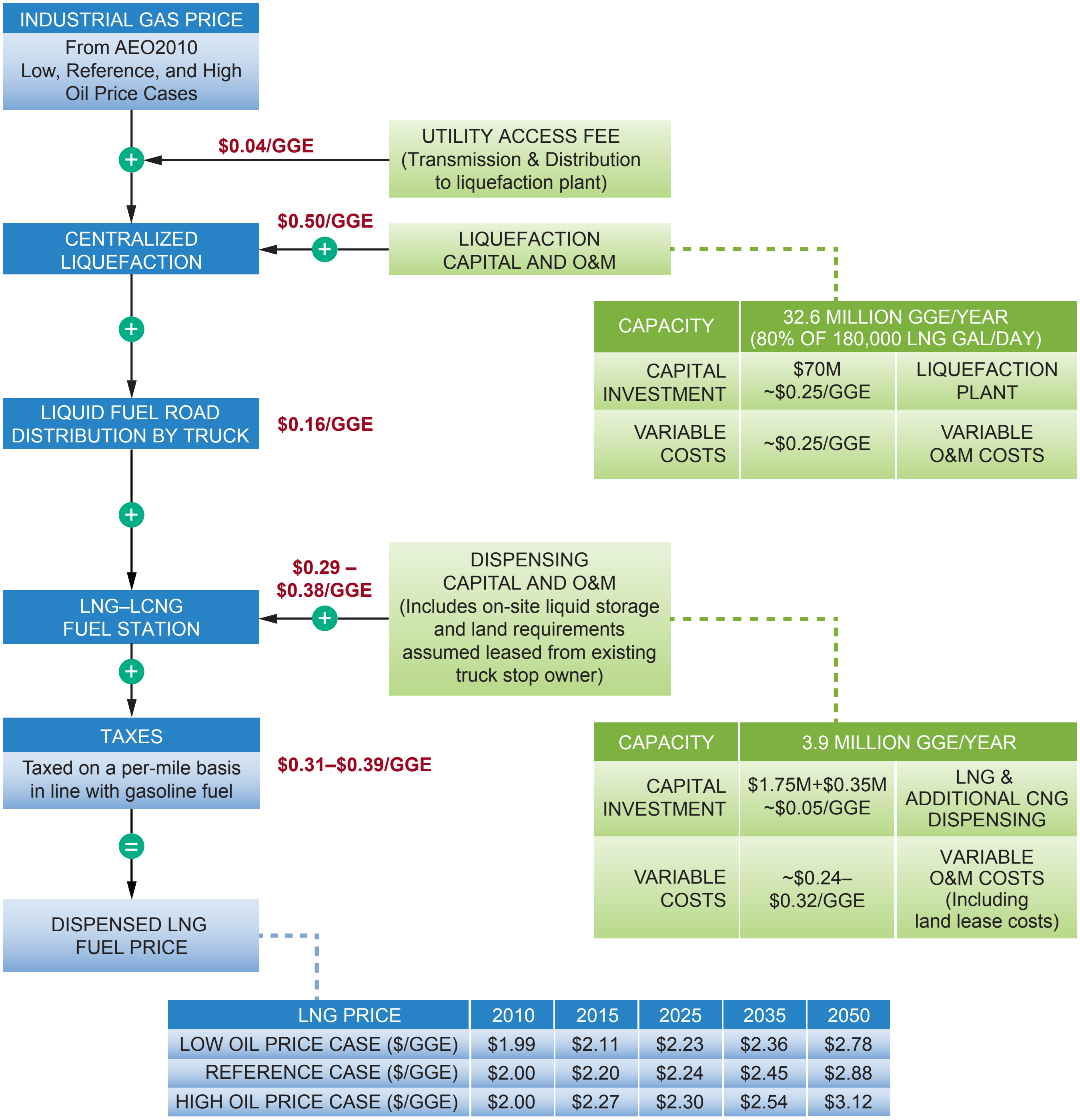
[29] Information provided by Clean Energy Fuels for their liquefaction plant at Boron, California.



CAPACITY	32.6 MILLION GGE/YEAR (80% OF 180,000 LNG GAL/DAY)	
CAPITAL INVESTMENT	$70M ~$0.25/GGE	LIQUEFACTION PLANT
VARIABLE COSTS	~$0.25/GGE	VARIABLE O&M COSTS

CAPACITY	3.9 MILLION GGE/YEAR	
CAPITAL INVESTMENT	$1.75M+$0.35M ~$0.05/GGE	LNG & ADDITIONAL CNG DISPENSING
VARIABLE COSTS	~$0.24–$0.32/GGE	VARIABLE O&M COSTS (Including land lease costs)

LNG PRICE	2010	2015	2025	2035	2050
LOW OIL PRICE CASE ($/GGE)	$1.99	$2.11	$2.23	$2.36	$2.78
REFERENCE CASE ($/GGE)	$2.00	$2.20	$2.24	$2.45	$2.88
HIGH OIL PRICE CASE ($/GGE)	$2.00	$2.27	$2.30	$2.54	$3.12

Figure 14-12. *LNG Fuel Economics For Heavy-Duty Markets*

Fuel distribution from the liquefaction plant to the station was assumed to be by road, in 10,000 gallon bulk haul tanker trucks on a 300-mile round trip. According to the California Alternative Fuels Assessment of 2006, these transportation costs are approximately $0.0004 per LNG mile. Converting units derives an estimate of $0.16 per GGE delivered.

Station capital costs were assumed to be $0.45 per GGE, operating at 80% utilization ($1.75 million total cost), with a further $350,000 for CNG dispensing. Because of the high dispensing capacity, the amortized cost of capital is low at just $0.05 per GGE if the station utilization is high.

Land costs were again assumed to be $0.5 million per acre for a three acre lot. These costs were not included as a capital item, but considered a variable cost since the business model assumed that stations would primarily be deployed at either fleet owned depots or existing truck stop facilities, and the land would be leased to the station developer.

In the current market, LNG is taxed by volume not by energy content. Federal tax on LNG is 24.3¢ per LNG gallon and the federal tax on diesel is 24.4¢ per gallon. Since LNG is taxed on a volumetric basis, LNG is taxed at a substantially higher rate than diesel. On an energy basis, one gallon of diesel is taxed at 24.4¢ and LNG is taxed at 41.3¢ per DEG. This is a 70% premium over conventional diesel. Similar treatments apply by state. Since the NPC was considering many new fuels and powertrains, with differing fuel energy contents and vehicle efficiencies, taxation was treated on a per-mile-equivalent basis to either gasoline or diesel, and hence in the treatment of LNG taxes were applied on an equal basis to diesel.

Using the assumptions illustrated in the models above, cost estimates were generated for CNG and LNG, using Industrial Gas prices from the AEO2010 Low, Reference, and High Oil Price Cases. These are illustrated in Figures 14-13, 14-14, and 14-15 and compared to AEO-based estimates of gasoline and diesel.

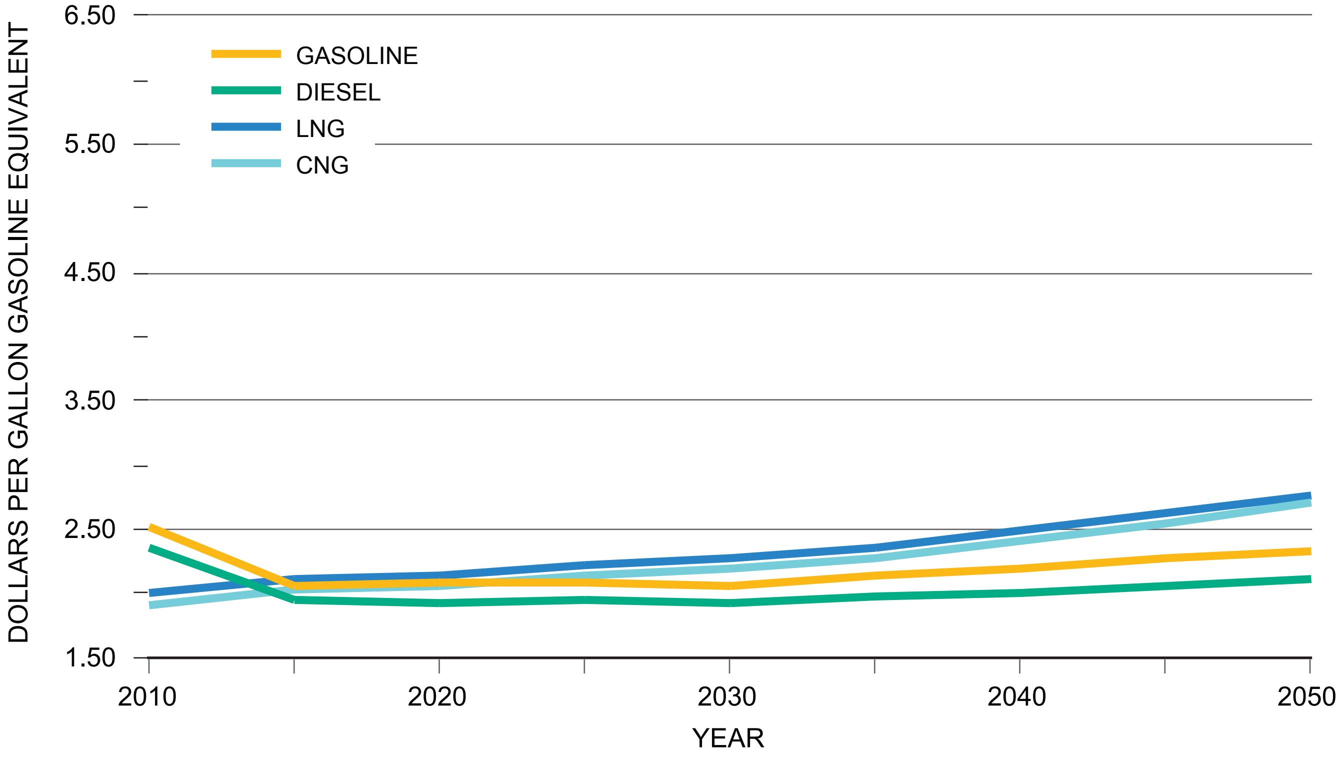


Figure 14-13. Estimated CNG and LNG Fuel Costs, Compared to Gasoline and Diesel in AEO2010 Low Oil Price Case

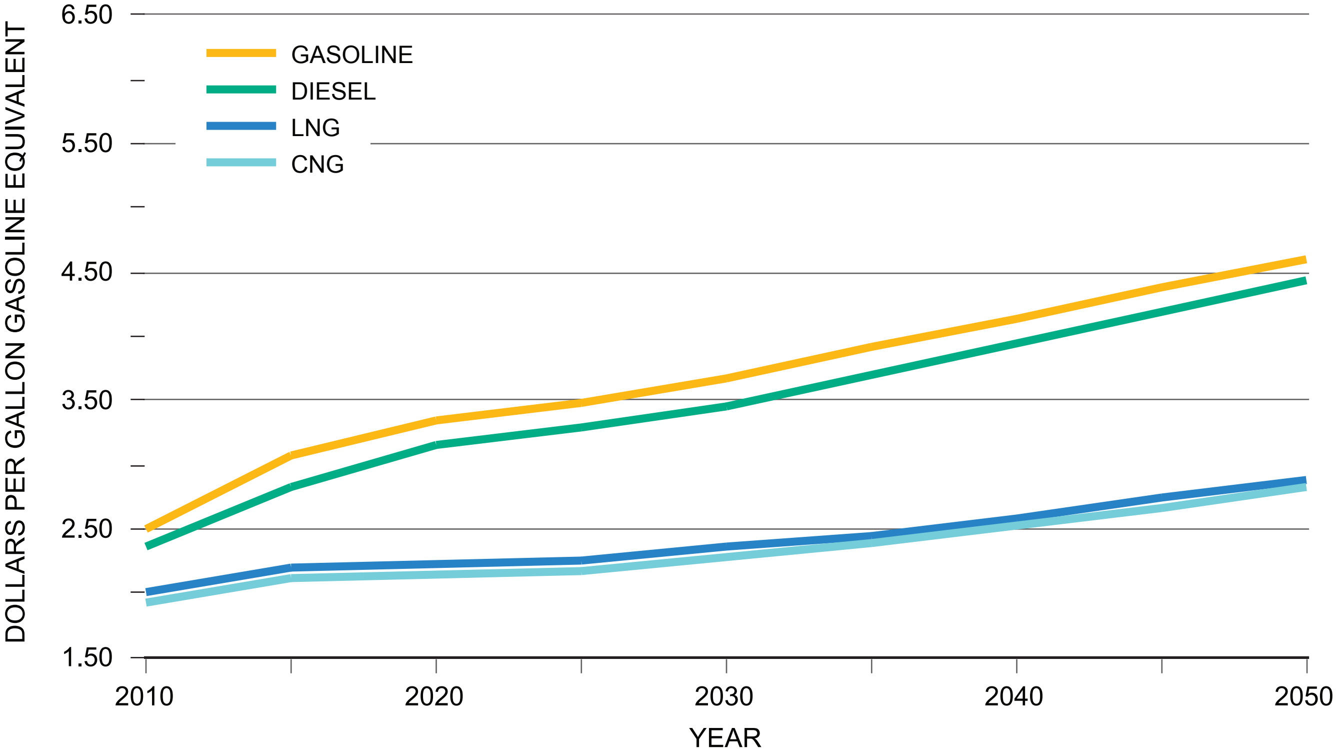


Figure 14-14. *Estimated CNG and LNG Fuel Costs,*
Compared to Gasoline and Diesel in AEO2010 Reference Oil Price Case

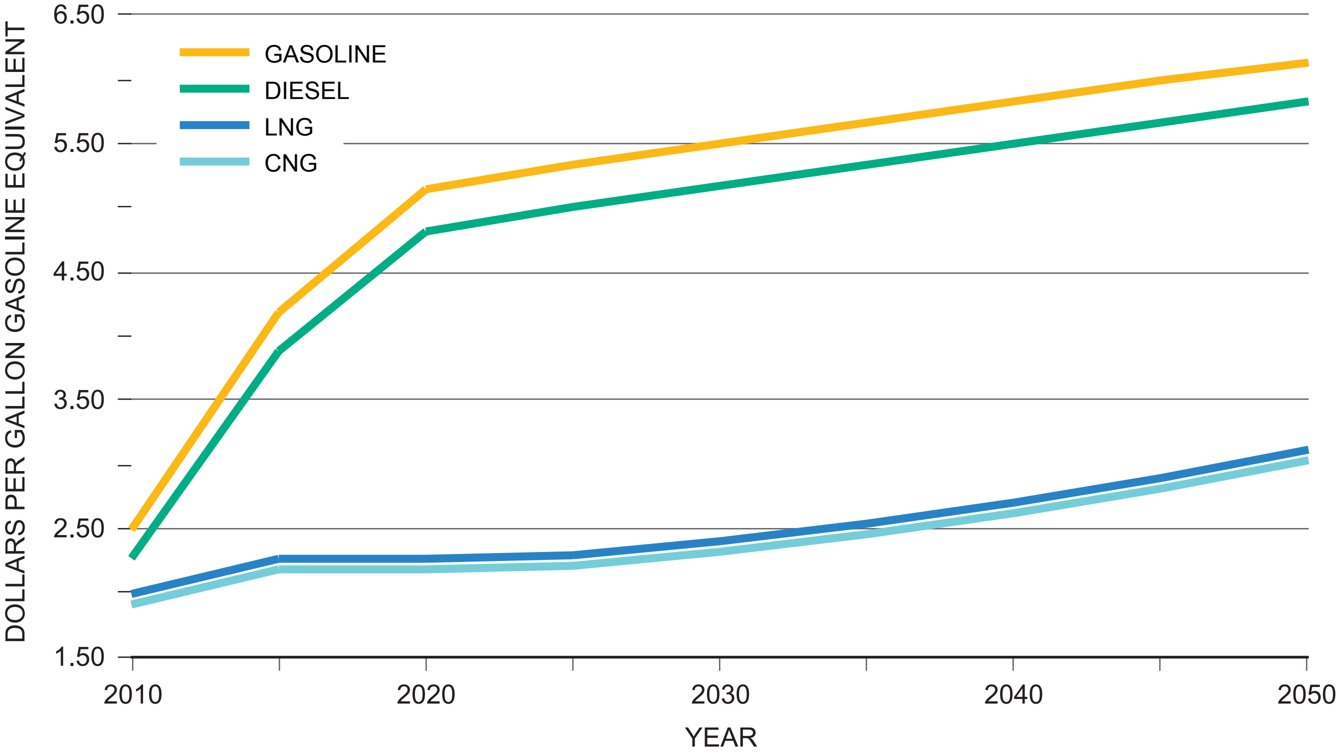


Figure 14-15. *Estimated CNG and LNG Fuel Costs,*
Compared to Gasoline and Diesel in AEO2010 High Oil Price Case

Based on the cost buildup, natural gas fuel prices become divergent from gasoline and diesel fuels, particularly in the Reference and High Oil Price Cases, due to the relatively low sustained price estimates for natural gas within the AEO2010. These fuel price differentials, if realized on a long-term basis, would provide a strong economic foundation for both LD and HD NGVs.

Considerations for Fueling Infrastructure

Although dispensing technology exists, building sufficient infrastructure to support a wide-scale, geographically disperse fleet of NGVs will be a significant economic challenge. The use of natural gas for transportation has expanded by increasing the number of stations and vehicles simultaneously to offer significant fuel cost savings to customers and a return on investment to the station developer. In many cases, the station developer has been a local gas distribution company or public utilities commission. As with other fuels, the key to natural gas deployment lies in identifying high concentrations of potential customers to build scale. These initial fleets allow the station to "base load" to cover fixed costs, and additional vehicles provide incremental throughput. Timing is important as developers must install stations to match the potential buying commitments of customers with new NGVs. To date, the demand from individual passenger vehicles has played only a minor role in supporting individual natural gas stations, particularly in the LD market.

The characteristics of HD and LD markets are different in terms of scale, fuel use by vehicle, and predictability of refueling events and locations. These differences can provide insights into the complexity of, and possible strategies for, infrastructure provision. Figure 14-16 illustrates how the challenge presented by infrastructure may increase as target markets expand from tethered urban fleets to a wide-scale fully fledged LD retail market.

Heavy-Duty Market Infrastructure – CNG and LNG

CNG and LNG refueling for HD trucks will likely be deployed similar to the way diesel fuel is currently dispensed through large truck fueling stations or at truck depots for individual fleets. Truck stops with LCNG systems may also be able to provide CNG fueling for LD vehicles, particularly private LD fleets, providing a possible bridging strategy between markets.

There are less than 10,000 truck stops across the nation providing diesel fuel to the HD truck fleet. These truck stops sell approximately 32 billion gallons of diesel for on-road HD trucks.[30] If 20 to 30% of these stations represent a minimum threshold for fuel availability, between 2,000 and 3,000 stations could eventually be needed to provide widely available fuel for a broad market share of natural gas trucks. These stations are expected to be a mix of private stations located at large fleet depots, supporting return-to-base or point-to-point regional trucking operations, and public access stations serving major freight corridors shown in Figure 14-17. Of fleets with six or more trucks, more than 40% of the vehicles are fueled at private, on-site stations.[31] These larger fleets may represent an early

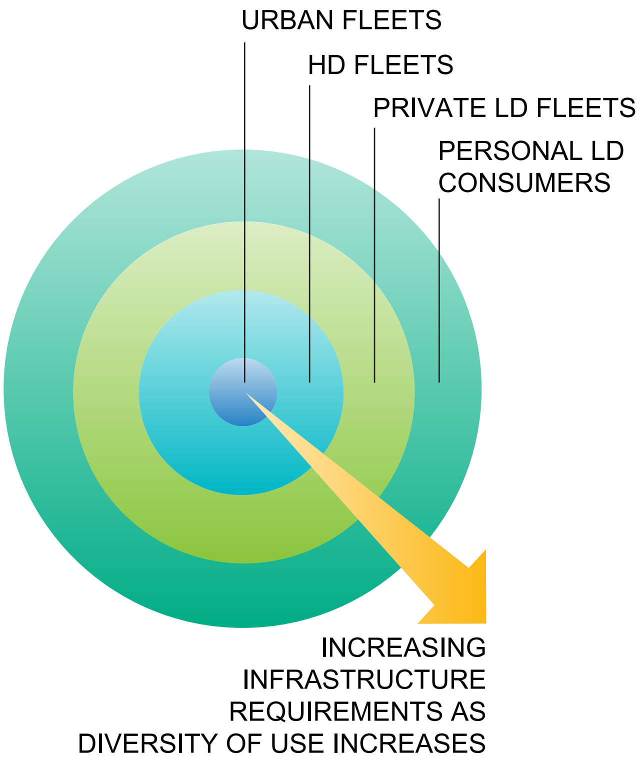


***Figure 14-16.** Infrastructure Challenge Increases with Market Expansion*

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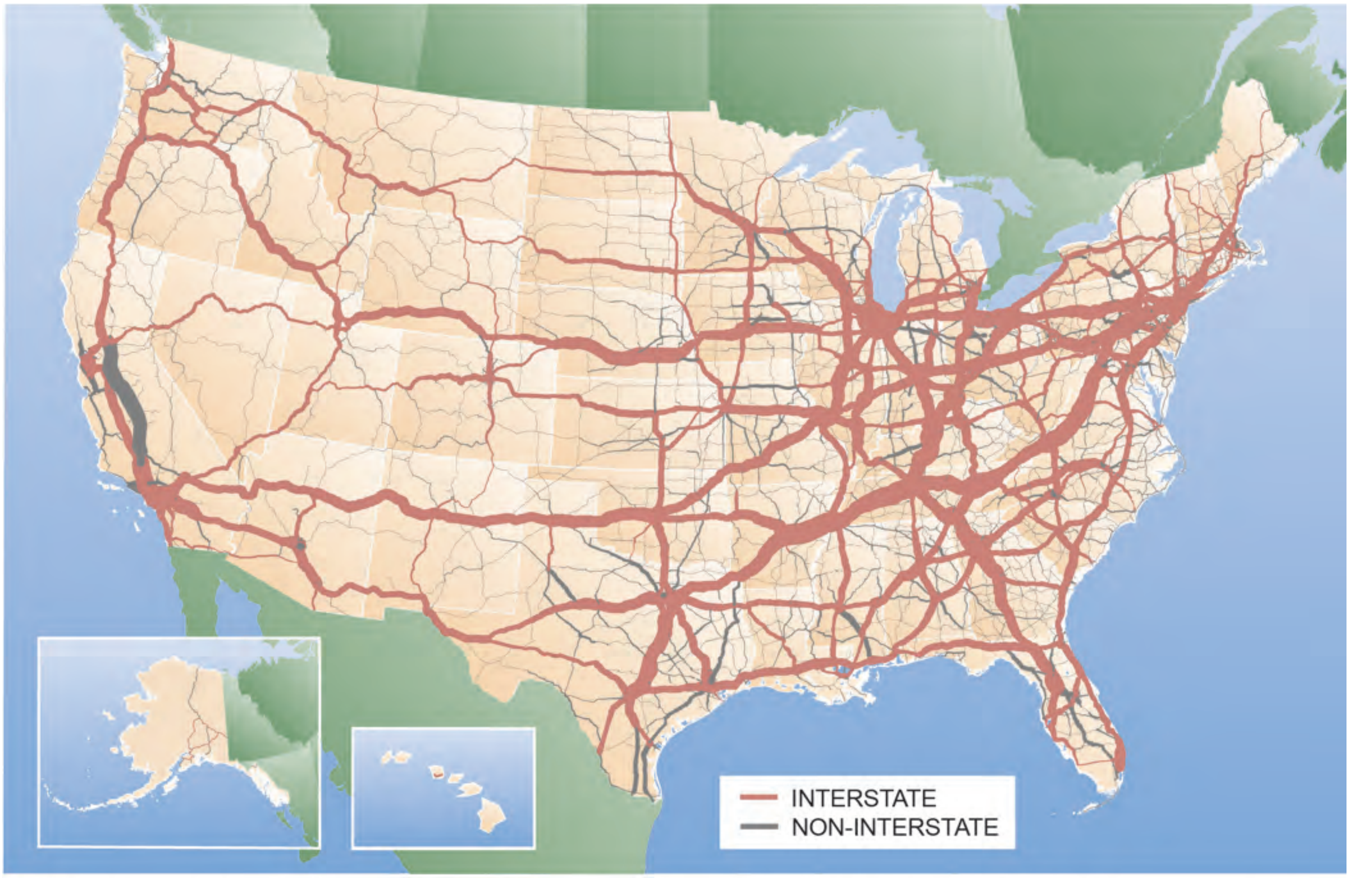
[30] The AEO2010 estimates that 40 billion gallons of diesel fuel is consumed in the United States.

[31] U.S. Department of Energy, Chapter 5 in *Transportation Energy Data Book: Edition 30,* June 2011, http://cta.ornl.gov/data/tedb30/Edition30_Full_Doc.pdf.



Note: Long-haul freight trucks typically serve locations at least 50 miles apart, excluding trucks that are used in movements by multiple modes and mail.

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

Figure 14-17. *Major Heavy-Duty Freight Corridors Could Support Fuel Infrastructure Growth*

adopter market where fueling infrastructure can be installed and sized in accordance with expected fuel use, resulting in well-utilized capital assets. Public access stations are likely to be co-located with existing truck stops, built with initial dispensing capacity to support transitional markets with capacity expansion capability as demand for natural gas fuel increases.

LNG liquefaction capacity is also required to support HD fueling. This may initially be provided by existing liquefaction plants serving peak shaving and export facilities. In the future, liquefaction capacity could require new medium-scale LNG production facilities located within 150–300 miles of the market to minimize transportation costs for the fuel.

Total capital requirements to provide 2,000 to 3,000 fuel stations could be between $10 and $20 billion. Additional capital of $20 to $60 billion may also be required if all fuel demand was to be satisfied by new liquefaction capacity.

Light-Duty Market Infrastructure – CNG

Initial customers for LD NGVs are more likely to be fleets such as taxis, utilities, and private corporations where annual mileage and fuel use may be higher than typical personal vehicle use. Infrastructure for these customers may be established at central locations, or within constrained operational boundaries.

To serve a wide-scale retail market, in the absence of home fueling, a significant portion of the existing retail gasoline infrastructure may either need to be replicated, or at least be supplemented with CNG fuel availability at existing sites.

There are three primary approaches that have been used to evaluate the future distribution requirements for alternative fueling stations to support the overall growth of the market. One approach states this growth as a percentage of existing gasoline fueling stations, with common range of market penetration targets between 10 and 30% of the existing 160,000 service stations. Another approach recommends an optimal ratio of stations to vehicles to be achieved in the market. A natural gas vehicle-to-refueling-station ratio of one refueling station to every thousand NGVs is calculated to maximize both convenience to the customer and efficiency and profitability to the service station operator. Finally, plotting station capacity by metropolitan statistical areas accounts for the scale service stations achieve in more densely populated areas. Each method offers perspective on market growth that will be required for NGV infrastructure development.[32]

If 30% of the existing gasoline infrastructure represents a metric for wide-scale CNG availability for LD markets, total capital requirements could be substantial, in the range of $100 to $200 billion.

The AEO2010 projected growth in total vehicle miles traveled of almost 50%. Depending on fuel economy improvements and vehicle stock growth, additional service stations may be required if the existing stations cannot substantially improve in efficiency or offer diversity of product to serve a growing customer base.

Carbon Intensity of Natural Gas as a Transportation Fuel

Methane, the major constituent of natural gas, is a greenhouse gas (GHG) with a potency of approximately 21 times greater than carbon dioxide.[33] With a carbon to hydrogen ratio of just 1:4, natural gas has the lowest carbon content of fossil fuels used in transportation. The full well-to-wheels analysis for NGVs must include different feedstock sources, whether the fuel is supplied as CNG or LNG, the combustion cycle of the vehicle, and what equivalent fuel and engine technology it is being compared against.

Natural gas contributes to a low GHG profile compared to gasoline, diesel, and other fuels if the full fuel supply chain limits the unintended release of methane and it is used in vehicles with high combustion and high fuel efficiency.

The domestic natural gas fuel supply chain has the potential for gas losses through the production, processing, transmission, storage, and distribution segments of the industry. While natural gas has a favorable environmental profile with respect to other fossil energy sources, GHG emissions associated with the natural gas supply chain raises potential issues. The NPC's 2011 *Prudent Development* study offers a comparative analysis of current life cycle studies for natural gas.

Fueling station design and the proper operation of stations and vehicles to minimize losses to atmosphere are critical to maintain the economic and environmental benefits of natural gas. Venting from LNG vehicles and fueling stations is due primarily to the fact that LNG must be maintained at cryogenic temperatures in order to stay in a liquid phase. To mitigate venting, the station should be designed and operated so that no vapor is released to atmosphere or that any excess vapor is recovered and used.[34,35] It is not economically feasible to install equipment to recover and re-liquefy boil-off vapors, so the fuel has to be used within two weeks. In stations with high utilization rates, however, the very act of refilling the storage tanks can have the effect of re-condensing methane in the gas state, thereby improving the pressure-time characteristics of storage. Additionally, for stations with mixed dispensing of both LNG and CNG, any boil-off methane could be captured and injected into the CNG distribution intake stream. For stations that use fuel predictably, this boil-off is not an issue but its widespread acceptance is challenging. It is important to note that at larger scales such as LNG use in marine or shipping/receiving terminals, boil-off is

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[32] Sonia Yeh, "An empirical analysis on the adoption of alternative fuel vehicles: The case of natural gas vehicles," *Energy Policy* 35, no. 11 (November 2007): pages 5865-5875, http://escholarship.org/uc/item/2k09h787.

[33] Methane's relatively short atmospheric lifetime of 12 years, coupled with its potency as a greenhouse gas makes it a candidate for global warming over the near term (i.e., 25 years). See http://www.epa.gov/methane/scientific.html.

[34] Charles Powars, "Best Practices to Avoid LNG Fueling Station Venting Losses," report prepared for Brookhaven National Laboratory, June 2010.

[35] The GREET default assumption for fueling station boil-off is 0.1% per day with 80% recovery, which is equivalent to 0.02% per day vapor venting. GREET documentation does not discuss specific assumptions regarding LNG fueling station boil-off recovery technologies.

not an issue as there are liquefaction systems that recover boil-off and either consume the gas or convert it back to LNG.

In LD applications, the literature references a 25% GHG emission reduction for NGVs when compared to conventional, spark-ignited, multi-point fuel injected gasoline engines. The range of quoted reductions spans from 7 to 30% for North American sourced CNG.[36] For HD vehicles, the comparisons to diesel engines must encompass both CNG and LNG and consider spark ignited and compression ignition engines.[37] The results vary depending on the natural gas engine technology being analyzed, but for North American sources of natural gas, the range spans from 11 to 29%.[38,39]

Hurdles for Natural Gas Infrastructure

The challenges facing natural gas infrastructure are primarily economic and logistical (see Figure 14-18). Both CNG and LNG have mature supply chain technologies although there are a number of opportunities for future technology enhancements and new developments. The hurdle analysis for natural gas supply and infrastructure indicates significant improvements required in three areas:

- Fuel station availability
- Home refueling
- Dispensing capital investment.

While current technologies can provide an adequate supply of fuel, there is opportunity to improve fueling speed and storage costs. Advances to compressor technology address both station availability and dispensing investment hurdles. Lube-less compressors allow for contaminant-free CNG at pressure. The use of standard-sized compressors coupled in series with booster compressors provides a lower cost method of utilizing local gas pressures though standardized equipment. The advent of "smart compressors" employing advanced electronics for monitoring and adjusting have improved reliability and reduced operating costs. Improved system integration and electronics enables compressors the option to "fast fill" by isolating compressor stages and injecting higher pressure standby gas. The continued development and cost reduction of small fit-for-purpose CNG "fuel island" modules allows for the gradual addition of CNG to conventional fueling stations. A promising technology that provides for CNG to areas without pipeline gas supply is LCNG technology.

Home refueling can also improve availability, but it currently lacks scale and efficiency. Breakthrough compression technology for home refueling could ease infrastructure transition issues for NGVs.

REGULATORY CONSIDERATIONS FOR NATURAL GAS VEHICLES

In order to understand the future of NGV development and deployment in the United States, a basic understanding of the regulatory framework for emissions and safety is needed.

Emissions Regulations and Certification

The current Environmental Protection Agency (EPA) regulations require companies that provide natural gas conversions of gasoline vehicles to obtain a Certificate of Conformity or an Executive Order from the California Air Resources Board (CARB) for the specific conversion kit/engine family for a specific model year.[40] Testing confirms that emissions standards are met. Once obtained, an aftermarket conversion may be performed on a vehicle that falls within the engine family covered by the Certificate. New applications must be submitted by the Certificate holder for each subsequent model year to allow conversion of future year vehicles.[41] Due to the complex nature of the certification process and

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[36] Alan Krupnick, *Energy, Greenhouse Gas and Economic Implication of Natural Gas Trucks,* Resources for the Future, June 2010, http://www.rff.org/rff/documents/rff-bck-krupnick-naturalgastrucks.pdf.

[37] The current literature considers spark ignited CNG engines, both stoichiometric and lean burn.

[38] Norman Brinkman et al., *Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems – A North American Study of Energy Use, Greenhouse Gas Emissions and Criteria Pollutant Emissions,* General Motors Corporation and Argonne National Laboratory, May 2005, http://www.transportation.anl.gov/pdfs/TA/339.pdf.

[39] California Air Resources Board, *Detailed California Modified GREET Pathway for CNG from North American Natural Gas,* California Environmental Protection Agency, Air Resources Board, Stationary Sources Division, report version 2.1, February 28, 2009, http://www.arb.ca.gov/fuels/lcfs/022709lcfs_lfg.pdf.

[40] This also ensures compliance with anti-tampering legislation.

[41] U.S. Environmental Protection Agency (website), "Alternative Fuel Conversion," Regulatory guidelines, updated February 1, 2012, http://www.epa.gov/oms/consumer/fuels/altfuels/altfuels.htm.

HURDLE	REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	RATING	COMMENTS
FUEL PRODUCTION:			
GAS RESOURCE AVAILABILITY	Sufficient resource to support large scale vehicle deployment and use	🔵	Sufficient reserves to supply in excess of 8 tcf added demand from North American sources
CENTRALIZED LIQUEFACTION	Large scale liquefaction capable of cost effectively supplying large vehicle fleets	🟡	Mature technology, but significant investment required to build scale capacity dedicated to vehicle fuel
DISTRIBUTED LIQUEFACTION	Localized, small scale liquefaction (<50,000 gal/day) providing LNG at fleet depots	🟡	Small scale liquefaction improves smaller fleet penetration. Solutions required to be cost effective at low output
RNG (BIO/GAS) FUEL	Efficient RNG feedstock collection systems for widescale, scalable production	🟡	Feasible for localized fleets. Approx 4.5 tcf supply potential but significant logistics to aggregate feedstocks. Thermal gasification required to maximize feedstock compatibility
FUEL QUALITY & COMPOSITION	No vehicle performance derate due to geographic or seasonal fuel quality variation	🔵	Need harmonized codes & standards for CH_4 content, impurities, etc., to ensure emissions, driveability and vehicle quality, reliability, and durability
FUEL DISTRIBUTION:			
PIPELINE CNG-FOSSIL	Uniform pipeline gas standards and incremental expansion to serve all markets	🔵	Existing pipe network enables access to most, but not all geographic markets. Expansion for use of NG in other industries should include provision for Transport demand
PIPELINE CNG-RNG	RNG must be fully fungible with pipeline gas system for mass market uptake	🟡	Need harmonized, consistent and achievable utility gas specifications for RNG injection to pipelines
LNG VIA TRUCK	Must add no insurmountable cost to dispensed fuel	🔵	Dedicated trailers required for cryogenic storage. Lower delivered energy per trailer load increases number of deliveries but cost can be accommodated in fuel price
LNG VIA RAIL	Broad availability of dedicated rail car use available for transportation and storage	🟡	Few dedicated rail cars. Could supplement truck transport but not market critical
FUEL STORAGE:			
STATION CNG STORAGE	*Not applicable*		*Not applicable*
CENTRALIZED LNG STORAGE	Sufficient centralized storage available to fulfill demand during production disruptions	🔵	Peak shavers could be used for reserve storage. They also provide a bridge to support vehicle deployments while dedicated liquefaction capacity is built
STATION LNG STORAGE	On-site fuel storage can accommodate dispensing capacity without fugitive emissions release	🟡	Fuel storage achievable within land requirements. Fuel venting can be an issue if throughput is not predictable. LCNG stations can use boil off fuel, or pipeline reinjection
LIGHT-DUTY CNG DISPENSING:			
FUEL STATION AVAILABILITY	Fleet solutions, plus geographic availability and dispensing capacity to replicate 30% of current gasoline network	🔴	Limited availability today, approx. $50 billion to build new dedicated CNG stations, plus up to $30 billion if land purchases required rather than upgrade existing gasoline stations
STATION-BASED COMPRESSION	Low cost highly reliable compression to accept a wide range of input pressures	🔵	Can generally use low pressure pipeline for feed, or use variable first stage compression if needed
EASE & SPEED OF REFUELING	Does not result in greater inconvenience for customers relative to conventional vehicles	🔵	Advances in compression reduce station O&M costs. Some increase in refuel duration. Need to implement widespread use of temperature compensated fill algorithms or pre-chilled fuel to guarantee complete tank fill
HOME REFUELING	Any CNG LD vehicle can be cost effectively refilled at home overnight or in a few hours	🔴	Not specifically required for market penetration, but would add to customer appeal. High cost technology and potential reliability and safety concerns
HEAVY-DUTY CNG/LNG DISPENSING:			
FUEL STATION AVAILABILITY	Fleet solutions, plus geographic availability and dispensing capacity to match 30% of current diesel truck stops	🟡	Limited availability today. Initial expansion via fleet centric stations. LCNG stations will make both LNG and CNG available for multiple vehicle types
LNG/LCNG STATION DESIGNS	Low cost, highly reliable and standardized systems to streamline robust network build out	🔵	Mature technologies, can be modularized for scale. LCNG can serve multiple vehicle types, and provide CNG to areas where pipeline network is not available
EASE & SPEED OF REFUELING	Does not result in greater inconvenience for customers	🔵	Some increase in refueling duration but manageable within operations. Training required for LNG dispensing – handling cryogenics, dedicated staff under truck stop model
FUEL ECONOMICS:			
DISPENSING CAPITAL INVESTMENT	Manageable total investment with minimal impact on dispensed fuel costs	🔴	Multi-billion dollar investment to provide ubiquitous supply, replicating 30% of gasoline or diesel dispensing capacity
DISPENSED FUEL COST	Sustainably lower than diesel or gasoline fuel	🔵	Even with land, liquefaction, & dispensing capital, Natural Gas can be materially lower price than equivalent hydrocarbon fuels. RNG competitive with gasoline and diesel

🟩 PRIORITY FOCUS AREA TO ENABLE WIDE-SCALE COMMERCIALIZATION

🔵 MINIMAL/NO BARRIERS

🟡 WILL TAKE INVESTMENT AND TIME, BUT PATHWAY FOR SUCCESS HAS BEEN IDENTIFIED

🔴 SIGNIFICANT BARRIER OR HIGH RISK OR HIGH UNCERTAINTY OR REQUIRES "BREAKTHROUGH OR INVENTION"

Figure 14-18. *Hurdle Assessment for Natural Gas Fueling Infrastructure* the expenses associated with each certificate, there are only a small number of companies in the aftermarket industry today, converting a limited number of engine families and vehicles.

HD engine certification regulations (40 CFR Part 86, CCR Title 13) provide two pathways for natural gas engine classification: Otto cycle and Diesel cycle. Otto cycle engines are subjected to regulations built around gasoline engine applications, while Diesel cycle engine regulations are based on the typical characteristics of diesel engines. Although the alternative pathways refer to operating cycle (Otto cycle using throttled operation at part load and Diesel cycle using un-throttled operation), in reality the relevant pathway is distinguished on the basis of whether the natural gas engine parent is a gasoline (Otto) or diesel engine.

Table 14-2 outlines the three categories of HD engine regulation according to the Gross Vehicle Weight Rating—light heavy-duty, medium heavy-duty, and heavy heavy-duty. The associated truck classifications are provided for reference.

By its nature, the light heavy-duty diesel engine category tends to be a mix of engines meeting the Diesel and the Otto cycle requirements. In contrast, the majority of the engines in the medium and heavy categories tend to be certified using the Diesel engine provisions as they are based on diesel engine platforms. One of the key distinguishing features of the alternative pathways is the useful life. For Otto engines, this is 10 years or 110,000 miles, whichever occurs first, across all categories. For Diesel engines, the useful life for medium heavy-duty diesel engines is 10 years or 185,000 miles, whichever occurs first, and for heavy heavy-duty diesel engines, useful life rises to 10 years, 435,000 miles, or 22,000 hours, whichever occurs first.[42]

Heavy-Duty Diesel Engine Category	Gross Vehicle Weight Rating	
	Federal	California
Light (Class 2b to 5)	>8,500 lbs and <19,500 lbs (Class 2b to 5)	>14,000 lbs and <19,500 lbs (Class 4 and 5)
Medium (Class 6 and 7)	≥19,500 lbs and ≤33,000 lbs	
Heavy (Class 8)	>33,000 lbs	

Table 14-2. *Heavy-Duty Engine Classifications for Certification*

Since 2007, engines have been certified to a range of emission levels in order to comply with the phase-in of the 0.2 grams per brake horsepower-hour (g/bhp-hr) nitrogen oxide (NOx) requirement. This mandates a 50% phase-in for 2007, 2008, and 2009 and 100% phased in for 2010 onwards. Averaging, banking, and trading (ABT) allowed manufacturers to comply on average and also allowed manufacturers to generate credits for early introduction of lower emission engines that could be used later to offset emissions from engines with emission levels higher than the standard. From 2010, all natural gas engine families certified by the EPA and CARB meet the 0.2 g/bhp-hr NOx standard and the 0.01 g/bhp-hr particulate matter standard.

Regulations also exist for retrofit conversions.[43,44] In California, the regulations enable the conversion of engines as long as they do not significantly increase emissions levels in comparison to the parent engine and also meet certain other criteria such as warranty and labeling requirements. The EPA operates a verified retrofit program that allows verification of emissions reductions. Currently, the EPA-verified technology list does not include any natural gas conversions.

In recent years, the majority of HD natural gas engines have been certified according to new engine regulations. The EPA database indicates that in the 2010 model year, seven distinct HD natural gas engine families were certified by four manufacturers.

Evolution of Greenhouse Gas Regulations

Greenhouse gas regulations for LD vehicles were finalized in 2010 by the EPA and the Department of

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[42] There are supplemental clauses in CFR 2007 § 86.004-2 that offer further definition for a vehicle that travels limited miles. For an individual engine, if the useful life limit of 22,000 hours is reached before the engine reaches 10 years or 100,000 miles, the useful life shall become 10 years or 100,000 miles, whichever occurs first.

[43] Modifications to the "California Certification and Installation Procedures for Alternative Fuel Retrofit Systems for Motor Vehicles Certified for 1994 and Subsequent Model Years" as decided at the board hearing on July 27, 1995.

[44] U.S. Environmental Protection Agency (website), National Clean Diesel Campaign (NCDC), "Clean Diesel Verification Overview," accessed January 15, 2012, http://epa.gov/cleandiesel/verification/.

Transportation's National Highway Traffic Safety Administration (NHTSA) for model years 2012 through 2016. These regulations set standards for tailpipe emission levels of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) in passenger cars, LD trucks, and MD trucks. The N_2O and CH_4 emission levels were set to cap the emissions of current gasoline and diesel vehicles such that future levels would not exceed current levels. Due to concerns voiced by OEMs, the EPA agreed to allow automakers to meet the N_2O and CH_4 standards by using an optional CO_2-equivalent approach. This approach allows manufacturers to convert the N_2O and CH_4 test results into CO_2-equivalent values utilizing the global warming potentials for each and adding these to the value of the CO_2 emissions.[45] Aftermarket converters were recently granted alternative approaches to meeting the methane standards.

GHG regulations for HD vehicles and engines were finalized by the EPA in July 2011, predominantly in 40 CFR Parts 1036 and 1037. The key issues for natural gas engines are the implementation of a methane emission cap at a low level (0.1 g/bhp-hr) and the associated GHG emissions ABT provisions that allow natural gas engines to comply.

The basic premise of the regulation is to set a benchmark GHG level for engines and vehicles based on 2010 models and then implement a range of percentage reductions in 2014 and 2017. The 2010 benchmark values for engines take into consideration the average CO_2, CH_4, and N_2O emission levels of diesel engines, the incumbent technology. The CH_4 and N_2O benchmark values from diesel engines are low and the caps for coming years (2014 and 2017) were set at a correspondingly low value. Natural gas engines emit 10 to 15 times the CH_4 level of the cap, but CO_2 levels well below the standard based on diesel engine performance. Hence, natural gas engine manufacturers will be required to use ABT provisions to generate CO_2 credits and use them to compensate to the overage in CH_4 levels. Parallel mechanisms exist for N_2O emissions, but this is considered to be less of an issue for natural gas engines.

Natural gas engines are still expected to generate CO_2 credits even after allowance for CH_4 emissions. There may be technological evolution of CH_4 emission controls such as combustion and aftertreatment in order to maximize credit generating potential under the regulations, but this will be dependent on the value of any credits generated under the scheme and the cost of implementing new CH_4 technologies.[46]

On-Board Diagnostics (OBD) Requirements

Starting in 1988, CARB regulations required that all LD vehicles be equipped with an "on-board diagnostics" system, commonly referred to as OBDI. Further regulations were then adopted in 1994, requiring an "on-board computer" to monitor the vehicle emission system and methodology to notify the vehicle operator of malfunctions, the advent of OBDII.[47] U.S. federal regulations also began to require OBD functionality in 1994. Starting in the 2005 model year for LD vehicles and 2013 for HD vehicles between 8,500 and 14,000 pounds, all conversions must demonstrate that they are OBDII compliant on all fuels, and no false OBD codes or malfunction indicator lights may be set.[48] Alternative fuel conversions cannot negatively impact the gasoline OBD system in the case of bi-fuel LD vehicles; HD conversions currently do not require OBD compliance for the alternative fuel, but must remain compliant on gasoline. Beginning in 2013, HD CNG engines will require Engine Manufacturer Diagnostics plus NOx monitoring. As of the 2019 model year, federal (2020 CARB) and beyond HD vehicles are required to meet full OBDII requirements when operating on CNG.

Many aftermarket converters are either not able to meet the requirements of CARB OBDII (especially in the case of bi-fuel conversions), or have insufficient volumes to warrant the additional expense of certification. This can have a material impact on the number of solution offerings in an early growth

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[45] M. Rood Werpy et al., *Natural Gas Vehicles: Status, Barriers, and Opportunities,* ANL/ESD/10-4, Argonne National Laboratory, Energy Systems Division, August 2010, http://www.transportation.anl.gov/pdfs/AF/645.PDF.

[46] The regulations provide a Global Warming Potential (GWP) of 25 for CH_4 and 298 for N_2O.

[47] CanOBD2 (Innova website), OBD Knowledge: "History of On-Board Diagnostics," 2012.

[48] U.S. Environmental Protection Agency (website), "On-Board Diagnostics – Vehicle and Engine Manufacturers," Regulatory guidelines, November 2011, http://www.epa.gov/otaq/regs/im/obd/manufact.htm.

market where production and sales volumes have not reached sufficient scale.

Safety Standards and Regulations

The NGV industry is also governed by a number of additional regulations, codes and standards relating to vehicle and fueling infrastructure safety, covering both CNG and LNG technologies.

Infrastructure codes and standards were originally developed for industrial applications and were applied to refueling technologies. The first vehicle component level standards were developed in New Zealand and Canada, and were derived from stationary standards, as both markets were early adopters of CNG technologies. These standards have since been drawn into a number of component requirements for NGV subsystem integration, as well as fueling stations.

The inclusion of NGVs in mainstream automotive standards has increased the safety performance of vehicles. These include FMVSS 303 Fuel System Integrity of Compressed Natural Gas Vehicles, FMVSS 304 Compressed Natural Gas Fuel Container Integrity in the United States and CMVSS 301.1 in Canada. The United Nations and European Union are developing NGV legislation to harmonize with the requirements in ISO standards.

HEAVY-DUTY ENGINES AND VEHICLES

The initial use of natural gas in HD vehicles was sparked by reductions in criteria air pollutants that could be achieved compared to diesel engines. Many municipal fleets started to adopt NGVs for transit and refuse applications, with a smaller number of trucks purchased for vocational uses.

As technology and fuel economy improved, a small number of private freight companies began to explore the use of natural gas engines with the aim of reducing fuel costs. Annual fuel use and the resulting fuel cost can vary depending on the vehicle class and its application (see Figure 14-19).

Figure 14-19. *Typical Annual Fuel Consumption in Heavy-Duty Trucks*

In Class 8b combination trucks running high annual mileage, UC Davis estimates fuel can be up to 40% of the total cost.[49] Figure 14-20 shows a typical operating cost breakdown of a Class 8b truck. In an industry with small operating margins, managing the cost of fuel is a key strategic activity, and hence the drive to improve fuel economy or minimize the purchased cost of fuel.

Some of the critical technical pathways for natural gas systems in HD vehicles include:

- Combustion strategy
- Torque and power
- Fuel economy and fuel strategies
- Complexity of changes to base diesel engine
- Aftertreatment
- Fuel storage (CNG and LNG)
- System incremental cost.

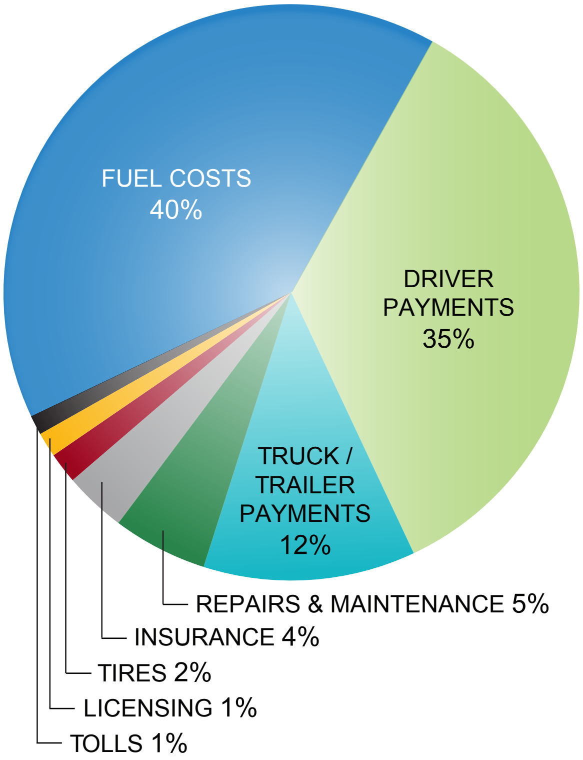

Figure 14-20. *Typical Operating Cost Breakdown of Class 8b Truck*

Natural gas fuel can be stored as CNG or LNG. In all cases, the engines themselves require fuel supplied to the engine in gaseous form as no systems inject or introduce natural gas fuel into the engine itself as a liquid.

Heavy-Duty Natural Gas Engine Options

Due to its high auto ignition temperature, natural gas needs an ignition source when used in engines, and two paths are in use today:

- Spark ignition
- Compression ignition, using diesel fuel as the ignition source.

Both approaches are typically built off existing diesel engine blocks to retain the structural robustness and durability required in this market. The choice of ignition approach drives many of the subsequent technical requirements. Some of the key technical characteristics of the two approaches are summarized in Figure 14-21 and discussed in more detail in the following sections.

Spark Ignition Engines

Adapting diesel engines to operate with natural gas using spark ignition technologies similar to gasoline engines has been the prevalent approach to date. The adaptation involves lowering compression ratio, modifying cylinder heads to incorporate spark plugs, and the addition of a throttle to modulate airflow, often accompanied by a reduced size of turbocharger because of the lower air demands relative to diesel. Options are available that incorporate exhaust gas recirculation (EGR). By employing EGR and stoichiometric air-fuel ratios, in-cylinder emissions can be kept low with ignition timings optimized for fuel efficiency while simultaneously using a relatively conventional three-way catalyst for tailpipe emissions control. Compared to the diesel baseline engine, the natural gas variants typically have a reduced thermal efficiency due to throttling and low compression ratio resulting in approximately 7 to 10% lower fuel economy in current applications.[50]

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[49] UC Davis Institute of Transportation Studies, Freight Transport ECI/ESP 252, 2009.

[50] American Trucking Association, "Is Natural Gas a Viable Alternative to Diesel for the Trucking Industry?" June 2, 2010.

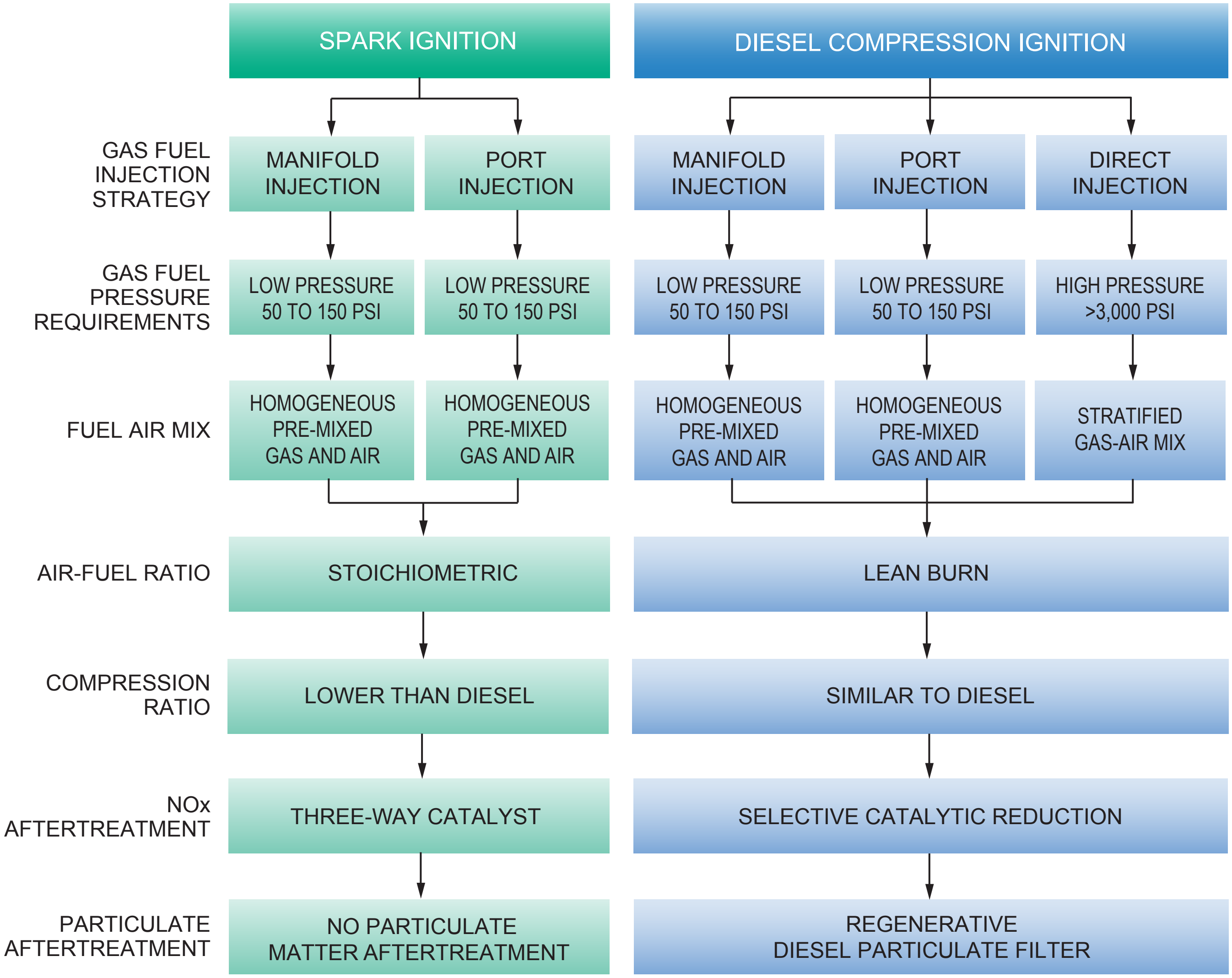

Figure 14-21. *Technical Approaches to Natural Gas Heavy-Duty Engines*

Potential advantages for spark ignition natural gas engines include removal of a diesel particulate filter and the ability to comply with NOx emissions regulation without the use of selective catalytic reduction (SCR).

Lean burn natural gas engines have at times been part of the technology options and remain in the portfolio of at least one supplier of transit buses. However, as NOx emissions regulations continued to tighten, lean burn engines faced increasing challenges to extend their low NOx operation with highly dilute charge mixtures. Lean burn engines were largely replaced by stoichiometric-EGR engines that could make use of three-way catalysis for tailpipe NOx emissions controls.

Compression Ignition Engines

An alternative to using spark plugs to provide the ignition source for the natural gas fuel is to use a small quantity of diesel injected into the combustion chamber to act as the ignition source. In order to do this, the engine needs to be configured with two fuel systems—gas and diesel.

Pre-Mixed Charge Compression Ignition – Dual Fuel

One approach is to retain the complete diesel fuel injection system and add a second gas fuel injection system to introduce low-pressure gas in the intake manifold or the intake ports of the engine. The retained diesel fuel injection system is used to provide a relatively small but load-dependent quantity of diesel that acts as the ignition source for the charge mix. Combustion instigated by this diesel injection ignites the main natural gas fuel charge. The gas charge is premixed with air and EGR and can be sensitive to combustion knock at high loads or misfire at lean air-fuel ratios. As a result, the fuel split between diesel and gas is varied considerably across the operating range of the engine. Particulate filters are required to control particulate matter emissions, and NOx control methods are similar to diesel.

Dual fuel engines have the potential to achieve the same power, torque, and fuel efficiency as the diesel engine, although some variation in efficiency maps may occur. Typically between 60 and 80% of the diesel fuel can be displaced by natural gas in this configuration. Such an engine can operate on diesel alone, but it cannot operate on gas only since the diesel is required as the ignition source. Given the current level of refueling infrastructure, the potential to operate on diesel only is a potential market advantage.

Compression Ignition, Direct Injection of Gas

High-pressure direct injection (HPDI) compression ignition engines operate on the diesel cycle with combustion characteristics very similar to diesel engines. The torque and power potential for HPDI gas engines is in principle equal to diesel. Both the diesel and the natural gas are injected directly into the combustion chamber (see Figure 14-22). A small quantity of diesel is used as the ignition source, and provides between 5 and 10% of total fuel energy. Gas is injected at high pressure (>3,000 psi) in fuel sprays similar to diesel. Due to the absence of premixed gas and air in the cylinder, combustion knock is not an issue and high levels of gas utilization can be achieved across the entire engine operating range. Operation on diesel alone is not enabled in this engine type, nor is operation on gas alone. Diesel particulate filters are used for particulate emission control, and as with diesel the choice for NOx control is either SCR catalysts or very high levels of EGR.

Source: Westport Innovations Inc.

Figure 14-22. *High-Pressure Combined Natural Gas and Diesel Fuel Injector*

Since compression ignition natural gas engines are built around diesel engine architectures, some compromise in gas operation is inherent. For example, combustion chambers and intake ports are designed to optimize fuel air mixing for diesel operation where diesel injection energies are very high (20,000 to 30,000 psi). These designs are not inherently optimal for gas and diesel combustion when the highest gas injection pressures are <4,000 psi. Reconfiguring combustion and intake systems tailored specifically for natural gas operation may result in further improvements in combustion characteristics and fuel efficiency. Combustion optimization is an area for future technology development.

Control strategies for compression ignition engines closely mirror those used for their diesel counterparts. Modifications are required for more complex fuel metering, timing, and control algorithms. A significant degree of integration with the base engine controls is required for optimal engine operation and compliance with emissions regulations.

Fuel Storage and Supply Systems for Heavy-Duty Natural Gas Engines

In principle, vehicles with each of the engine technologies above can be fueled with either CNG or LNG, as outlined in Figure 14-23. The choice is largely driven by vehicle range requirements, space availability, and cost.

CNG systems for HD vehicles are very similar to those used in LD vehicles, although because of the large fuel storage requirements they are largely

Type 4 carbon fiber composite cylinders in order to minimize weight. Fuel is stored at 3,600 psi and discharge pressure is regulated down to match the feed pressure required by the engine fuel system. Because of the low energy density of natural gas compared to diesel, CNG has largely been restricted to vehicle applications that either require only modest operating range or that can accommodate significant numbers of cylinders such as transit buses and refuse collection. Recent improvements in CNG storage technology and product offerings have led to higher capacity CNG cylinders, a development that is spurring an interest in CNG for freight trucks with either frame rail or back-of-cab mounted CNG storage. See Figure 14-24 for an example of a CNG freight truck with back-of-cab fuel storage, and Figure 14-25 for an example of a CNG refuse truck with roof-mounted storage.

The main fuel components in an LNG fuel system are the storage tank, an LNG vaporizer to convert liquid to warm gas (for LNG systems), pressure regulators, and filtration systems. LNG storage systems are vacuum-insulated cryogenic fuel tanks to keep the fuel at approximately -162°C or -260°F. In most LNG systems, the fuel naturally resides as both a liquid and a vapor within the tank and the vapor pressure is used to drive liquid fuel out of the tank (saturated LNG). This liquid fuel then passes through a vaporizer that adds heat to the liquid and transforms it into warm gas to feed the engine. A separate economizer loop allows vapor to be extracted from the tank under conditions where vapor pressure buildup is excessive. Figure 14-26 shows a schematic of such an LNG tank.[51] This design is used for both spark ignition engines and compression ignition engines that only require relatively low fuel supply pressure for the engine.

HPDI engines, where fuel injection pressures are higher (>3,000 psi), require a slightly different approach. A high-pressure pump compresses liquid

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[51] Chart Industries (website), "How the Tank Works," 2009, accessed November 15, 2011.

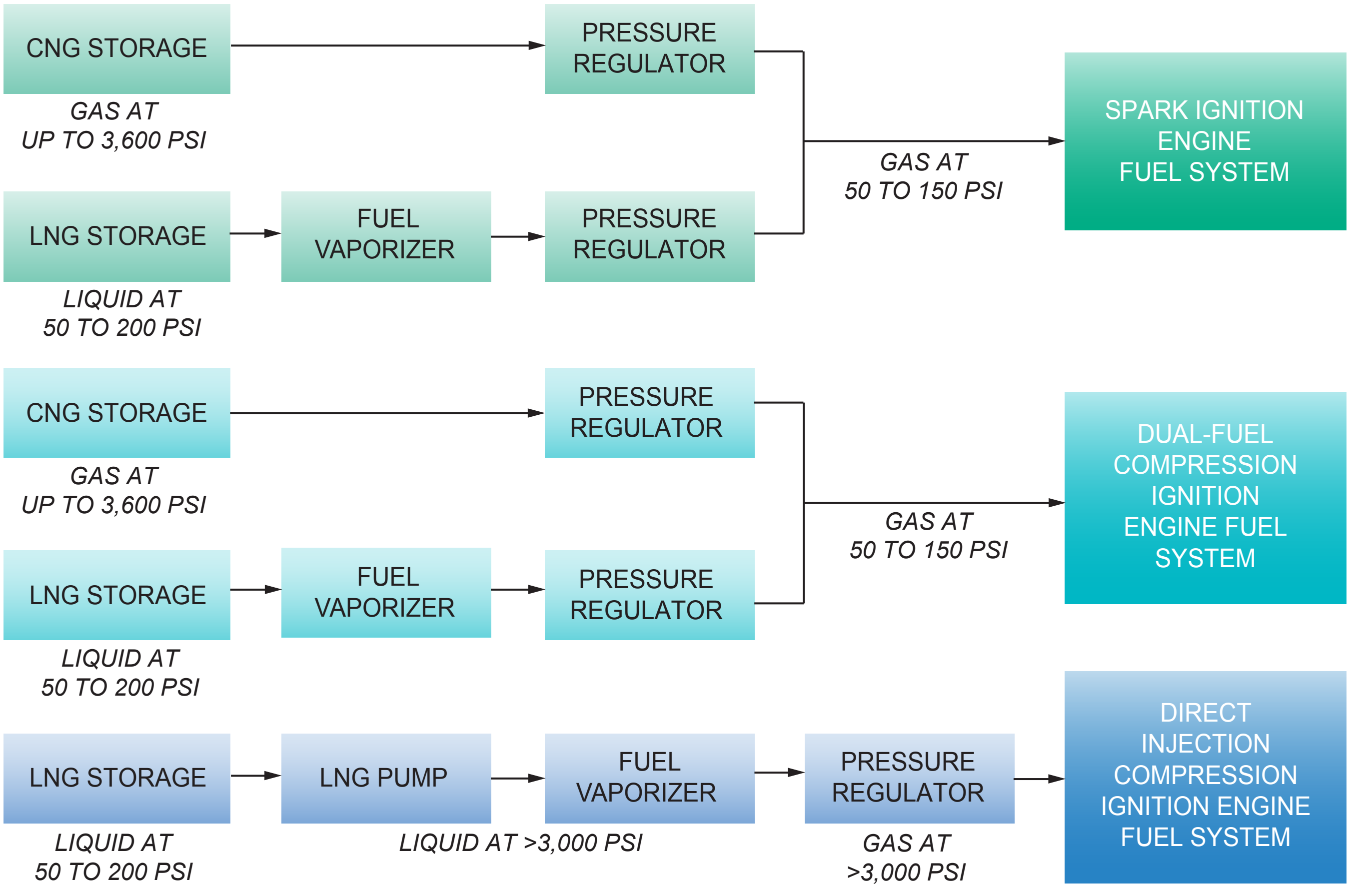


Figure 14-23. *Illustrative Comparison of CNG and LNG Fuel Systems*

Figure 14-24. CNG Freight Truck with Back-of-Cab Fuel Cylinders

Figure 14-25. CNG Refuse Truck with Roof-Mounted Fuel Storage

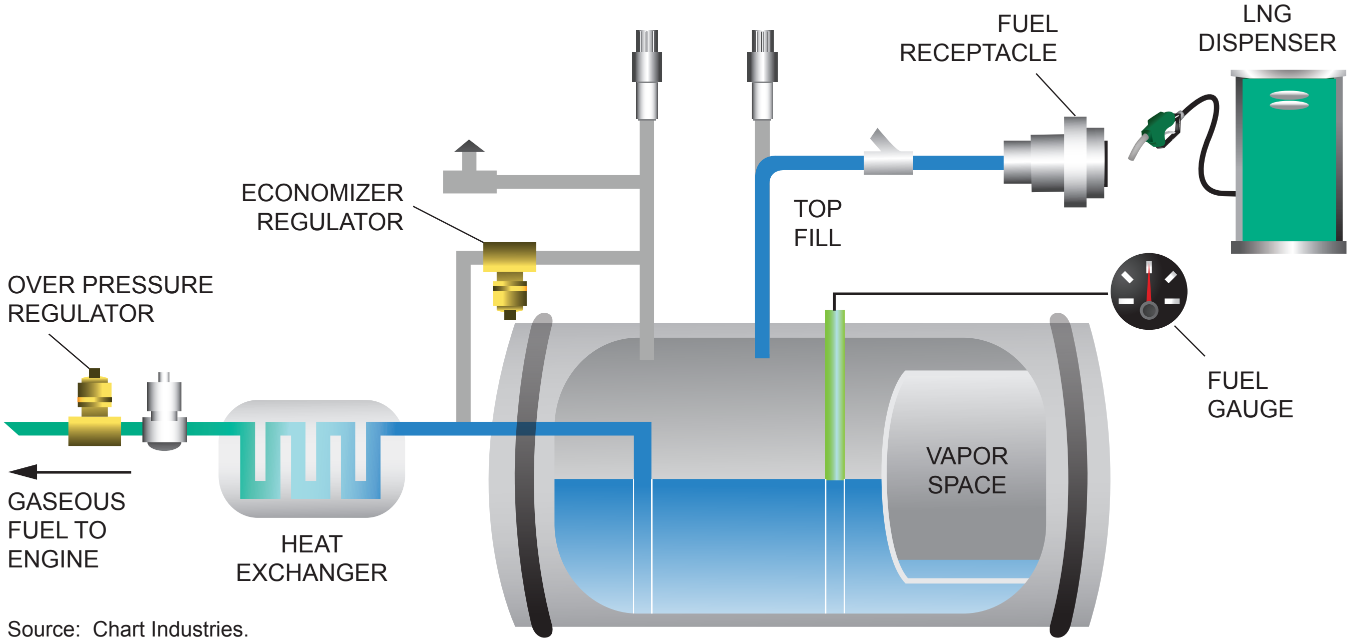
fuel to the desired pressure before it is converted to high-pressure gas by a similar vaporizer system. In this approach, only fuel that is in a liquid phase can be drawn out of the tank. Figure 14-27 shows an example of this high-pressure pump.

Cost Structure of Heavy-Duty Natural Gas Vehicle Systems

While HD NGVs currently have a price premium over equivalent diesel-fueled vehicles, there exists significant potential for that premium to be reduced over time through technology and production scale.

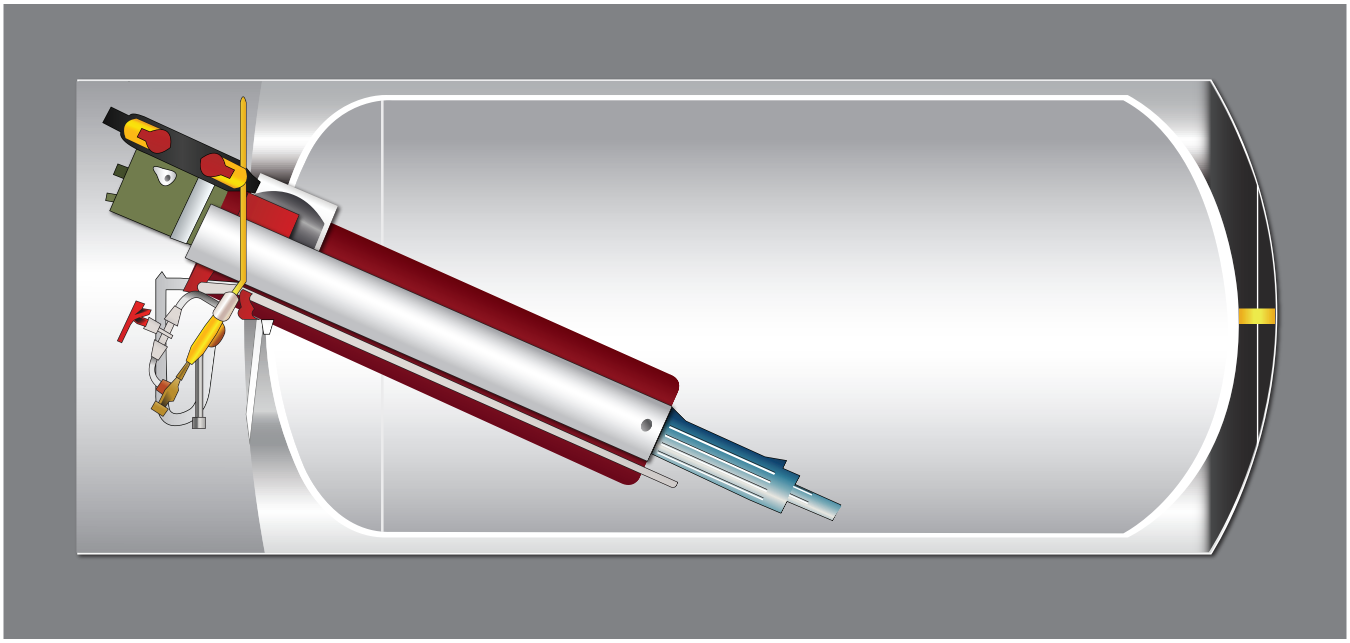
Cost Structure of Heavy-Duty Natural Gas Engines

The cost structure of the spark ignition and direct injection compression ignition engines have been estimated and translated into a Retail Price Equivalent (RPE) value based on information provided



Source: Chart Industries.

Figure 14-26. LNG Fuel Tank Schematic



Source: Westport Innovations.

Figure 14-27. *Example of LNG Tank with Submerged High-Pressure Fuel Pump*

by manufacturers of these two engine types.[52] The final cost of systems supplied to OEMs was adjusted using a factor of 1.3. These two technologies were selected as representative of the lower and upper cost ranges for natural gas engines, and it is anticipated that the cost structure for dual-fuel engines would lie between the two.

Spark ignition engines have the potential to be cheaper than their diesel counterparts since the engine fuel system and aftertreatment (AT) can be substantially lower cost than diesel systems. The engine cost/RPE structure is considered the same regardless of whether the fuel storage system is CNG or LNG. Based on an existing 8.9 liter engine, a major manufacturer indicates that 2010 incremental RPE of a spark ignited natural gas engine over and above that of an equivalent diesel engine ranges between $7,410 and $3,250. By 2015, with assumptions of increased manufacturing scale, the net incremental natural gas engine price is projected to improve to a premium of $3,000 or a cost advantage of $2,200. These provide the basis for RPE estimates in Table 14-3.

Compression ignition engines with direct injection natural gas fuel systems have a higher engine and fuel system cost structure than spark ignition engines. Based on information provided by a major manufacturer of a 15-liter engine, the selling price

	2010 Retail Price Equivalent				2015 Retail Price Equivalent			
	R&D	Engine	AT or Engine Deletes	Engine Total	R&D	Engine	AT or Engine Deletes	Engine Total
Spark Ignition–CNG								
Low	$433	$7,367	-$4,550	$3,250	$265	$2,952	-$5,395	-$2,178
High	$650	$9,750	-$2,990	$7,410	$399	$6,338	-$3,770	$2,967

Table 14-3. *Near-Term Incremental Retail Price Equivalent of Spark Ignition Natural Gas Engines in Class 7&8 Combination Trucks*

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[52] These data were provided by Westport Innovations Inc. and Cummins Westport Inc.

to OEM customers for engine and fuel tanks ranges from:

- $40,000 to $50,000 for single LNG tank systems[53]
- $60,000 to $70,000 for dual LNG tank systems.

Applying a 1.3 scalar to get to RPE, it is estimated that the 2010 RPE premium of the engine portion is between $26,000 and $39,000 over its equivalent diesel counterpart, with modest reductions by 2015 as production scale increases. These provide the basis for RPE estimates in Table 14-4.

Costs for dual-fuel engines are estimated to fall between those of spark ignition and direct injection natural gas engines because they have a lower cost gas injection system than direct injection but cannot avoid the diesel aftertreatment.

Cost Structure of CNG and LNG Fuel Systems for Heavy-Duty Vehicles

The installed RPE of CNG fuel systems ranges from $300 to $450 per DEG, while that of saturated LNG systems ranges from $200 to $300 per DEG.[54] These estimates are applicable to spark ignition and dual-fuel engine technologies. The RPE of the appropriate LNG fuel storage systems for direct injection compression ignition engines is estimated to be approximately $475 per DEG, based on manufacturer information. This cost increase over LNG systems for spark ignition engines is a result of a unique tank design to accommodate the fuel pump, the pump itself, and hydraulic pump control systems.

Cost Structure of Engine and Fuel Systems for Class 7&8 Combination Natural Gas Trucks

For Class 7&8 combination trucks, fuel storage estimates are based on an assumed requirement for a 500-mile driving range between refueling, with a reserve capacity of 20%. Fuel economy of spark ignition engines was assumed at 5.5 miles per DEG, and 6.1 miles per DEG for compression ignition engines. Combining engine and fuel storage costs, the range of current incremental RPE for natural gas HD vehicles is $26,500 to $91,000, depending on engine type and fuel storage approach. Fuel storage cost is a significant portion of the total RPE. RPE cost estimates for 2010 and 2015 are provided in Table 14-5.

Cost Structure of Engines and Fuel Systems for Class 7&8 Single Unit Natural Gas Trucks

Using a similar set of assumptions, modified to reflect that single unit trucks on average have a lower driving range and hence lower fuel storage requirements, Table 14-6 illustrates the RPE structure for this vehicle class.

Further to this evaluation of near-term pricing, if market adoption of natural gas HD vehicles were significant, economies of scale could be achieved. A consistent cost reduction metric assumption used throughout this study is that upon achieving scale, cost reduction of new technologies advances at 3% per year for the first five years, 2% for the next five years, and in the long term improves at 1% per year. Applying these assumptions to estimate future RPE trajectories, with an implicit assumption that

	2010 Retail Price Equivalent				2015 Retail Price Equivalent			
	R&D	Engine	AT or Engine Deletes	Engine Total	R&D	Engine	AT or Engine Deletes	Engine Total
Compression Ignition–CNG								
Low	$0	$0	$0	$26,000	$0	$0	$0	$22,750
High	$0	$0	$0	$39,000	$0	$0	$0	$35,750

Table 14-4. *Near-Term Incremental Retail Price Equivalent of Compression Ignition Direct Injection Engines in Class 7&8 Combination Natural Gas Trucks*

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[53] These prices cover the cost of converting the engine from diesel to natural gas, and for provision of LNG tanks as noted.

[54] Cost data quoted by Agility Fuel Systems to the NPC study team.

	2010 Retail Price Equivalent						2015 Retail Price Equivalent					
	Engine Total	Storage ($/DEG)	Storage (DEG)	No. of Tanks	Storage RPE	Total System Incremental RPE	Engine Total	Storage ($/DEG)	Storage (DEG)	No. of Tanks	Storage RPE	Total System Incremental RPE
Spark Ignition–CNG												
Low	$3,250	$300	124	3	$37,080	$40,330	-$2,178	$300	124	3	$37,080	$34,903
High	$7,410	$450	124	3	$55,620	$63,030	$2,967	$450	124	3	$55,620	$58,587
Spark Ignition–CNG												
Low	$3,250	$200	117	2	$23,412	$26,662	-$2,178	$200	117	2	$23,412	$21,234
High	$7,410	$300	117	2	$35,118	$42,528	$2,967	$300	117	2	$35,118	$38,084
Compression Ignition–CNG												
Low	$26,000	$473	110	2	$52,000	$78,000	$22,750	$414	110	2	$45,500	$68,250
High	$39,000	$473	110	2	$52,000	$91,000	$35,750	$414	110	2	$45,500	$81,250

Table 14-5. *Near-Term Incremental Retail Price Equivalent for Class 7&8 Combination Natural Gas Trucks*

	2010 Retail Price Equivalent						2015 Retail Price Equivalent					
	Engine Total	Storage ($/DEG)	Storage (DEG)	No. of Tanks	Storage RPE	Total System Incremental RPE	Engine Total	Storage ($/DEG)	Storage (DEG)	No. of Tanks	Storage RPE	Total System Incremental RPE
Spark Ignition–CNG												
Low	$3,250	$300	41	1	$12,360	$15,610	-$2,178	$300	41	1	$12,360	$10,183
High	$7,410	$450	41	1	$18,540	$25,950	$2,967	$450	41	1	$18,540	$21,507
Spark Ignition–CNG												
Low	$3,250	$200	38	1	$7,529	$10,779	-$2,178	$200	38	1	$7,529	$5,352
High	$7,410	$300	38	1	$11,294	$18,704	$2,967	$300	38	1	$11,294	$14,261
Compression Ignition–CNG												
Low	$26,000	$473	55	1	$26,000	$52,000	$22,750	$414	38	1	$15,572	$38,322
High	$39,000	$473	55	1	$26,000	$65,000	$35,750	$414	38	1	$15,572	$51,322

Table 14-6. *Near-Term Incremental Retail Price Equivalent for Class 7&8 Single Unit Natural Gas Trucks*

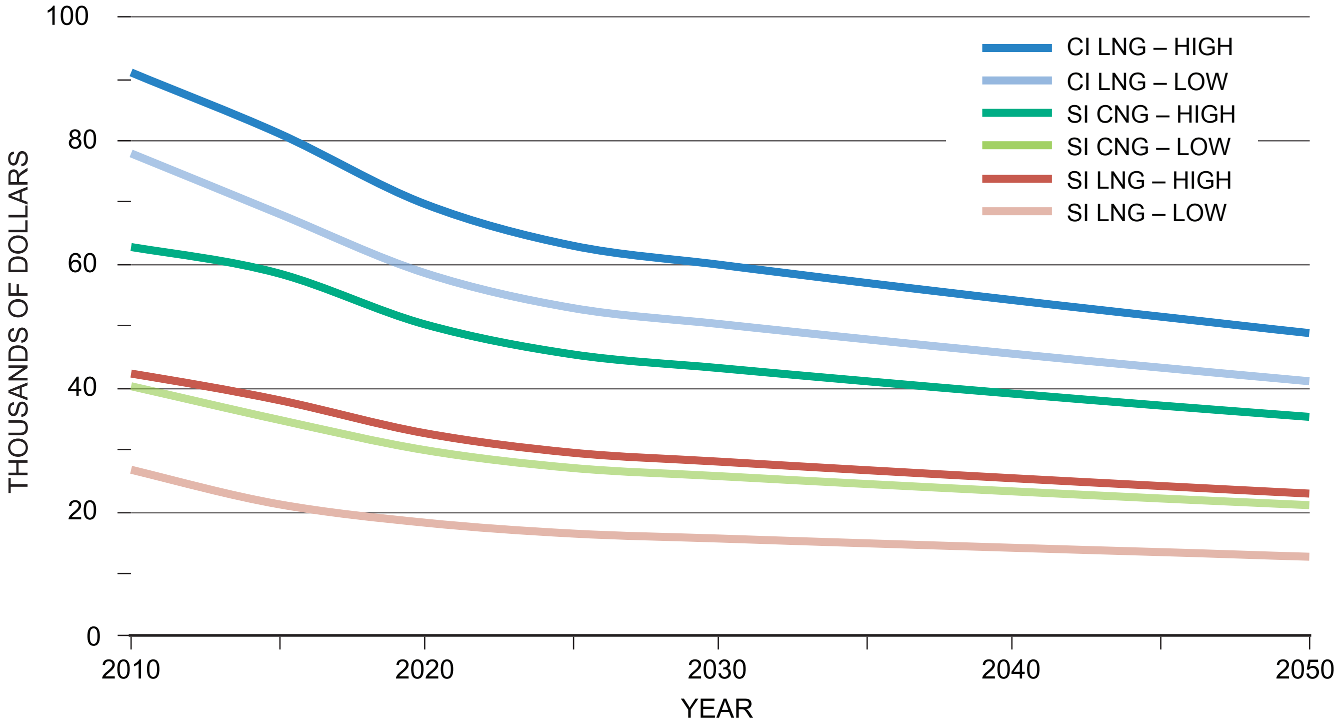
fuel storage capacity is not reduced due to any fuel efficiency improvements, it appears that the price premium associated with natural gas trucks can close substantially, especially if fuel storage was optimized. Figures 14-28 and 14-29 illustrate these RPE trajectories.

Cost Structure of Engines and Fuel Systems for Class 3-6 Natural Gas Trucks

Currently for Class 3-6 trucks, spark ignition engines and CNG are the dominant technologies. Based on the manufacturer data discussed earlier, an equivalent incremental RPE trajectory for Class 3-6 CNG trucks has been developed and is shown in Figure 14-30.

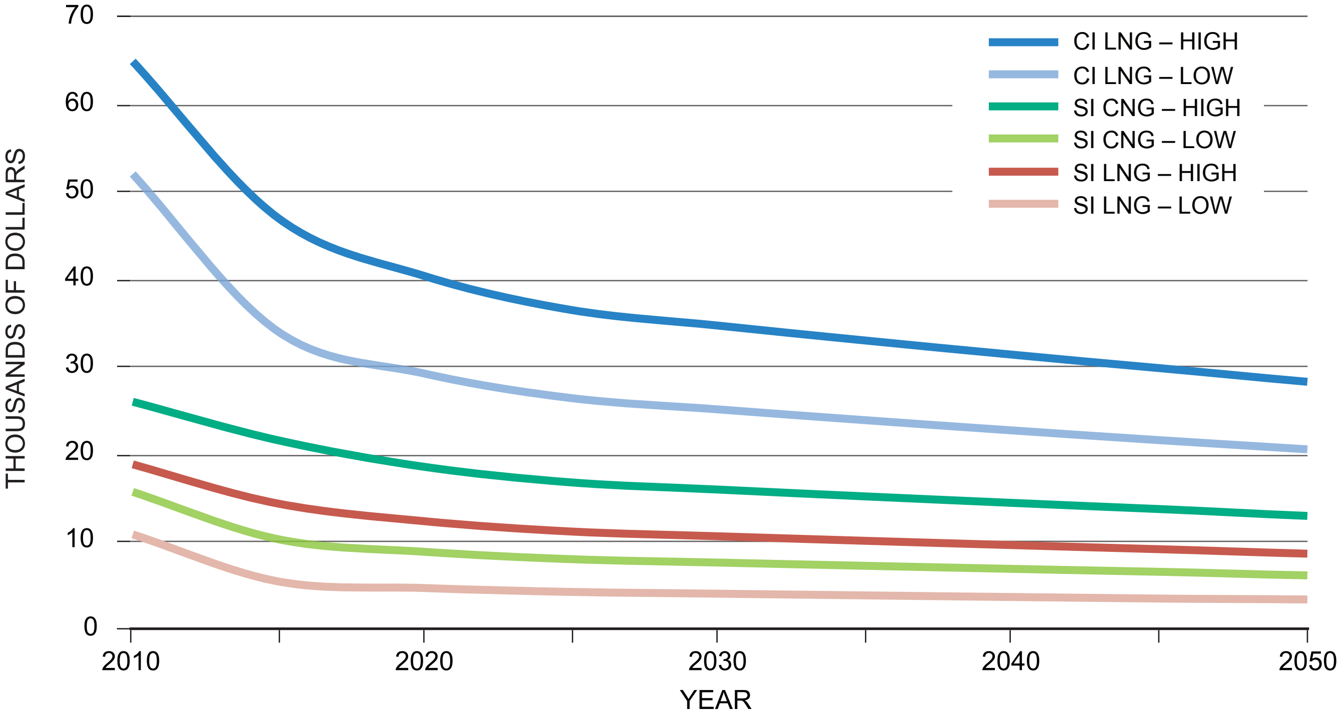
Care is needed when comparing the costs of natural gas trucks to ensure that key engine and fuel system assumptions are defined, including:

- Natural gas engine technology approach
- CNG or LNG fuel storage
- Driving range requirements
- Duty cycle and fuel economy assumptions.



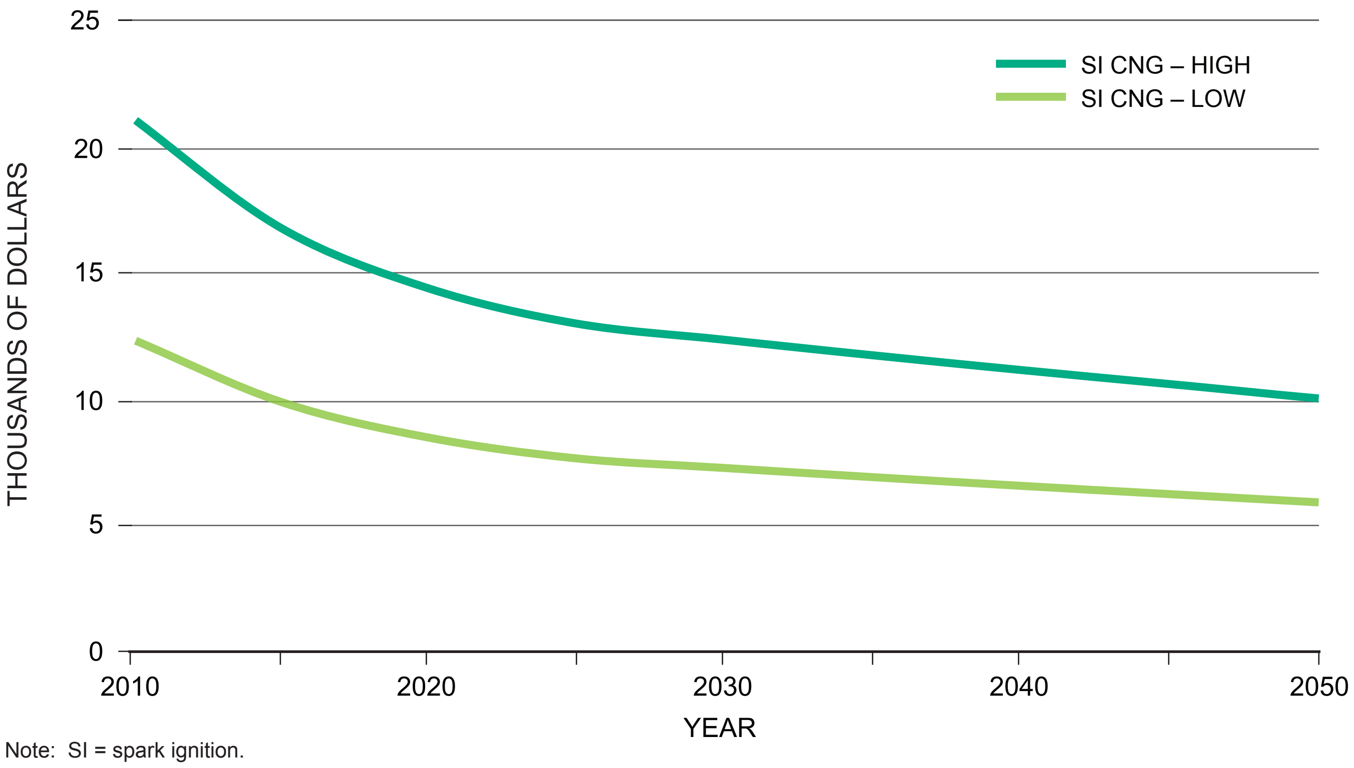
Note: CI = compression ignition; SI = spark ignition.

Figure 14-28. *Estimates of Incremental Retail Price Equivalent Trajectories for Class 7&8 Combination Natural Gas Trucks*



Note: CI = compression ignition; SI = spark ignition.

Figure 14-29. *Estimates of Incremental Retail Price Equivalent Trajectories for Class 7&8 Single Unit Natural Gas Trucks*



Note: SI = spark ignition.

Figure 14-30. *Estimates of Incremental Retail Price Equivalent Trajectories for Class 3-6 CNG Trucks*

Incremental RPE structures range from approximately $10,000 to $91,000 in the near term, depending on vehicle class. Over time, that premium could reduce to between $5,000 and $50,000.

Fuel consumption is a primary performance attribute for HD freight vehicles. Reductions can come from a combination of engine, transmission/driveline, trailer, aerodynamics, and operational factors. The National Research Council (NRC) illustrates the energy balance of a fully loaded Class 8 tractor-trailer in Figure 14-31.[55] These are more fully discussed in Chapter Ten, “Heavy-Duty Engines & Vehicles.” Performance associated with fueling options is briefly discussed in this section.

As with diesel, there exists potential to improve fuel consumption from an HD natural gas engine. Spark ignition technology already benefits from turbocharging and is able to match the power and torque of the diesel equivalent engine. It is often necessary to reduce airflow in spark ignition HD engines, since these engines operate at stoichiometry as opposed to the highly diluted charge characteristics of diesel engines. Compression ignition natural gas engines also achieve the same torque and power output as their diesel counterparts and do so with almost identical thermal efficiency since they retain a high compression ratio and diesel combustion cycle. As with spark ignition, additional benefits could be achieved through combustion chamber optimization to reflect the differing combustion characteristics of natural gas and blends of natural gas and diesel.

Advanced combustion regimes such as premixed charge compression ignition (PCCI) and homogeneous charge compression ignition (HCCI), with very low in-cylinder emissions and high thermal efficiency, can also be accomplished using natural gas. However, as with gasoline and diesel fuel, these combustion options currently face challenges associated with control and robustness.

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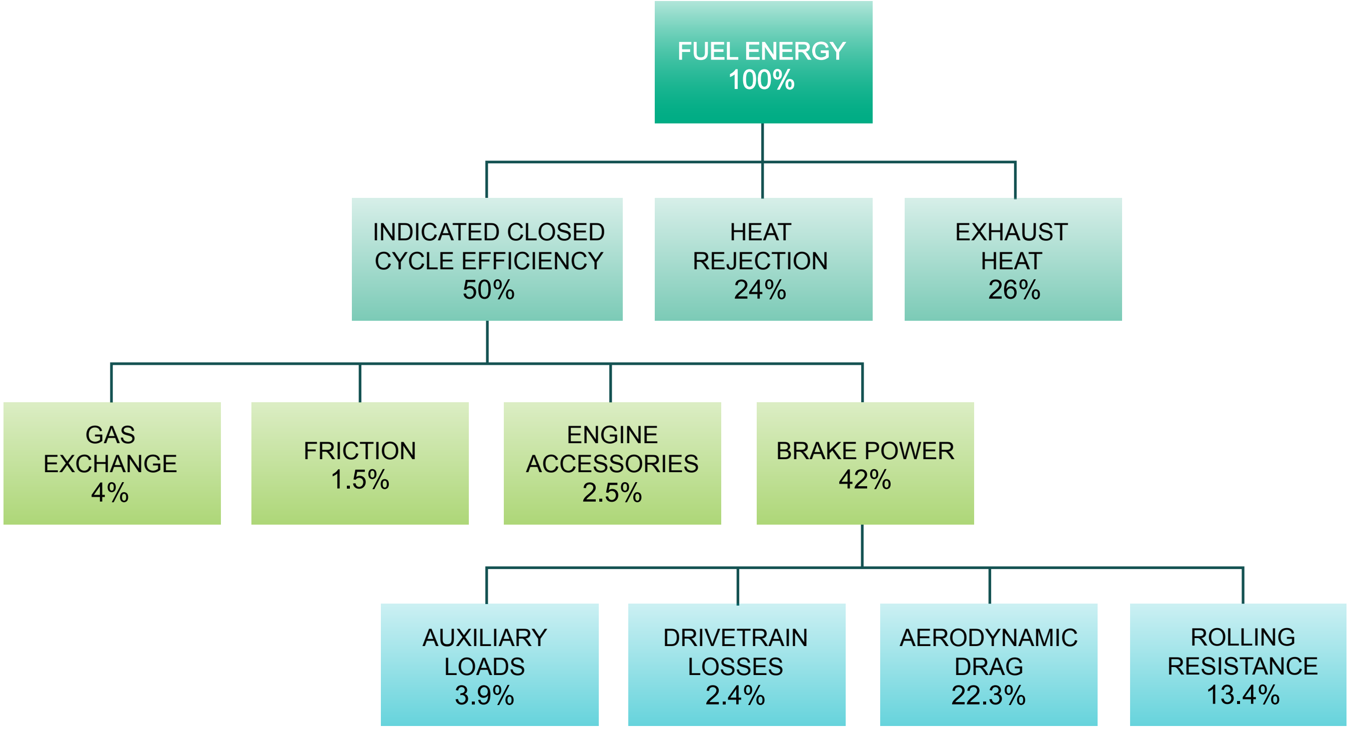
[55] National Research Council of the National Academies, *Technologies and Approaches to Reducing the Fuel Consumption of Medium and Heavy Duty Vehicles,* 2010, Figure 5-1, http://www.nap.edu/catalog.php?record_id=12845.



Source: National Research Council.

Figure 14-31. *Energy Balance of a Fully Loaded Class 8 Tractor-Trailer on a Level Road at 65 mph*

The NRC identified pathways to achieve significant fuel consumption reduction of up to 50% in diesel HD trucks (Table 14-7).[56] About a third of this reduction is available through engine technologies and could be mirrored with natural gas engines. The balance, being vehicle technologies, would also be available to NGVs.

Fuel consumption reductions translate into GHG emissions reductions for both diesel and natural gas. Using carbon coefficients from GREET 1.8d, Figure 14-32 illustrates fuel economy versus GHG relationships for both diesel and natural gas trucks. The analysis assumes that a diesel truck achieves 6.1 mpg at baseline conditions and an NGV with similar engine and vehicle systems is subject to a 5% fuel economy penalty. Based on the GREET fuel carbon coefficients, the natural gas truck would have a 21% lower GHG profile under baseline conditions. In order to achieve a 50% reduction in GHG emissions, the diesel vehicle fuel consumption must be reduced by 50%. Due to the lower carbon profile of LNG (assuming North America pipeline gas), a 50% reduction of GHG emissions is achieved when the fuel consumption of the natural gas truck is reduced by approximately 37%.

The use of bio-methane or RNG can result in more than 80% GHG reductions for natural gas trucks. A number of refuse fleets in North America are already operating on 100% RNG, as well as LD and HD fleets in Europe. Further discussion of the potential impact of RNG is provided in later sections of this chapter.

An analysis of a number of studies of truck fuel economy conducted by EPA/NHTSA,[57] NESCCAF,[58]

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[56] Ibid., Table 6-2.

[57] U.S. Environmental Protection Agency and National Highway Traffic Safety Administration, *Proposed Rulemaking to Establish Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles,* Report EPA-420-D-10-901, October 2010, http://epa.gov/OMS/climate/regulations/hd-preamble-regs.pdf.

[58] Northeast States Center for a Clean Air Future and the International Council on Clean Transportation Southwest Research Institute, *Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO_2 Emissions,* October 2009, http://www.nescaum.org/documents/heavy-duty-truck-ghg_report_final-200910.pdf.

Application	Engine	Aerodynamics	Rolling Resistance	Transmission and Driveline	Hybrids	Weight
Tractor trailer	20	11.5	11	7	10	1.25
Straight truck box	14	6	3	4	30	4
Straight truck bucket	11.2	0	2.4	3.2	40	3.2
Pickup truck (gasoline)	20*	3	2	7.5	18	1.75
Pickup truck (diesel)	23†	3	2	7.5	18	1.75
Refuse truck	14	0	1.5	4	35	1
Transit bus	14	0	1.5	4	35	1.25
Motor coach	20	8	3	4.5	NA	1.05

* Compared to a baseline gasoline engine.
† Compared to baseline diesel engine.

Table 14-7. *NRC Fuel Consumption Reduction Paths for Heavy-Duty Trucks*

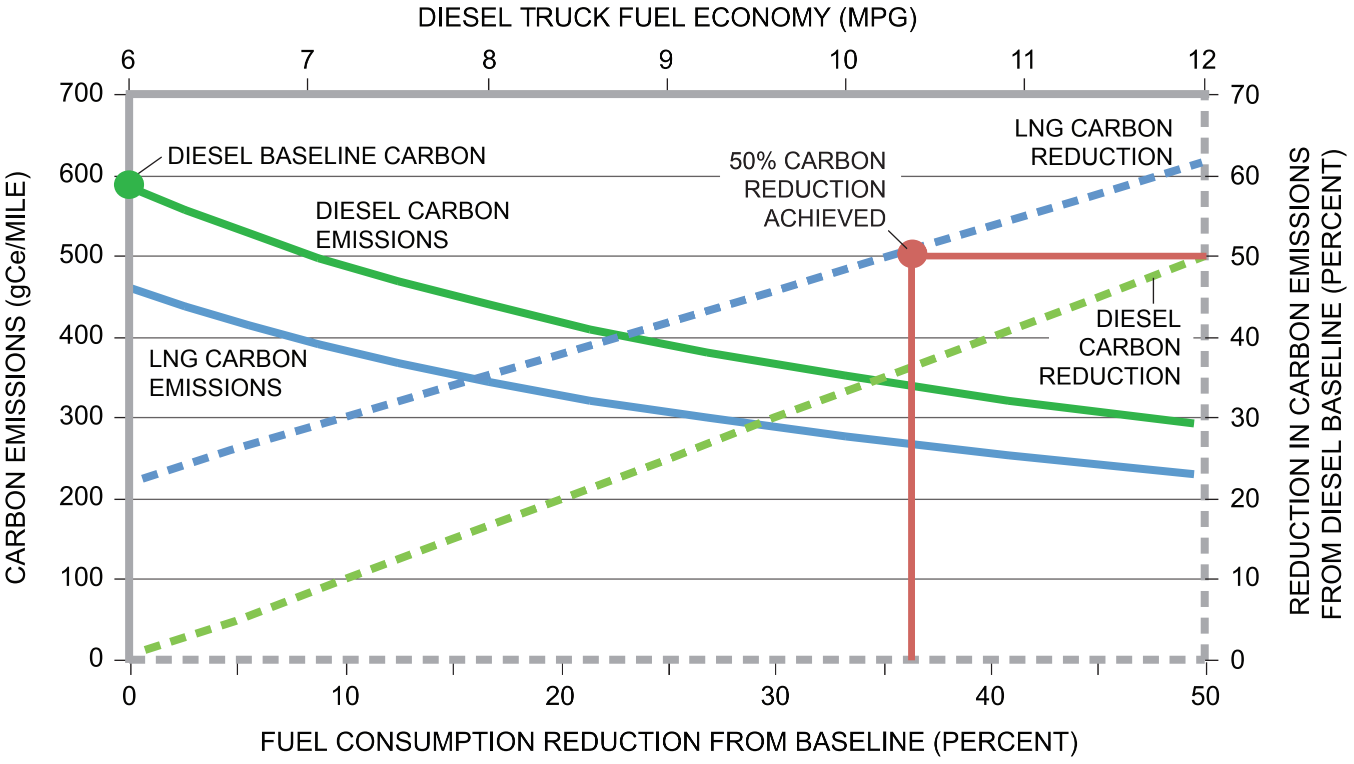


Figure 14-32. *Impact of Fuel Economy Improvements on Diesel and Natural Gas Carbon Emissions in Class 8 Trucks*

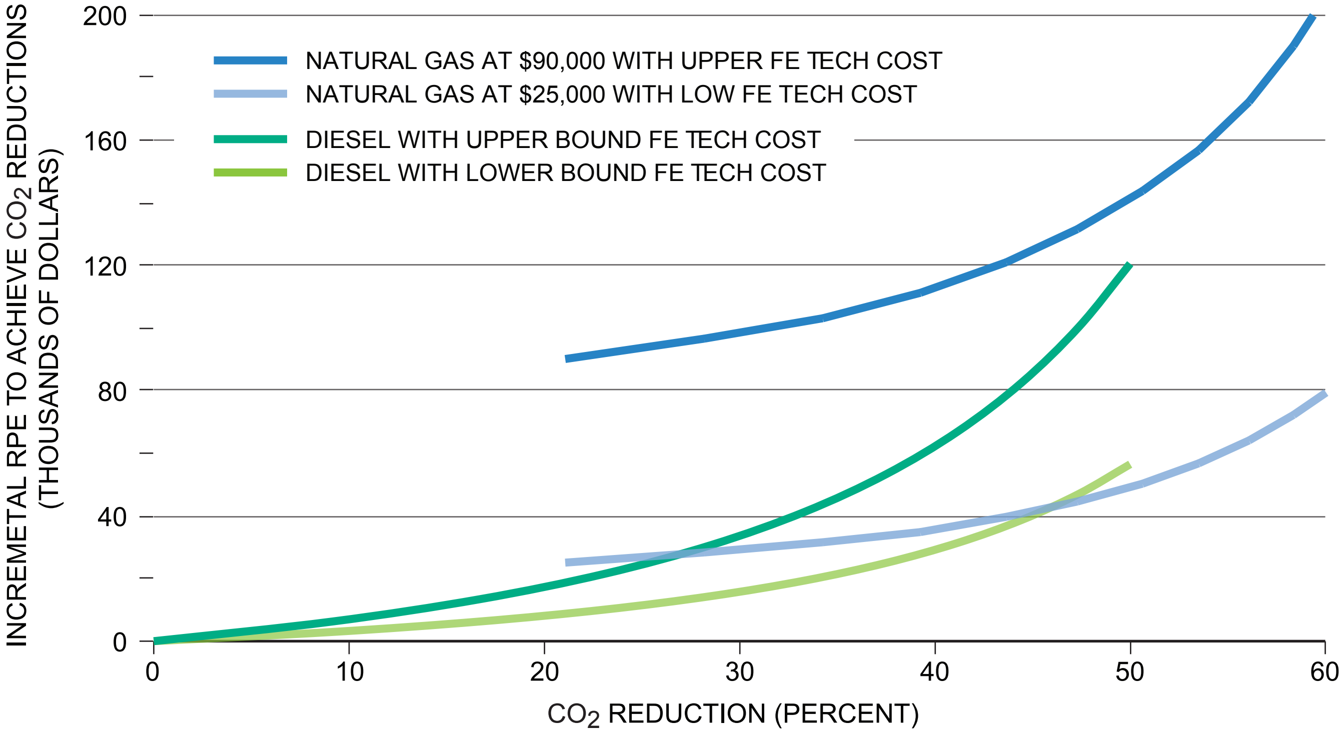
and Rocky Mountain Institute[59] illustrates the relationship between fuel consumption reduction and estimated technology cost. An upper and lower bound is used to represent the range of assessments of the cost of fuel economy technology. These technologies, including both engine and vehicle advances, offer a pathway to 50% reductions in fuel consumption but with substantial cost premiums.

Figure 14-33 illustrates the "first cost" (RPE) trade-offs for CO_2 reduction comparing diesel and natural gas, assuming that natural gas and diesel engines can achieve similar reductions in fuel consumption using the same technologies.

Diesel technologies have first cost advantage for modest efficiency and GHG reductions, while that advantage goes away at deeper reductions. It should be noted though that as natural gas systems reduce in cost, the curves for natural gas would drop vertically, becoming increasingly competitive with diesel. However, since the HD market is often economically driven by the cost of fuel, evaluating technologies based solely on capital cost may not provide the most appropriate comparison.

Economics of Heavy-Duty Natural Gas Vehicles

Based on the fuel use profiles in Figure 14-19, annual fuel cost savings of Class 8b trucks operating on natural gas are presented in Figure 14-34, for a range of fuel price spread assumptions. From this analysis, if natural gas fuel is priced advantageously, the savings arising from fuel costs could be substantive, offsetting the initial cost premium of natural gas engine systems within a few years of operation. This chart is based on current fuel economy levels, and as such the cost savings benefits would decrease if fuel economy improved through the addition of new engine and vehicle technology improvements.



Note: FE = fuel economy.

Figure 14-33. *"First Cost" (RPE) Trade-Offs for Reducing CO_2 Emissions in Class 8 Trucks*

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[59] Michael Ogburn, Laurie Ramroth, and Amory Lovins, *Transformational Trucks: Determining the Energy Efficiency Limits of a Class-8 Tractor-Trailer,* White Paper, Document # T08-08, Rocky Mountain Institute, 2008, http://www.rmi.org/Knowledge-Center/Library/T08-08_TransformationalTrucksEnergyEfficiency.

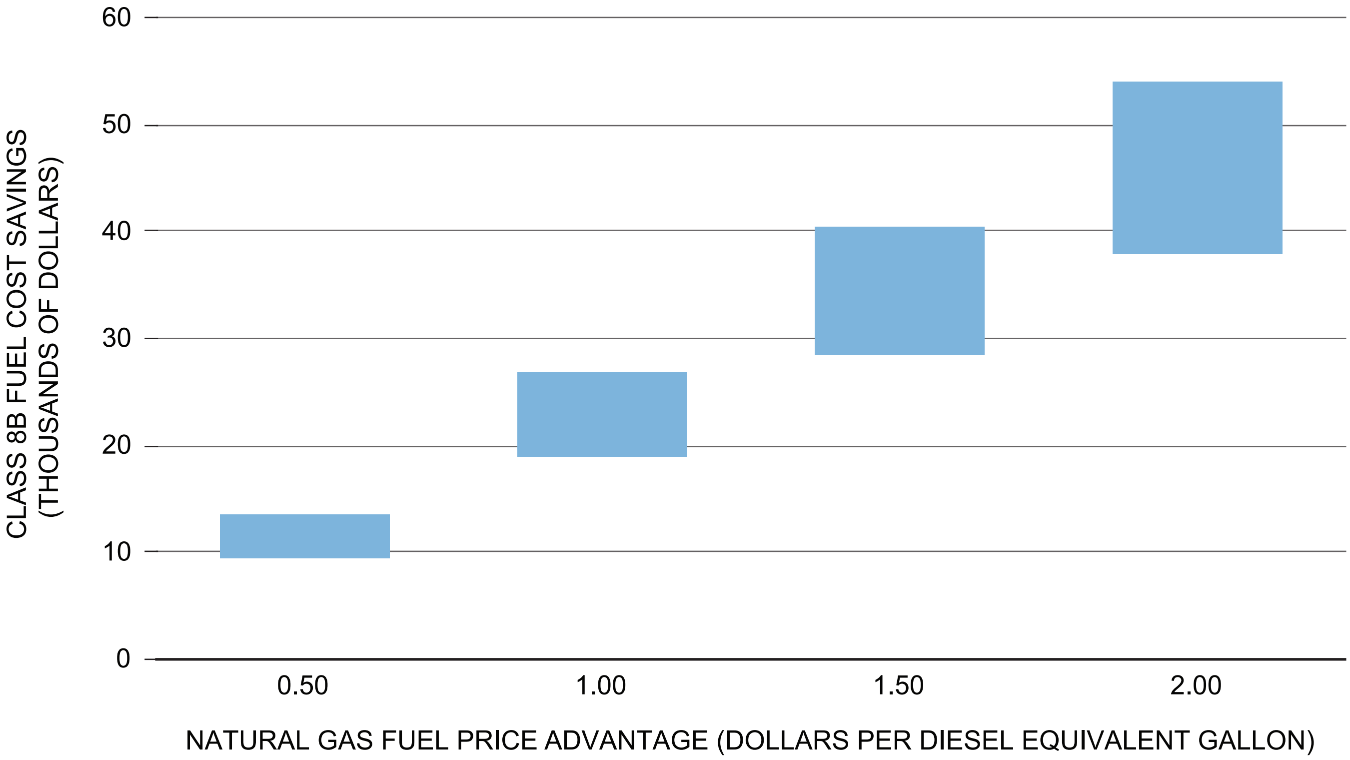

Figure 14-34. *Range of Potential Annual Fuel Cost Savings for Class 8b Trucks*

Variables for assessing long-term cost-benefit of different technologies include vehicle costs, fuel price assumptions, and time to payback. Payback is a frequently used metric by the trucking industry and is calculated as time it takes to recoup the incremental investment in natural gas technology via fuel cost savings. Assuming a Class 8 truck travels 120,000 miles per year with an average fuel economy of 6.1 mpg, the fuel price spread between natural gas and diesel in order to achieve payback in two or four years is shown in Figure 14-35 as a function of the price premium of a natural gas truck.

If natural gas fuel is $1.00 per DEG lower than diesel fuel, natural gas trucks will achieve payback within four years if the system price is less than $80,000, and within two years for systems costing less than $40,000. If the fuel price spread increases, the time required to payback the incremental truck premium is reduced. In the study reference case, the fuel price differential exceeds $2.00 per DEG after 2020, which would reduce the payback period to two years and one year, respectively, in the above analysis.

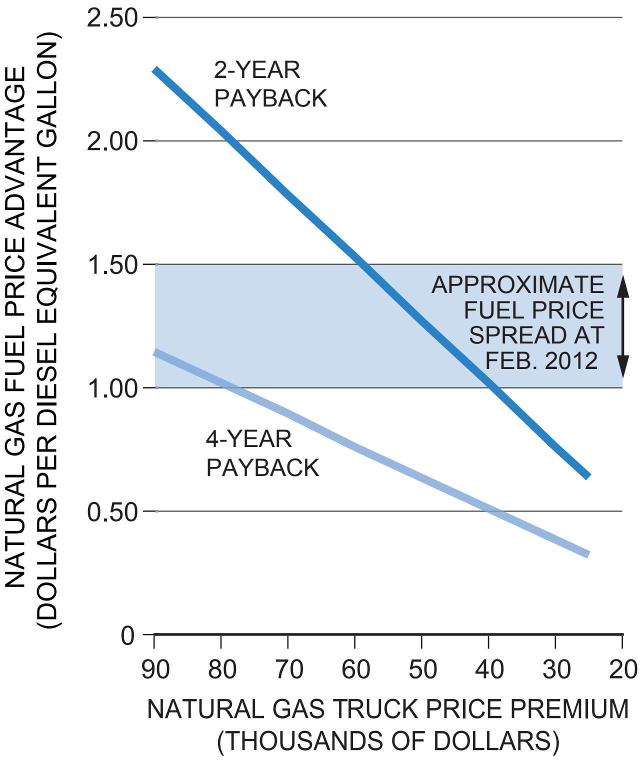

Figure 14-35. *Fuel Price Spread Required for Economic Payback*

Clearly, assessing the cost effectiveness of CO_2 reduction from either diesel or natural gas trucks is a multi-dimensional exercise, with a number of input parameters. While fuel cost savings can dominate the analysis when fuel use is high, the relative effect of these savings is diminished as higher fuel economy technology is considered.

Hurdle Summary for Heavy-Duty Natural Gas Vehicles

Based on the discussion of fuel supply, refueling infrastructure, and vehicle technologies, Figure 14-36 provides a summary of the readiness of natural gas HD vehicles to expand to wide-scale commercialization. The hurdles cover items of technical, logistical, and commercial scope. The diagram highlights the main technological, commercial, and logistical criteria that NGVs need to address. Many of the attributes are coded as blue, but several key attributes are coded yellow or red indicating that commercial, logistic, and technical advances are required.[60]

There are few technical barriers to an expansion of natural gas vehicles in HD applications given product advancements made over recent years. The primary challenge remains one of system cost relative to comparable diesel and gasoline trucks, both in terms of engine systems and fuel storage and the availability of refueling infrastructure.

Continued engine developments to optimize systems for operation with natural gas would result in further performance enhancements. A greater degree of OEM involvement is required to achieve greater system optimization for natural gas fueling, to increase the range of engine options, and to incorporate advanced fuel economy technologies in both natural gas and diesel vehicles.

TECHNOLOGY AND PRODUCT ATTRIBUTES OF LIGHT-DUTY NATURAL GAS VEHICLES AND ENGINES

The following elements will be considered in review of LD NGV technology:

- Powertrain integration
- Vehicle fuel storage
- Vehicle integration and fuel system packaging
- Vehicle performance and utility attributes.

In many cases, the European market represents the leading edge of current NGV technology in the LD segment. However, both European and North American OEMs offer fully integrated factory products featuring advanced powertrains alongside natural gas options.

Powertrain Integration Strategies

Customer requirements in terms of power, torque, acceleration, maneuverability, and range hold true for NGVs as they do for gasoline and diesel vehicles of all types. These are more fully addressed in Chapter Nine, "Light-Duty Engines & Vehicles."

Bi-fuel (natural gas and gasoline fueled) vehicles represent an entry pathway into the market for NGVs since they can extend the operating range of the vehicle in the absence of readily available natural gas refueling. Bi-fuel systems are commonplace among NGV fleets in Europe. Due to the differing fuel characteristics, operation on one of the fuels is often compromised. For example, if the compression ratio is optimized for CNG then a de-rated gasoline performance rating may be implemented to avoid engine knock.

In LD NGV applications based on gasoline engines, gaseous fuel is generally introduced into the intake manifold, displacing airflow and reducing overall power and torque potential, particularly on naturally aspirated engines. The adoption of turbocharging in gasoline engines can help address this.

Further developments in spark ignited natural gas engines to improve natural gas performance include:

- Compression ratio optimization to take advantage of the high octane rating of natural gas.
- Improved piston chamber design to optimize air motion for natural gas combustion.
- Improvements in materials for intake/exhaust valves and valve seats to reduce wear since natural gas is a low lubrication fuel.
- Valve train optimization to the air and EGR characteristics of natural gas engines.

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[60] Blue color coding indicates minimal or no barrier, with yellow and red indicating increasingly significant barriers.

HURDLE	REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	RATING	COMMENTS
ENGINE:			
POWER & TORQUE	NG ratings should be equal to Diesel for target HD applications	🔵	Able to match majority of ratings by engines size as diesel
EFFICIENCY	Within 10% of diesel to preserve fuel economy, GHG, with long term pathway for improvement	🔵	Compression Ignition engines meet diesel efficiency. Spark Ignition within 10% in some applications
HOT/COLD WEATHER PERFORMANCE	Equal cold performance to ICEs	🔵	Utilize similar strategies to gasoline or diesel
EMISSIONS COMPLIANCE	Emissions compliance with no incremental aftertreatment over diesel	🔵	Able to comply with use of DPF and/or SCR. Spark Ignition complies with three-way catalyst
FUEL SUBSTITUTION	Maximize diesel displacement for optimum fuel efficiency and cost trade-off	🔵	100% diesel substitution by Spark Ignition. Up to 95% with Compression Ignition
FUEL QUALITY ROBUSTNESS	Tolerant to expected range of NG composition without excessive de-rate	🟡	Able to operate down to 75 MN (methane number) without damage. Benefit from fuel quality sensing to adjust power under extreme fuels
DURABILITY	Engine durability equal to Diesel	🔵	With shared architecture, ratings and OEM support. May require dedicated NG maintenance
OEM PRODUCTION	Factory built, first fit engines to provide build capacity and diversity of product options	🟡	Limited range of engine options available today but OEM engagement increasing. Minimal plant investment required
NG OPTIMIZED DESIGNS	Engine systems designed specifically for NG operation	🟡	Current HD NG engines use diesel architecture. Custom designs not required for acceptable performance, but could offer improvements
ONBOARD FUEL STORAGE:			
CNG STORAGE CAPACITY	No impact on required vehicle operating range compared to diesel	🟡	Acceptable for municipal, transit, refuse and urban delivery. Unsuitable for long haul. Benefit from R&D in high density storage – adsorbent nano-structures
LNG STORAGE CAPACITY	No impact on required vehicle operating range compared to diesel	🔵	400 to 600 mile range is possible with dual LNG tank systems, but high cost premium in low volume
FUEL VENTING	No unintentional venting of fuel	🟡	LNG must be used within timeframe. OK for high use fleets. Benefit from dev't of vapor recovery & reinjection systems
CRYOGENIC SYSTEM DURABILITY	No impact on vehicle robustness or failure rate	🟡	High Pressure LNG pumps needed for some Compression Ignition systems. Durability needs continued improvement. Fuel level sensing robustness
VEHICLE:			
VEHICLE OPTON AVAILABILITY	Broad range of OEM vehicles tailored for different segments and vocations	🔵	Increasing diversity of vehicle options available today. Will grow as market expands
OEM INTEGRATION	Optimized vehicle integration into vehicle platform and factory build	🔵	OEM involvement is obsoleting requirement for retrofit NG conversions
OPERATING RANGE	Fit for purpose by segment, vocation, without excessive refueling	🟡	Some current limitation. Leverage fuel economy technology to reduce fuel storage required and increase range
TELEMATICS	Compatible with IT based scheduling, monitoring & optimization systems	🔵	No restriction, investment in product options required and system tailoring for NG needed
WEIGHT & CARGO LOAD	Weight increase manageable without operating impact	🟡	NG fuel storage increases vehicle weight (and may displace cargo in some applications). Benefit from lightweighting and fuel economy improvement
SAFETY	No unmanageable saftey risks from vehicle operation & maintanenance	🔵	Appropriate use of design, codes & standards, education and training
VEHICLE ECONOMICS:			
VEHICLE PRICE PREMIUM	Competitive with comparable ICE vehicle	🔴	Significant premium today, requiring extended capital or incentives. Can be reduced with volume & OEM engagement
FUEL COST PER MILE	Equal or less than comparable ICE vehicle	🔵	Combined fuel efficiency and lower fuel price creates operating cost advantage
PAYBACK PERIOD	Within 3 years to offset capital expense	🟡	Can be achieved with low fuel cost, and sufficient mileage. Assisted by price premium reductions
TOTAL COST OF OWNERSHIP	Competitive with, or lower than, diesel	🔵	Fuel cost savings dominate over longer periods. Secondary market required to protect residual value to first owner

🟩 PRIORITY FOCUS AREA TO ENABLE WIDE-SCALE COMMERCIALIZATION

🔵 MINIMAL/NO BARRIERS

🟡 WILL TAKE INVESTMENT AND TIME, BUT PATHWAY FOR SUCCESS HAS BEEN IDENTIFIED

🔴 SIGNIFICANT BARRIER OR HIGH RISK OR HIGH UNCERTAINTY OR REQUIRES "BREAKTHROUGH OR INVENTION"

Figure 14-36. *Hurdles for Heavy- and Medium-Duty Natural Gas Vehicles*

- Improved exhaust aftertreatment systems to manage the methane emission requirements of natural gas engines.
- Improvements in conventional spark plugs and ignition systems to address potential increased wear due to the need for increased ignition energy in natural gas operation.
- Turbocharged, downsized, high compression ratio engines for improved fuel efficiency. The high octane rating of natural gas may even offer greater benefits than for gasoline, although gasoline injection has the advantage of charge cooling.
- Improved electronics and control systems that are fully integrated with vehicle systems including provisions for full OBDII requirements (see "Engine Management System Conversion Challenges" below).
- Direct injection natural gas to improve combustion efficiency (see "Engine Fuel Delivery Shift from Port Fuel to Direct Injection Challenges" below).

Engine Management System Conversion Challenges

Over and above base powertrain accommodations, fuel control and associated diagnostic systems are necessary. In general, these are described by three basic approaches.

- Dedicated CNG. One method is to build a gasoline vehicle, disable gasoline fuel system controls, and then retrofit the appropriate natural gas systems. A second alternative is to build the vehicle as a ground-up, CNG-fueled vehicle. The former is the more common approach in the aftermarket.
- Aftermarket CNG Bi-Fuel. Most systems of this type install an additional CNG controller through the data link connector for the gasoline engine. For the most part, the base engine control module is not aware of the presence of this CNG controller. The diagnostics system is essentially running gasoline diagnostics.
- Integrated CNG Bi-Fuel Controls Approaches. Potential methods for integrating CNG functionality may include either a supplier derived or specific fuel injector control module on a control area network (CAN) bus or a full function engine control module (ECM) with all CNG plus gasoline functionality in a single controller. In order to implement an OBDII compliant dual-fuel solution, significant modifications to the base vehicle electronic control unit (ECU) software are required to accommodate both fuels, either in a single controller or secondary controller approach. Aftermarket converters typically do not have access or ability to modify proprietary OEM control software; therefore it has not been possible to bring fully OBDII compliant dual-fuel CNG applications to market. Even OEMs have not offered dual-fuel CNG vehicles since the 2006 model year.

Engine Fuel Delivery Shift from Port Fuel to Direct Injection Challenges

Fuel economy legislation is leading to the development of even more fuel efficient engine technologies. Many powertrains are shifting from gasoline injected at the intake ports (Port Fuel Injection [PFI]) to injecting gasoline directly into the combustion chamber (Gasoline Direct Injection [GDI]). GDI presents new challenges for NGV conversions:

- Thermal management of GDI fuel delivery system components such as the high-pressure pump and injectors needs to be addressed as a result of no cooling offered to the gasoline injector when operating on natural gas.
- Engine oil pumps, nozzles, and coolers may require design changes in order to manage heat due to the high combustion chamber temperatures in natural gas mode.
- Adapting base vehicle GDI controls to CNG PFI, and accommodating PFI components in base engine GDI architecture.
- Turbocharger designs may need to change in order to achieve a faster response time to minimize performance differences between gasoline and natural gas operation.

Through improvements in volumetric efficiency, power output, and the efficiency of downsized direct injection, CNG engine performance can be extended, approaching that of diesel, as illustrated in Figure 14-37.[61]

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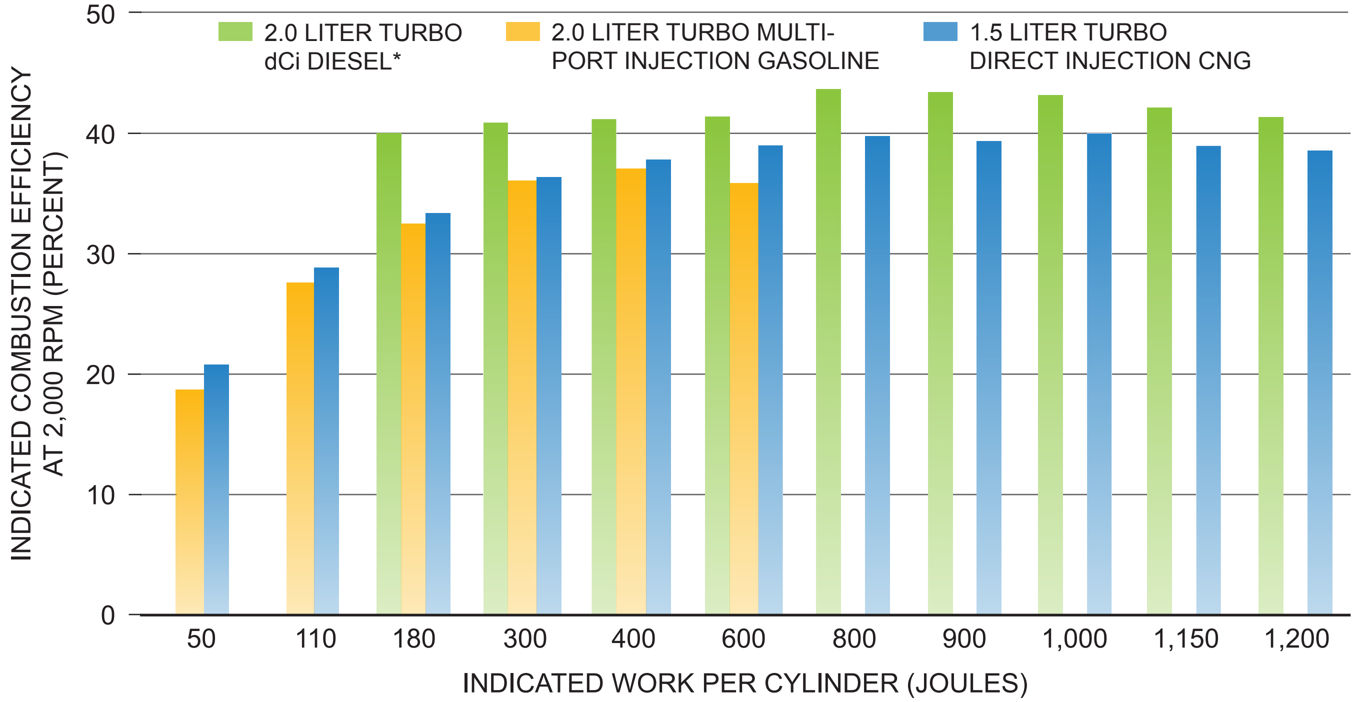
[61] Benoit Douailler et al., *Direct Injection of CNG on High Compression Ratio Spark Ignition Engine: Numerical and Experimental Investigation,* SAE Technical Paper 2011-01-0923, April 12, 2011, http://papers.sae.org/2011-01-0923/.



*Based on Renault common-rail diesel injector (dCi) technology.

Source: SAE International, Technical Paper 2011-01-0923.

Figure 14-37. *Increased Power Capability of Direct Injection CNG*

Additional Powertrain/ Vehicle Enhancement Challenges

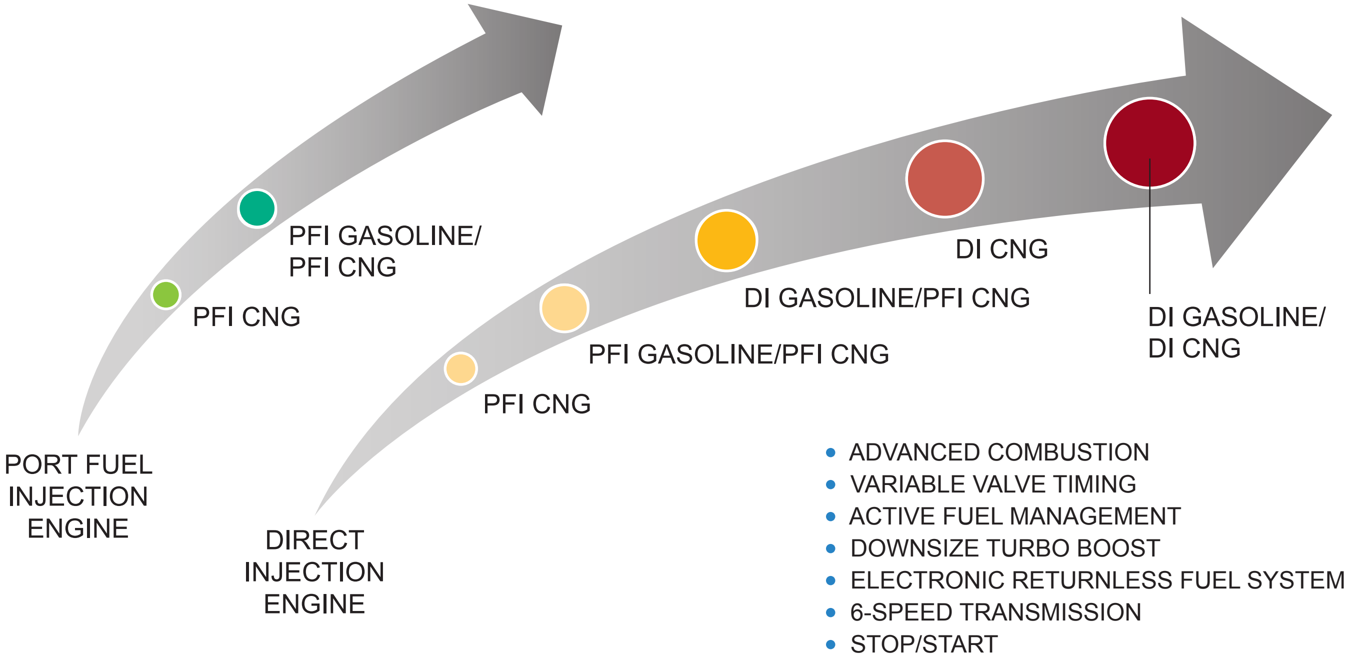
Gasoline and diesel powertrains will continue to evolve as illustrated in Figure 14-38 and incorporate advanced combustion, variable valve timing, active fuel management (cylinder deactivation), downsized turbo boost, electronic returnless fuel systems, six speed transmissions, and stop/start technologies to achieve fuel economy improvements. The incorporation of natural gas fuel variants will require suitable comprehension by design, software control, and calibrations to understand the additional base powertrain complexity. Currently, in the United States there are no recognized OEM offerings operating on CNG that comprehend the full range of these base powertrain advancements. European models are starting to incorporate some of them where they are adopted by gasoline vehicles.

As discussed within Chapter Nine, "Light-Duty Engines & Vehicles," a range of technologies exist for both powertrain and vehicle enhancements that if applied to LD CNG vehicles would result in a significant improvement in overall NGV fuel economy. Table 14-8 summarizes the possible impact such technologies could have, highlighting the range of fuel economy considered for NGVs in each vehicle class being evaluated in this study. Adding such technology advancements comes at a cost,

	2010 Fuel Economy (mpGGE – lab)*	Max Fuel Economy Considered (mpGGE – lab)*
Small Car	34.5	69.0
Large Car	32.3	64.6
Pick Up	23.9	47.8
Small SUV	27.3	54.6
Large SUV	24.4	48.8

* Fuel economy estimated in a laboratory in contrast to on the road. To convert to on-road use, a multiplier of 0.8 may be used.

Table 14-8. *Range of NGV Fuel Economy Considered within this Study*



Note: PFI = port fuel injection; DI = direct injection.
Source: General Motors.

Figure 14-38. *Technology Pathways for Advanced Light-Duty CNG Engines*

and therefore the trade-off between fuel economy, vehicle cost, and fuel price is critical in determining the cost effectiveness of any given solution set for NGVs.

Improvements in fuel economy for LD vehicles will assist with the extension of the operating range for a given natural gas fuel tank size, or permit smaller and potentially less expensive fuel storage solutions for a given range. Smaller fuel storage containers would also lend to simpler vehicle packaging and integration.

Fuel Storage – CNG Cylinders

Most of the early CNG containers were Type 1 steel due to the cost effectiveness of this design type and materials of construction. As technologies advanced and newer materials became available, additional designs emerged: first the Type 2 composite hoop wrapped steel containers, followed by the fully wrapped Type 3 and Type 4 containers. Current U.S.-based cylinder manufacturers produce Type 3 and Type 4 products. All Type 1 products come from offshore suppliers.[62]

Figure 14-39 shows trade-offs between weight and cost for the different types of CNG cylinders available.[63]

Future opportunities for cost reduction of CNG cylinders in LD applications generally include optimization of current technologies. The largest cost driver of Type 3 and Type 4 containers is the cost of materials for the composite outer wrap, made primarily with carbon fiber. Reduction of material costs may be achieved in the future through

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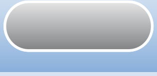
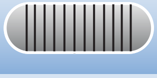
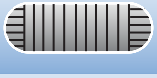
[62] Because developing economies will continue to make up the majority of the forecasted market for CNG-powered vehicles, the Type 1 pressure vessels are expected to maintain a market share of about 93% (by unit volume) over the next few years. Composites World (website), "The Outlook for Composite Pressure Vessels," *Composites Technology,* February 2009, http://www.compositesworld.com/articles/the-outlook-for-composite-pressure-vessels.

[63] Owens Corning, "Innovation in Composite CNG Cylinders," Industry presentation for JEC Asia 2009 Automotive & Mass Transport Forum (2009), http://www.ocvreinforcements.com/pdf/library/Owens_Corning_Innovation_Composite_CNG_Cylinders_JECAsia2009_091009.pdf.

the development of improved winding patterns for the composite wrap to reduce the amount of carbon fiber necessary for a given design, as well as improvements in manufacturing methodologies for the production of the carbon fiber strands.

Another opportunity for mass and cost savings in CNG storage is through modification in industry standards to align with requirements for hydrogen-fueled vehicles. The current standards for CNG fuel systems are prescriptive in nature, requiring containers to meet an initial burst pressure ratio based upon the materials of construction and container type.[64] Comparable hydrogen storage requirements are developed from a vehicle end-use perspective, and contain performance-based requirements that specify sequential testing along with end-of-life strength requirements. The current testing results show that the initial burst pressure for a given design may be reduced based upon end-of-life performance in this testing sequence. A reduction in the initial burst pressure could allow a corresponding reduction in the amount of materials used in the construction of the container.

Advanced new material alternatives, including the application of high strength metallic materials and the development of new composites could potentially lead to less expensive storage without incurring significant weight penalties. Novel storage technologies such as adsorbent materials, or metal organic frameworks, that increase the storage density of methane, could allow smaller volume tanks on an energy basis, which would be beneficial to vehicle packaging. Additionally, these new technologies may enable storage of natural gas at lower system pressures with the potential to decrease fueling infrastructure costs by reducing need for high-pressure compression systems. Such technology advances could be an enabler to home-refueling systems since a significant element of the cost of home refueling is the need for small-scale, high-pressure compressors. However, with low-pressure storage and low-pressure dispensing, fuel filling times may be extended due to the low mass flow rate of fuel into the tank. This

	TYPE 1	TYPE 2	TYPE 3	TYPE 4
				
MARKET SHARE	93%	4%	< 2%	< 2%
STRUCTURE	Metal	Metal Liner Reinforced with Resin Impregnated Continuous Filament (Hoop Wrapped)	Metal Liner Reinforced with Resin Impregnated Continuous Filament (Fully Wrapped)	Resin Impregnated Continuous Filament with a Non-Metallic Liner
MOST COMMONLY USED	CrMo Steel	CrMo Steel with Glass Fiber	Aluminum with HP Glass and/or Carbon	HDPE Liner with Carbon
INDICATIVE COST – U.S.$/LITER	$3 to $5	$5 to $7	$9 to $14	$11 to $18
INDICATIVE WEIGHT – KG/LITER	0.9~1.3	0.8~1.0	0.4~0.5	0.3~0.4

Note: Evident weight reduction (up to 75%) in adopting Types 3 and 4, but comes at a cost.

Sources: CompositeMarketReports.com, CompositeWorld.com.

Figure 14-39. *Classification and Comparisons of Light-Duty CNG Cylinder Options*

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[64] Mark Trudgeon, *An Overview of NGV Cylinder Safety Standards, Production and In-Service Requirements,* July 2005, http://www.apvgn.pt/documentacao/overview_of_ngv_cylinder_safety_standards.pdf.

may not be an issue for overnight home refueling, but could be a hurdle for refueling at retail stations.

New alternatives for fuel storage should be considered as a multi-dimensional system, with careful consideration of cost, mass, and volume on the engine and vehicle. While the opportunity to employ low-pressure storage can reduce the need for expensive compression at dispensing locations, the impact on the legacy vehicle fleet must be considered in any analysis. There are a number of funded projects in this area and additional research and development would be required before these technologies are considered commercially viable.[65]

Vehicle Integration – Packaging of CNG Fuel Storage

Adapting LD gasoline or diesel vehicles to CNG can compromise overall vehicle design and performance attributes due to the challenge of integrating fuel storage systems. In bi-fuel CNG gasoline vehicles, the primary fuel system is retained and addition of the CNG fuel tank consumes vehicle cargo space. Even in dedicated CNG vehicles, the lower volumetric energy density of CNG relative to gasoline requires either greater fuel storage volume (space claim) or reduced GGE fuel storage (range limitation).[66]

For passenger cars, CNG containers have typically been located in the luggage compartment of the vehicle, which naturally reduces the available cargo space. Figure 14-40 shows the 2006–2010 Model Year Honda Civic GX, a dedicated CNG vehicle with a single 8 GGE CNG fuel tank mounted in the luggage compartment.[67] The advertised cargo capacity of this vehicle is 6.0 cubic feet, which is a reduction from the advertised 12.5 cubic foot capacity for the gasoline version.

As LD NGVs increase in the marketplace and OEMs are able to modify gasoline vehicle architectures to accommodate the additional space requirements of the CNG storage systems, the vehicle attribute tradeoffs are more transparent to the customer. With full OEM integration, stimulated by significant product demand, CNG fuel tanks may be better integrated within the overall vehicle platform.

The current Opel Zafira ecoFLEX CNG vehicle is produced for the European market (Figure 14-41).[68] The Zafira's ultra-compact rear axle allows the CNG fuel storage system to be integrated, along with a small gasoline tank, under the load floor of the vehicle with no impact to the cargo or passenger capacity of the vehicle.

Another example of CNG tank integration in a small A-segment vehicle is represented by the Fiat Panda Natural Power, where two Type 1 steel tanks with a total capacity of 72 liters have been located under the floor with no reduction of the trunk volume, while still maintaining a 10-liter gasoline tank, as illustrated in Figure 14-42.[69]

In LD trucks, the CNG storage cylinders are typically packaged within the pickup box. Other options, most notably utilized on LD vans, include under-floor and in-vehicle integration of CNG cylinders, although careful consideration must be given to other vehicle attributes such as ground clearance, break-over, and ramp departure angles. Sufficient protection of containers and valve systems for under-vehicle mounted systems is also a consideration that can increase overall vehicle mass. Other key integration trade-offs to be considered include cargo space, location and size of spare tires, and access to fueling receptacles, among others.

Vehicle Performance and Utility Attributes

Owner satisfaction in relation to CNG LD vehicle attributes has not been frequently surveyed. Based on a 2001 survey, interviewees were "most

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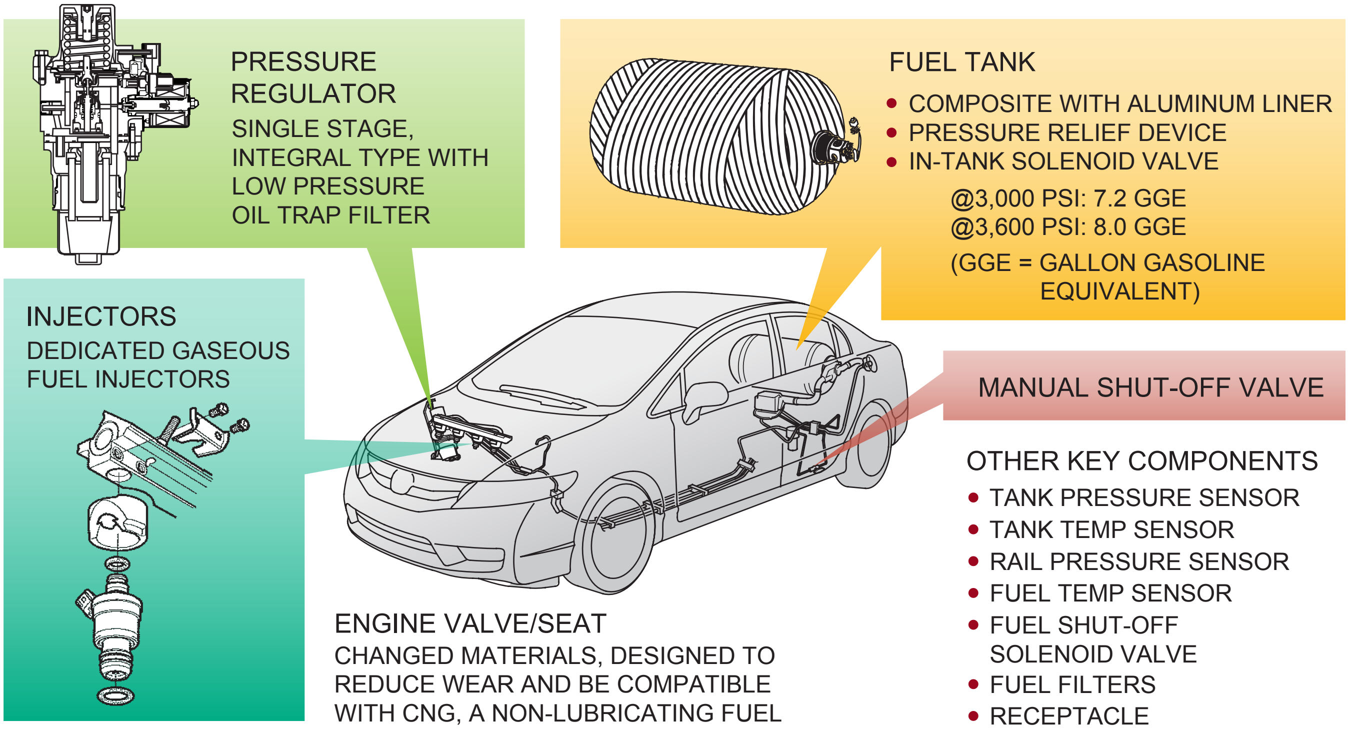
[65] Shengqian Ma and Hong-Cai Zhou, "Gas storage in porous metal-organic frameworks for clean energy applications," *Chemical Communications* 46 (2010): pages 44-53, http://www.chem.tamu.edu/rgroup/zhou/PDF/075.pdf.

[66] The cost/mass/vehicle attribute tradeoffs for the light-duty segment must take into account the market segment for the individual vehicle and the integration of the packaging. What may not make sense for a passenger car that packages the fuel storage in the luggage compartment (Honda Civic) may make sense for one that integrates fuel storage under vehicle (VW Passat/Opel Zafira). Additionally, different considerations may be made for pickup truck/full size van segments.

[67] Honda Civic 2006-1010 Service Manual, GX Supplement.

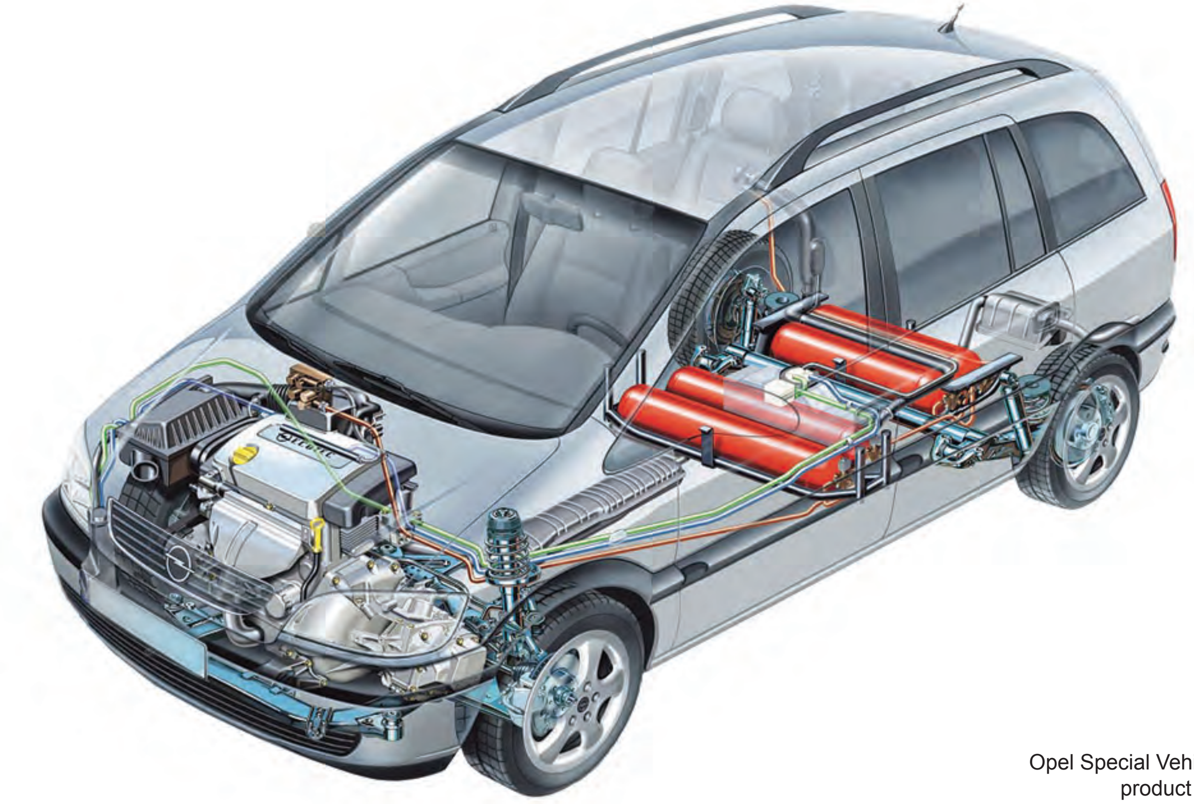
[68] Opel Special Vehicles GmbH, *Zafira 1.6 CNG Monovalent Plus: The Natural Gas Alternative,* product information, August 2002, http://www.apvgn.pt/veiculos/zafira_1_6cng_ingles.pdf.

[69] Information provided by email from Patricia Strabbing, External Affairs, at Chrysler Group LLC.



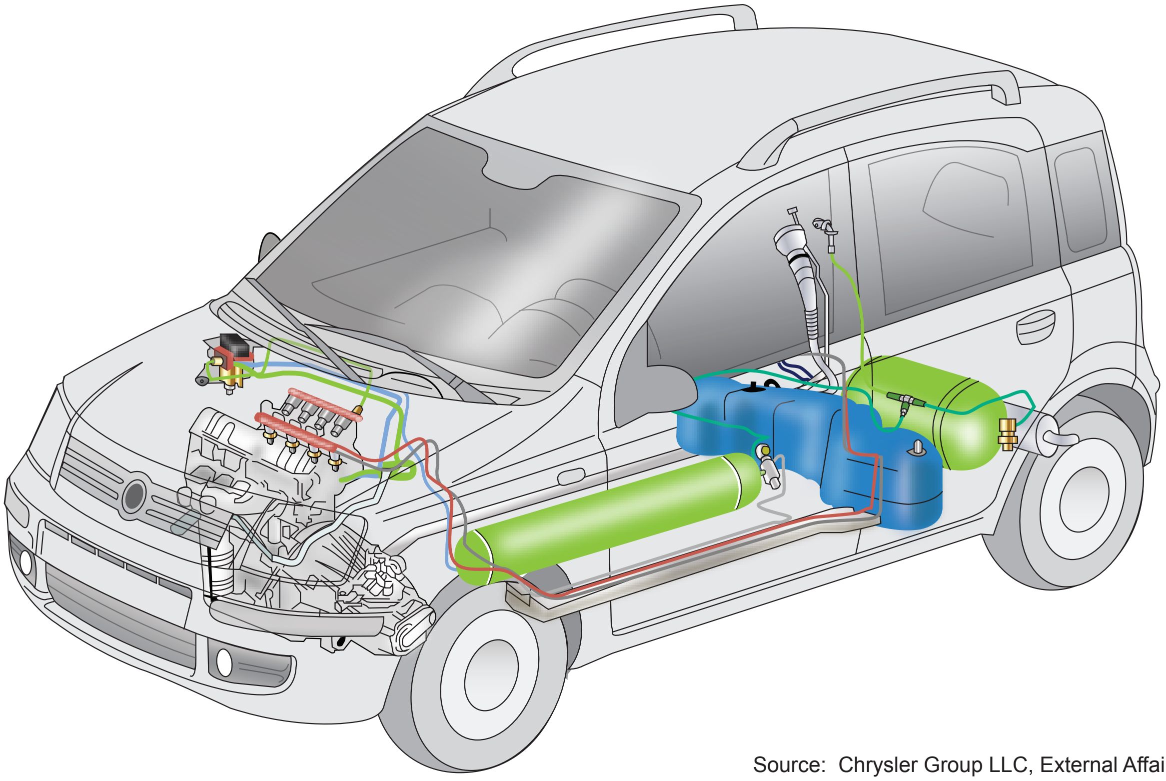
Source: Honda Civic 2006-2010 Service Manual, GX Supplement.

Figure 14-40. *Honda Civic GX Dedicated CNG Vehicle*



Source:
Opel Special Vehicles GmbH,
product information.

Figure 14-41. *Opel Zafira ecoFlex CNG*



Source: Chrysler Group LLC, External Affairs Office.

Figure 14-42. *European A-Segment, Bi-Fuel Fiat Panda Natural Power*

satisfied" with overall performance.[70] An April 2008 Consumer Reports article on the Honda Civic GX CNG vehicle stated that "drivers are not expected to notice a significant difference in performance between a CNG-powered vehicle and one fueled by gasoline. Acceleration is comparable, and the car starts and drives normally."[71] Several factors seem to be key to achieving NGV performance comparable to a vehicle operating on gasoline: similar power/torque curves, optimized compression ratios, similar transmission ratios, and a mass impact of less than 10%.

From the 2001 survey, the primary element of dissatisfaction was the reduced trunk space, as the majority of these respondents were owners of passenger cars with the CNG cylinder mounted in the trunk. The respondents indicated that limitations in trunk space precluded the vehicle being used for other travel where trunk space was required. The second highest source of dissatisfaction was the driving range of the vehicle. The volume of the CNG cylinder is often limited by the amount of space available for packaging and integration into the vehicle, causing drivers to fill the vehicle more frequently than with gasoline vehicles. Fully integrated solutions for fuel storage systems may help to overcome much of the impact on cargo capacity, and advancements in fuel economy are expected to increased vehicle range.

As discussed earlier, a wide range of technologies for fuel economy improvement are applicable to NGVs. Table 14-9 illustrates the fuel volume requirements for a fixed driving range of 300 miles based on the ranges of fuel economy from Table 14-8, assuming CNG stored at 3,600 psi. The direct relationship between fuel capacity and system space requirements results in significant volume considerations for vehicle integration. A step

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[70] Brian Anthony Abbanat, "Alternative Fuel Vehicles: The Case of Compressed Natural Gas (CNG) Vehicles in California Households," Master's Thesis, University of California, Davis (2001), interviews with seventeen vehicle owners, http://pubs.its.ucdavis.edu/download_pdf.php?id=368.

[71] Consumer Reports, "The Natural Gas Alternative: The Pros and Cons of Buying a CNG-Powered Honda Civic," product review (April 2008), http://www.consumerreports.org/cro/cars/new-cars/news/2006/the-pros-cons-of-buying-a-cng-powered-honda-civic/overview/0609_how-to-jump-start-a-car_ov.htm.

change in fuel energy storage density is required in order to fully mitigate the concerns about vehicle weight and storage space in NGVs.

Cost Structures of Light-Duty NGVs

The cost structure for NGVs is typically higher than that of equivalent gasoline vehicles due to the high cost of fuel storage and the cost of additional components. The cost structure varies between Europe and North America due to different regulatory and market requirements and also depending on whether vehicles are configured as bi-fuel with gasoline or as dedicated NGVs. In the case of bi-fuel vehicles, a lower cost structure may be possible due to a reduction in CNG fuel storage capacity given that the vehicle is able to default to gasoline operation. However, this comes at the cost of the possibility of performance compromise due to the differing requirements of gasoline and natural gas combustion. For the purposes of this discussion, we have focused on estimates of the cost structure of dedicated CNG vehicles.

The availability of detailed cost information on natural gas components, systems, and vehicles in the public domain is relatively scarce, resulting in an approach to the economics of these technologies through market pricing. It should be recognized, however, that pricing is not derived solely from cost of the commodity as it may be influenced by the current incentives being offered in the marketplace, either financial (tax rebates) or non-financial (HOV lane access). To ensure adequate public data and equal approach, all prices quoted are the manufacturer's suggested retail price (MSRP).

Current Vehicle Pricing – U.S. and European Union

The range in vehicle prices currently offered in the United States or the European Union today varies considerably, as indicated by the sample of offerings from different OEMs shown in Table 14-10. Prices were representative of those effective as of June 2011.

In general, U.S. vehicle pricing is higher than European vehicle pricing. However, differences in technologies need to be understood when making this type of comparison. For example, CNG containers in the EU operate at a service pressure of 3,000 psi, while 3,600 psi is the norm for the U.S. market. Increasing pressure allows for increased range for a given volumetric capacity, but at a pricing premium. Similarly, different regulatory, emissions, and diagnostics requirements may contribute to the relative complexity of vehicle systems, and hence the cost of the systems. As detailed cost information is not available publicly, it must be recognized that an A to B comparison based on MSRP is not completely reflective of cost differential of system design and assembly.

Vehicle Cost and "Retail Price Equivalent" Analysis

In order to understand the cost potential for LD NGVs and to support integrated modeling phases of the study, the cost structure was segmented into a number of main areas:

- Fuel storage
- Compound mass
- Engine hardening

	2010 Fuel Economy (mpGEG – lab)	Fuel Required (GGE)	Fuel Storage Volume (Liters)	Max Fuel Economy Considered (mpGEG – lab)	Fuel Required (GGE)	Fuel Storage Volume (Liters)
Small Car	34.5	8.7	96.1	69.0	4.3	48.0
Large Car	32.3	9.3	102.6	64.6	4.6	51.3
Pickup	23.9	12.6	138.7	47.8	6.3	69.3
Small SUV	27.3	11.0	121.4	54.6	5.5	60.7
Large SUV	24.4	12.3	135.9	48.8	6.1	67.9

Table 14-9. *Impact of Fuel Economy on Reducing CNG Fuel Storage Requirements for 300-Mile Range*

Manufacturer	Model	Gasoline Price	CNG Price	Price Differential	
				€	$
General Motors	Savanna & Express Van			n/a	$14,890
Honda	Civic	$17,655	$24,590	n/a	$6,935
Fiat	Grand Punto 1.4 8V	€ 12,250	€ 16,500	€ 4,250	$6,063
Ford	Focus 2.0	€ 20,000	€ 23,400	€ 3,400	$4,850
Mercedes	B 180	€ 27,727	€ 29,334	€ 1,607	$2,292
Opel	Zafira 1.6 ecoFLEX	€ 20,995	€ 25,735	€ 4,740	$6,762
Volkswagen	Passat 1.4 TSI	€ 24,425	€ 29,825	€ 5,400	$7,703

Sources: Cars of Europe (website), "European Car Guide: All brands and models," market inventory database, accessed October 2011; and Byron Pope, "CNG Gaining Traction as Gas Prices Rise," WardsAuto, news article, April 11, 2011.

Table 14-10. *Current Retail Price Comparison of CNG vs. Gasoline Models*

- Emission certification, OBD, R&D costs, aftertreatment and controller calibration
- Fuel handling, fuel delivery, fuel injection, safety integration.

In each area, an upper and lower bound estimate was derived to reflect the uncertainty and variability in cost contributions. Furthermore, in order to project the cost trajectory and to set a consistent benchmark for integrated comparisons with other technologies, cost estimates have first been extrapolated to a point of initial material scale in 2020 (assuming volume productions commensurate with OEM production) and then discounted using a time-based reduction scale. An example of the result of this approach for the small car class is given in Figure 14-43.

The following sections discuss how the estimates for each cost category were developed. The starting point for the development of the Retail Price Equivalent Model was the calculation of the average MSRP of vehicles in each class for both the U.S. and European markets. The U.S. pricing for the small car and large SUV were based on current OEM offerings, and the large car, pickup, and small SUV were based on current aftermarket products as outlined in the previous section. Building from this starting point, estimates for the other categories can be made.

CNG Fuel Storage Costs

A range of storage costs were developed for low cost Type 1 steel tanks and more costly Type 4 carbon fiber fully wrapped composite lined containers. Storage costs were split into a fixed cost representing valves, fittings, and other factors that do not change significantly with cylinder size, and a variable cost based on storage volume (see Table 14-11).

Type 1 costs were based on the data in Figure 14-39. Type 4 cylinder costs were derived from cost estimates for hydrogen fuel storage, modified for the reduction in working pressure. These costs were founded on a study from TIAX for 10,000 psi carbon fiber cylinders, and adjusted to 3,600 psi working pressures with support of a major component supplier.[72,73] Acknowledging that carbon fiber cylinders are only produced in low volumes, a low volume penalty of 2.0 times RPE was applied in 2010, reducing to 1.0 in 2030.

For each vehicle class, storage was sized for a 300-mile driving range based on the assumed 2010 fuel economy of NGVs, resulting in the RPE projections for fuel storage assuming constant fuel economy as shown in Table 14-12.

It is worth noting that this analysis is based on an assumed required driving range of 300 miles. In the case of bi-fuel vehicles that have the flexibility

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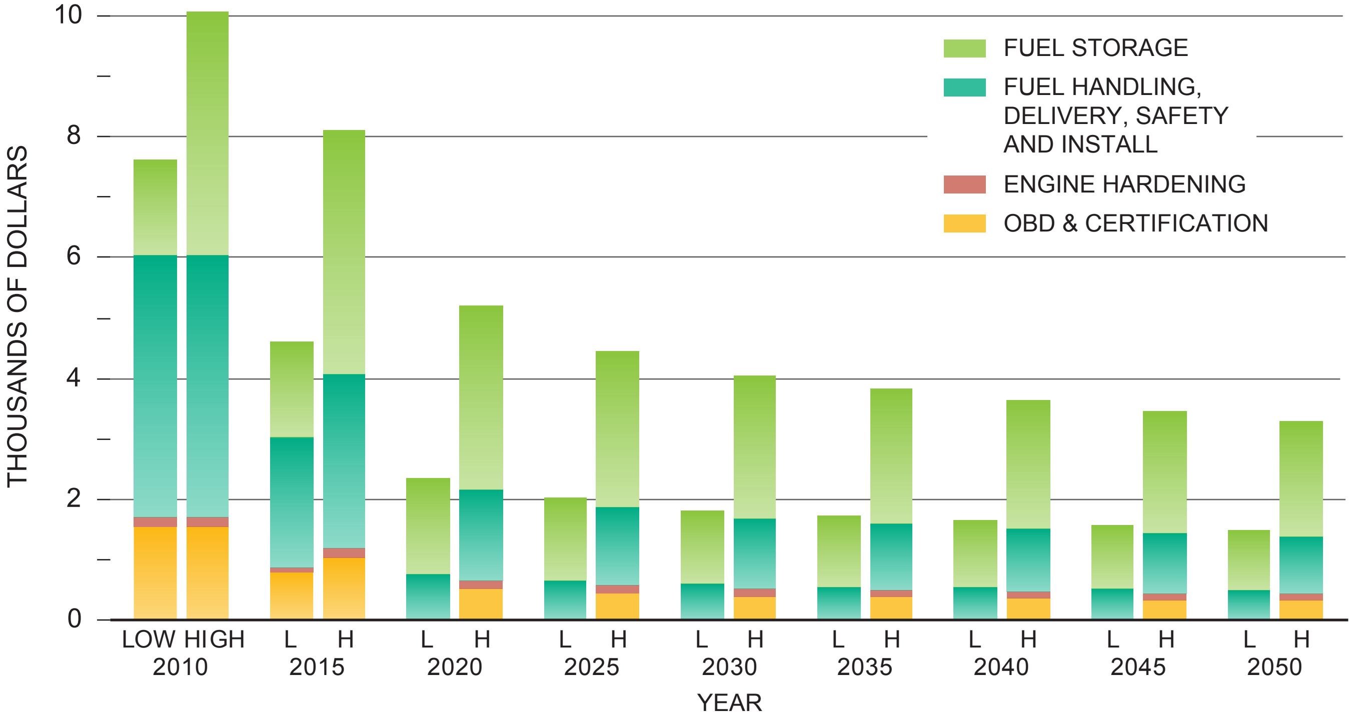
[72] Thanh Hua et al., *Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications,* Argonne National Laboratory and TIAX LLC, Report ANL-10/24, September 2010, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressedtank_storage.pdf.

[73] Neel Sirosh of Quantum Technologies, email message to Dick Kauling at General Motors, October 5, 2011.



Note: Assumes fixed fuel economy and fuel storage for 300-mile driving range.

Figure 14-43. *Estimate of Upper and Lower Bound of CNG Incremental Retail Price Equivalent in Small Car*

to fall back on gasoline operation, it is conceivable to reduce the storage capacity of CNG in order to reduce costs, and provide CNG operation that covers a smaller driving range more commensurate with the average daily use of typical LD consumer vehicles.

Cost of Compound Mass

The addition of CNG storage adds weight to the vehicle that may not have been incurred in the case of gasoline fuel tanks and this compound mass comes at a cost.[74] For the purposes of modeling, an assumption is made that for every pound of direct mass added via storage (including batteries) a further half pound of compound mass is added (representing mounting brackets and/or structural strengthening), at a cost of approximately $4.30 per pound in 2010, discounted over time (see Table 14-13). Storage mass was estimated at 28 pounds

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[74] The offset of the CNG tanks is technology dependent, and this is accounted for in the cost analysis (low cost Type 1 vs. high cost Type 4) and the associated cost of compound mass.

CNG Fuel Storage	2010	2015	2020	2025	2030	2035	2040	2045	2050
Type 1 Steel Tanks									
Fixed Cost	338	338	338	290	262	250	237	226	215
Variable $/GGE	115	115	115	99	89	85	81	77	73
Type 4 Carbon Fiber Tanks									
Fixed Cost	676	676	507	319	262	250	237	226	215
Variable $/GGE	311	311	233	147	121	115	109	104	99

Table 14-11. *CNG Storage Fixed and Variable Retail Price Equivalent*

CNG Cylinder Type	Lab Fuel Econ-omy (Miles per GGE)	On Road Fuel Econ-omy (Miles per GGE)	Volume of Fuel Required (GGE)	Retail Price Equivalent of CNG Storage								
				2010	2015	2020	2025	2030	2035	2040	2045	2050
Small Cars												
Type 1	34.5	27.6	10.9	$1,590	$1,590	$1,590	$1,365	$1,234	$1,173	$1,116	$1,061	$1,009
Type 4	34.5	27.6	10.9	$4,055	$4,055	$3,042	$1,915	$1,574	$1,497	$1,423	$1,354	$1,287
Large Cars												
Type 1	32.3	25.8	11.6	$1,673	$1,673	$1,673	$1,436	$1,298	$1,235	$1,174	$1,117	$1,062
Type 4	32.3	25.8	11.6	$4,280	$4,280	$3,210	$2,022	$1,661	$1,580	$1,502	$1,429	$1,359
Pickups												
Type 1	23.9	19.1	15.7	$2,144	$2,144	$2,144	$1,841	$1,664	$1,583	$1,505	$1,431	$1,361
Type 4	23.9	19.1	15.7	$5,553	$5,553	$4,165	$2,623	$2,155	$2,050	$1,949	$1,854	$1,763
Small SUVs												
Type 1	27.3	21.9	13.7	$1,915	$1,915	$1,915	$1,644	$1,486	$1,413	$1,344	$1,278	$1,216
Type 4	27.3	21.9	13.7	$4,934	$4,934	$3,700	$2,330	$1,915	$1,821	$1,732	$1,647	$1,566
Large SUVs												
Type 1	24.4	19.5	15.4	$2,108	$2,108	$2,108	$1,810	$1,636	$1,556	$1,480	$1,407	$1,338
Type 4	24.4	19.5	15.4	$5,455	$5,455	$4,091	$2,576	$2,117	$2,013	$1,915	$1,821	$1,732

Table 14-12. *Estimated Retail Price Equivalent of CNG Storage for 300-Mile Range*

CNG Cylinder Type	Mass per GGE (lbs)	Volume of Fuel Required (GGE)	Stor-age Mass (lbs)	Com-pound Mass (lbs)	Cost of Compound Mass Declines over Time								
					2010	2015	2020	2025	2030	2035	2040	2045	2050
					Cost of Compound Mass ($/lb)								
					$4.30	$4.30	$4.09	$3.89	$3.70	$3.52	$3.34	$3.18	$3.02
Small Cars													
Type 1	28.0	10.9	305	152	$655	$655	$623	$593	$563	$536	$510	$485	$461
Type 4	11.0	10.9	120	60	$257	$257	$245	$233	$221	$211	$200	$190	$181
Large Cars													
Type 1	28.0	11.6	325	162	$699	$699	$664	$632	$601	$571	$543	$517	$492
Type 4	11.0	11.6	128	64	$275	$275	$261	$248	$236	$225	$214	$203	$193
Pickups													
Type 1	28.0	15.7	440	220	$945	$945	$899	$855	$813	$773	$735	$699	$665
Type 4	28.0	15.7	440	220	$945	$945	$899	$855	$813	$773	$735	$699	$665
Small SUVs													
Type 1	28.0	13.7	384	192	$825	$825	$785	$746	$710	$675	$642	$611	$581
Type 4	11.0	13.7	151	75	$324	$324	$308	$293	$279	$265	$252	$240	$228
Large SUVs													
Type 1	28.0	15.4	431	215	$926	$926	$881	$838	$797	$758	$721	$685	$652
Type 4	11.0	15.4	169	85	$364	$364	$346	$329	$313	$298	$283	$269	$256

Table 14-13. *Estimated Retail Price Equivalent of Compound Mass from Fuel Storage*

per GGE and 11 pounds per GGE for Type 1 and Type 4 systems, respectively. With these assumptions, a cost component in the vehicle RPE can be assigned to compound mass.

Engine Hardening

The RPE estimate for 2010 engine hardening is based upon current average OEM engine hardening pricing. U.S. OEM van model offerings in the United States during the 2011 model year featuring hardened engines suitable for CNG are between $300 and $315. This is for 8-cylinder engines, so the pricing for 4- and 6-cylinder engines were prorated accordingly. This value is reduced through 2020 under the assumption that in higher production volumes the cost of engine hardening is reduced until there is no cost differential in valve train materials between CNG and gasoline engines. (See Table 14-14.)

Cost Contribution of Certification, OBD, Aftertreatment and Calibration

The 2010 RPE estimate associated with emissions and OBD compliance strategies and implementation was made by comparing the MSRP of vehicle models in Europe and the United States, and with some consideration that European NGVs are factory produced. An estimate was made that assigned the difference in MSRP to the differing costs between European and U.S. models to reflect calibration and controller differences, as well as R&D and engineering costs. Projecting forward to 2020 with the assumption of higher volume OEM-produced U.S. products, this incremental cost element was reduced under the assumption that there is little or no added cost to certification and engineering of CNG vehicles compared to a gasoline equivalent model. In the upper bound case, a nominal monetary amount was retained to reflect the possibility of additional components or costs associated with CNG fuel specific requirements. (See Table 14-15.)

Cost of Engine and Vehicle Fuel Delivery System and Safety Integration

This final category includes the integration of the fuel system into the engine and vehicle architecture and the associated safety requirements including vehicle crashworthiness. The total 2010 RPE price for this category was estimated as the balance of cost

	Retail Price Equivalent of Engine Hardening								
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Small Cars									
Lower Bound	$155	$78	$0	$0	$0	$0	$0	$0	$0
Upper Bound	$155	$155	$155	$133	$120	$114	$109	$103	$98
Large Cars									
Lower Bound	$230	$115	$0	$0	$0	$0	$0	$0	$0
Upper Bound	$230	$230	$230	$198	$179	$170	$161	$154	$146
Pickups									
Lower Bound	$310	$155	$0	$0	$0	$0	$0	$0	$0
Upper Bound	$310	$310	$310	$266	$241	$229	$218	$207	$197
Small SUVs									
Lower Bound	$230	$115	$0	$0	$0	$0	$0	$0	$0
Upper Bound	$230	$230	$230	$198	$179	$170	$161	$154	$146
Large SUVs									
Lower Bound	$310	$155	$0	$0	$0	$0	$0	$0	$0
Upper Bound	$310	$310	$310	$266	$241	$229	$218	$207	$197

Table 14-14. *Estimated Retail Price Equivalent of Engine Hardening*

	Retail Price Equivalent of Emissions, OBD, R&D, and Aftertreatment								
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Small Cars									
Lower Bound	$1,535	$768	$0	$0	$0	$0	$0	$0	$0
Upper Bound	$1,535	$1,023	$500	$429	$388	$369	$351	$334	$317
Large Cars									
Lower Bound	$4,900	$2,450	$0	$0	$0	$0	$0	$0	$0
Upper Bound	$4,900	$3,267	$500	$429	$388	$369	$351	$334	$317
Pickups									
Lower Bound	$4,481	$2,241	$0	$0	$0	$0	$0	$0	$0
Upper Bound	$4,481	$2,987	$500	$429	$388	$369	$351	$334	$317
Small SUVs									
Lower Bound	$5,550	$2,775	$0	$0	$0	$0	$0	$0	$0
Upper Bound	$5,550	$3,700	$500	$429	$388	$369	$351	$334	$317
Large SUVs									
Lower Bound	$3,890	$1,945	$0	$0	$0	$0	$0	$0	$0
Upper Bound	$3,890	$2,593	$500	$429	$388	$369	$351	$334	$317

Table 14-15. *Estimated Retail Price Equivalent Contribution of Certification, On-Board Diagnostics, and R&D*

accounting for the previous categories. The pricing for this category in 2020 reflects the potential cost savings associated with an integrated design approach and the assumption that all vehicles are fully OEM factory assembled. Higher CNG component costs, coupled with the potential for additional fuel specific design and validation requirements, were also factored into the 2020 pricing estimate. (See Table 14-16.)

Economics of Light-Duty NGVs

Evaluating the economics of any vehicle, including NGVs, is predicated on a number of assumptions, including mileage, fuel economy, fuel prices, and time period for economic comparison. In the example given in Table 14-17 and Figure 14-44, vehicle economics were compared over a five-year period, with assumptions on fuel prices and vehicle costs.[75] At fuel prices near parity, the cost of fuel used is almost identical for CNG and gasoline. The net difference in total vehicle costs over the five-year period is due to the assumed $6,000 incremental vehicle costs.

Identified in Figure 14-44, and illustrated more clearly in Figure 14-45, a change in gasoline fuel price to approximately $4 per gallon, with CNG prices at approximately $2 per gallon, would equalize the economics of the CNG vehicle if the vehicle cost remained the same. This is more illustrative of the relative fuel prices in the marketplace at the time of writing, April 2012.

Given the number of variables involved in economic comparisons and particularly recognizing the role of fuel prices and vehicle price premiums, the following figures further illustrate the relationship for payback of the incremental cost of NGVs in relation to gasoline vehicles.

In Figure 14-46, the analysis assumes a constant fuel economy of both gasoline and CNG vehicles of 34.5 miles per GGE in the laboratory (27.6 miles per GGE on-road). The graph uses an

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[75] Nazeer Bhore, "Natural Gas as a Transportation Fuel," corporate strategic planning document, Exxon Mobil Corporation, January 25, 2011, http://cta.ornl.gov/TRBenergy/trb_documents/2011%20presentations/Bhore%20Natural%20Gas%20-%20Session%20544.pdf.

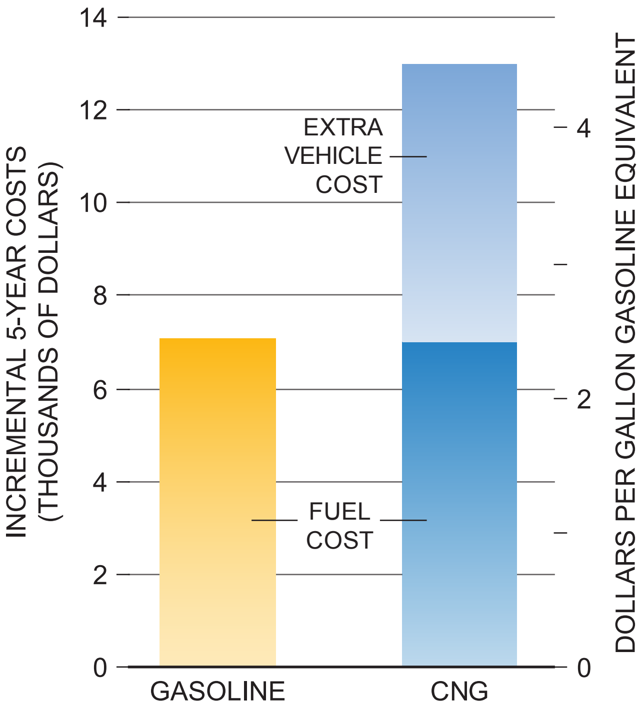
	Retail Price Equivalent of Engine & Vehicle Fuel System Integration								
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Small Cars									
Lower Bound	$3,670	$1,507	$345	$296	$268	$255	$242	$230	$219
Upper Bound	$4,068	$2,626	$1,243	$1,067	$965	$917	$872	$830	$789
Large Cars									
Lower Bound	$5,186	$1,905	$451	$388	$350	$333	$317	$301	$287
Upper Bound	$5,710	$3,330	$1,600	$1,374	$1,242	$1,181	$1,124	$1,068	$1,016
Pickups									
Lower Bound	$3,788	$2,163	$419	$360	$326	$310	$294	$280	$266
Upper Bound	$4,498	$3,954	$1,879	$1,613	$1,458	$1,387	$1,319	$1,254	$1,193
Small SUVs									
Lower Bound	$3,971	$1,760	$557	$478	$432	$411	$391	$372	$353
Upper Bound	$4,590	$3,280	$1,676	$1,439	$1,301	$1,237	$1,176	$1,119	$1,064
Large SUVs									
Lower Bound	$3,193	$2,185	$541	$465	$420	$399	$380	$361	$344
Upper Bound	$3,888	$3,961	$1,886	$1,620	$1,464	$1,392	$1,324	$1,259	$1,197

Table 14-16. *Estimated Retail Price Equivalent Contribution of CNG Fuel System, Integration, and Safety*

	Gasoline	CNG
Fuel Price ($ per gallon gasoline equivalent)	2.50	2.45
Fuel Price to Retailer*	1.80	0.80
Retailers Expense and Margin	0.20	0.25
Capital Charge for CNG Station	0.00	0.90
Fuel Taxes	0.50	0.50
5-Year Fuel Costs ($K)	7.1	7.0
Incremental Vehicle Costs ($K)	Base	+6.0

*Average U.S. wholesale price from 2002 to 2009, EIA.
Source: ExxonMobil 2010 Energy Outlook.

Table 14-17. *Personal Vehicle CNG Economics*



Source: ExxonMobil 2010 Energy Outlook.

Figure 14-44. *Example of Economic Comparison of CNG vs. Conventional Gasoline Vehicles*

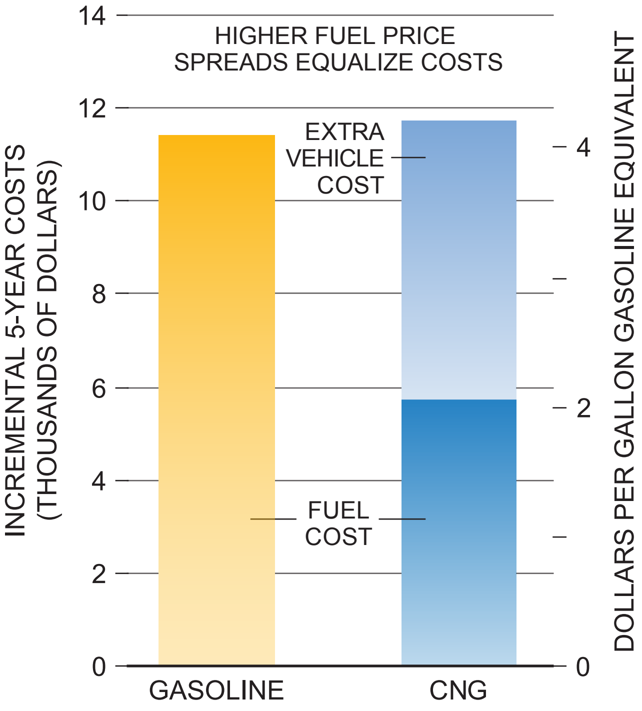


Figure 14-45. Example of Economic Comparison of CNG vs. Conventional Gasoline Vehicles at Higher Fuel Price Spreads

annual driving regime of 12,000 miles per year for a personal consumer and 24,000 miles per year for a fleet or utility customer.

Based on a current price premium of $7,000 to $8,000, a personal consumer driving 12,000 miles per year, requiring three-year recovery of the price premium, would require a fuel price advantage in excess of $5.00 per gallon with which to recoup the vehicle price premium. Conversely, a higher mileage customer such as a fleet, perhaps requiring a longer term five-year payback would reach this economic milestone with a fuel price advantage of $1.60 to $2.00 per gallon. Both examples have challenging economics, illustrating why incentives, tax credits, and other non-monetary incentives such as HOV lane access have been critical to supporting initial CNG vehicle adoption. If significant reductions in incremental vehicle cost premiums can be realized, as documented in this study, then the fuel price differential required to achieve payback is significantly reduced and every mile driven beyond that threshold would represent a relative savings.

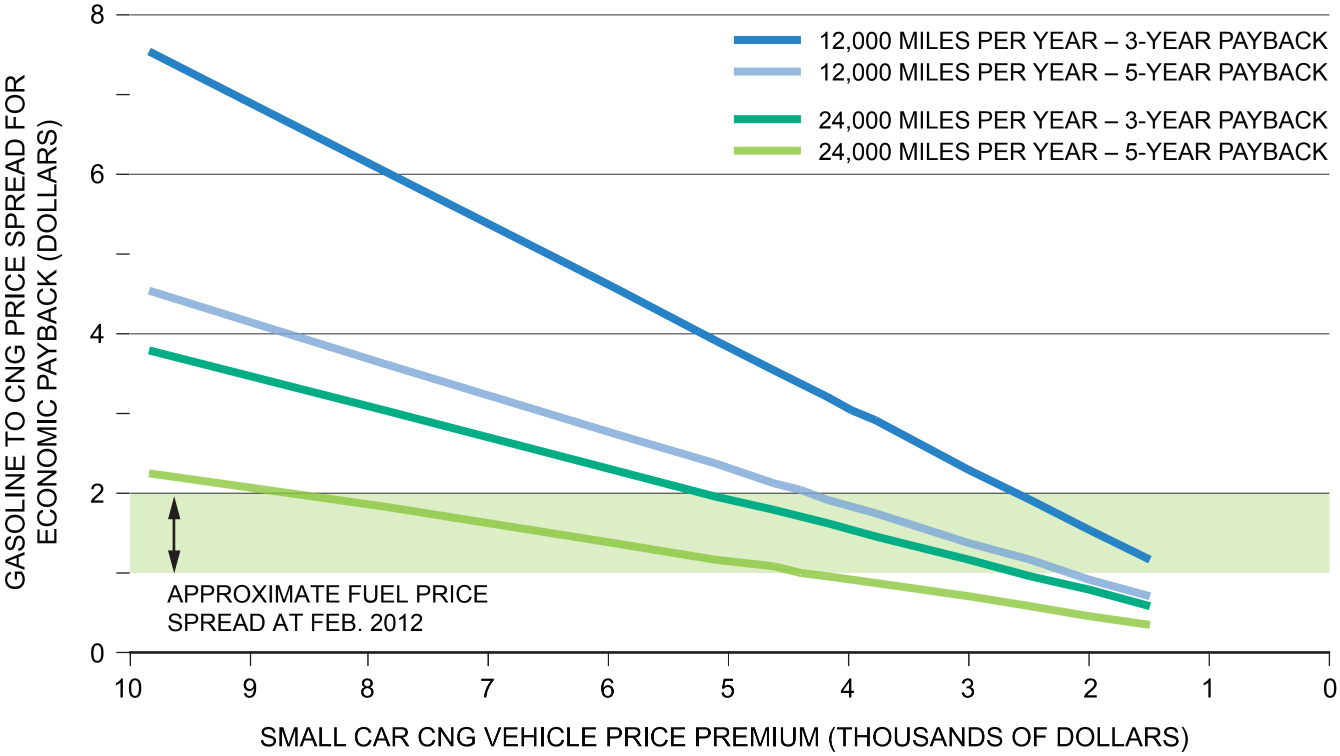


Figure 14-46. Economic Analysis of NGVs in Small Car Segment

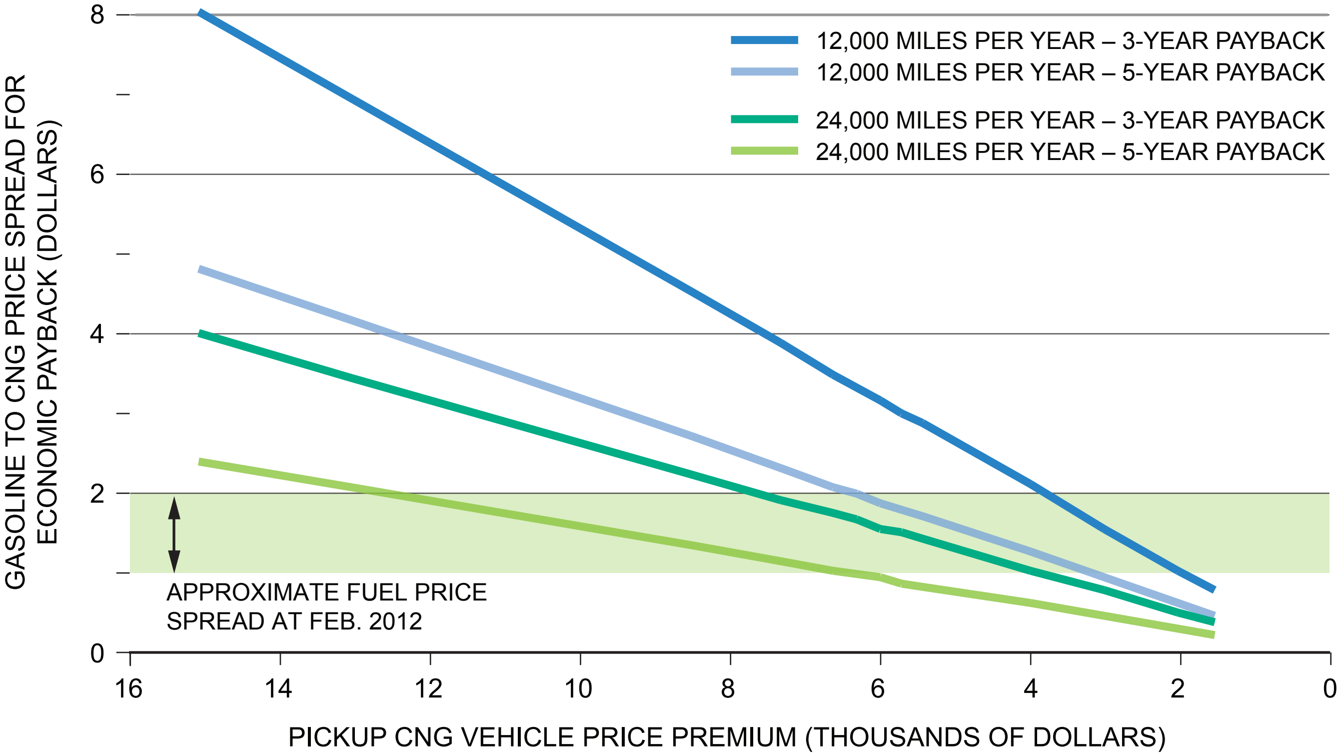


Figure 14-47. *Economic Analysis of NGVs in Pickup Segment*

To illustrate the impact of fuel economy on economics, Figure 14-47 shows a similar analysis for pickup trucks with an assumed lower on-road fuel economy of 19 miles per GGE.

At the same vehicle price premium of $7,000 to $8,000, the fuel price spread required for three-year payback in a low mileage case is approximately $4.00, and that for the longer payback, higher mileage customer is approximately $1.00. This highlights that under sustained price differential conditions, higher fuel consuming applications will reach economic competitiveness first. Conversely, in a future state where NGVs and other vehicle types have enhanced fuel economy, with lower total fuel use, the requirement for reduced vehicle price premiums and fuel price advantages will be higher in order to achieve economic parity or advantage.

Hurdle Summary for Light-Duty Natural Gas Vehicles

Based on the discussion of fuel supply, refueling infrastructure, and vehicle technologies, Figure 14-48 represents a summary of the current status of NGVs in terms of readiness to achieve wide-scale commercialization. The diagram highlights the main technological, commercial, and logistical criteria that NGVs need to address. Many of the attributes are coded as blue, but several key attributes are coded yellow or red indicating that commercial, logistic, and technical advances are required.[76]

The primary barriers to wide-scale adoption are related to economics and the price premium of NGVs. Fuel station availability is also a barrier, particularly during the transition from serving private fleets to providing wide-scale fuel availability to support a large personal consumer market.

With recent advancements in CNG technology, initial engine performance and vehicle drivability can be comparable to that of gasoline vehicles. Although NGVs are technically compatible with many of the advancements proposed for gasoline vehicles, demonstrating and quantifying the long-term fuel

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[76] Blue color coding indicates minimal or no barrier, with yellow and red indicating increasingly significant barriers.

HURDLE	REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	RATING	COMMENTS
ENGINE:			
POWER & TORQUE	Match equivalent gasoline engine ratings	🔵	When properly optimized for CNG, no impact on power or torque, particularly in dedicated configuration
FUEL ECONOMY	Minimal or no penalty relative to gasoline	🔵	Dedicated CNG engines can exceed gasoline efficiency via higher compression ratio
HOT/COLD WEATHER PERFORMANCE	Comparable performance to ICEs	🔵	Utilize similar engine control strategies to gasoline
ADVANCED FUEL ECONOMY POTENTIAL	Long term viable roadmap for continued improvement	🟡	Compatible with boosting, downsizing, hybridization, lightweighting, etc.
DIRECT INJECTION	Technical pathway for Direct Injection CNG	🔴	Non-critical as market can persist as PFI, but value in R&D needed to identify solution for dedicated CNG DI. Reliance on PFI only may incur fuel economy limit
EMISSIONS COMPLIANCE	Emissions compliance with no incremental aftertreatment over gasoline	🔵	May require custom catalyst formulations to meet future CH_4 standards
OBD COMPLIANCE	Fully compliant with all OBD requirements	🔵	Requires tailored Electronics and Software architecture to capture full range of CNG system states
NG OPTIMIZED DESIGNS	Engine systems designed specifically for NG operation	🔵	Piston, valvetrain, air handling optimization. Can be justified when sufficient market volume is achieved
DURABILITY	No penalty relative to gasoline	🔵	No impact with shared architecture, ratings and OEM support
OEM PRODUCTION	Factory built, first fit engines to provide build capacity and diversity of product options	🟡	Limited range of engine options available. Some plant investment required to adapt assembly lines
ONBOARD FUEL STORAGE:			
CNG STORAGE CAPACITY	No impact on required vehicle operating range compared to gasoline	🟡	Increased tank volume (and weight) due to low energy density of CNG. Sufficient fuel can be stored for 300 mile range. Near term cost issues
INCREASED ENERGY DENSITY	Not specifically required but would be beneficial	🔴	Not market critical, but R&D into nano-structure or adsorbent materials could provide step change in fuel energy storage, range extension or reduced packaging
FUEL VENTING	No unintentional venting of fuel	🔵	No issue for CNG systems
VEHICLE:			
VEHICLE OPTON AVAILABILITY	Broad range of OEM vehicles tailored for different segments and vocations	🟡	Majority of options available only as aftermarket today. More OEM produced "CNG ready platforms" being offered. Not a barrier if market pull is sufficient
OEM INTEGRATION	Optimized vehicle integration into vehicle platform and factory build	🔵	OEM involvement is obsoleting requirement for retrofit natural gas conversions
OPERATING RANGE	Minimum 250 to 300 mile range capability	🔵	Fuel storage can be integrated for 300 mile range. Improved fuel economy or fuel storage will further improve range.
CABIN & LUGGAGE SPACE	No functional impact relative to conventional gasoline & diesel vehicle	🟡	Requires OEM consideration for CNG within model architecture definition. Trending to no impact in Europe, with fuel tank/chassis/body integration
WEIGHT	Weight increase manageable without operating impact	🔵	Manageable. Type 1 CNG tanks can result in a weight increase, offsetting fuel economy. Type 4 carbon tanks significantly lighter, but more costly
SAFETY	No unmanageable safety risks from vehicle operation & maintanenance	🔵	Appropriate use of design, codes & standards, education, and training
VEHICLE ECONOMICS:			
VEHICLE PRICE PREMIUM	Premium relative to conventional vehicles is manageable within equivalent purchase constraints	🔴	Current high price premium only recovered over very high mileage use, e.g., fleet operations. Viable pathway to competitive price via OEM integration & scale
FUEL COST PER MILE	Equal or less than comparable ICE vehicle	🔵	Low cost per mile due to comparable vehicle efficiency and low cost fuel
TOTAL COST OF OWNERSHIP	Equal or less than comparable ICE vehicle	🟡	Long-term economics are much more favorable with scaled production and lower price premiums

🟩 PRIORITY FOCUS AREA TO ENABLE WIDE-SCALE COMMERCIALIZATION

🔵 MINIMAL/NO BARRIERS

🟡 WILL TAKE INVESTMENT AND TIME, BUT PATHWAY FOR SUCCESS HAS BEEN IDENTIFIED

🔴 SIGNIFICANT BARRIER OR HIGH RISK OR HIGH UNCERTAINTY OR REQUIRES "BREAKTHROUGH OR INVENTION"

Figure 14-48. *Hurdles for Light-Duty Natural Gas Vehicles* economy potential of NGVs is important in validating the competitive longevity of the technology.

As discussed earlier, a key technical area to be addressed is that of direct injection with CNG. In order for NGVs to fully benefit from advancements in gasoline technology in this area, solutions must be developed to enable direct injection of CNG coupled with high levels of charge boosting, increased compression ratio, and downsizing. This challenge is worthy of near-term focus in order to identify critical engine and powertrain architectures for long-term product planning.

The transition to fully OEM developed and produced NGVs is critical in enabling wide-scale adoption in the marketplace. Current manufacturing models based on aftermarket retrofits or second stage manufacturers introduce substantive inefficiencies in the cost structure of NGVs. The challenge lies in creating sufficient demand to justify this transition.

Solutions to the challenges of cabin and luggage space, as well as make-model availability, are also available with greater OEM integration and higher market demand. CNG fuel storage continues to impact luggage space and may remain a deterrent to many potential customers. As demonstrated in European models, particularly front wheel drive vehicles, the ability to protect chassis and platform architecture for non-intrusive CNG fuel storage is achievable but requires consideration in the planning process for new vehicle models.

RENEWABLE NATURAL GAS

Renewable natural gas is pipeline quality gas that is interchangeable with fossil natural gas and can be used as a 100% substitute for, or blended with, conventional gas streams for use in vehicle engines.[77] RNG is produced from a variety of biomass and/or biogas sources including landfill gas, solid waste, municipal wastewater, and agricultural manure via purpose-built anaerobic digesters. It can also be produced from lignocellulosic sources such as forestry and agricultural waste through the process of thermal gasification and methanation.[78] It is a renewable fuel, easily distributed via local, regional, and national infrastructure and is suitable for applications from LD passenger vehicles to HD freight trucks.

Fuel Supply Chain

The RNG fuel supply chain includes a range of biomass feedstocks such as municipal waste streams, agricultural manure, wastewater sludge, crop residues, energy crops including switchgrass and laygrass, forestry waste, and other lignocellulosic feedstocks. Anaerobic digestion is the most mature and commonly used conversion technology. It is a naturally occurring biological process in which organic material is broken down by bacteria in a low-oxygen environment resulting in the generation of methane and carbon dioxide. The processes and equipment for converting biomass sources into biogas via anaerobic digesters are well known and commercially available.[79] Once biogas is purified into RNG and the gas meets required pipeline quality specifications, commercial arrangements can be made to allow it to be injected into the natural gas grid and distributed via established fueling infrastructure for use in transport applications.[80]

In comparison, lower moisture feedstocks such as forestry waste, energy crops, and crop residue are better candidates for thermal gasification. Thermal gasification is the conversion of solid or liquid carbon-based materials by direct internal heating provided by partial oxidation.[81] It is an established industrial process that has been used mainly to convert coal into gaseous products and includes

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[77] Renewable natural gas is also referred to as biogas, renewable gas, or bio-methane. When compressed or liquefied, it is also called bio-compressed natural gas (bio-CNG) or bio-liquefied natural gas (bio-LNG).

[78] A technical comparison of the technologies for producing RNG is beyond the scope of this study. Although biomass can be converted to RNG using either process, anaerobic digestion is generally applied to wet biomass while thermal gasification is targeted for low-moisture feedstocks. It should be noted that both anaerobic digestion and thermal gasification refer to a family of technologies.

[79] Brad Rutledge, *California Biogas Industry Assessment,* White Paper, WestStart-CALSTART, April 2005, http://www.calstart.org/Libraries/Publications/California_Biogas_Industry_Assessment_White_Paper.sflb.ashx.

[80] A competing pathway for unpurified biogas is on-site electrical power generation or combined heat/power applications at the same facility where the biomass feedstock is located.

[81] The thermal gasification process uses substoichiometric air or oxygen to produce fuel gases like CO, H_2, CH_4, and lighter hydrocarbons as well as CO_2 and N_2 depending on the process used. It relies on chemical processes at elevated temperatures of 700 to 1,800°C. The advantage of gasification is that using the syngas is more efficient than direct combustion of the original raw feedstock as more of the energy contained in the raw feedstock is extracted.

a number of different technologies and combinations of technologies.[82] While thermal gasification of coal is a mature technology, thermal gasification of woody biomass to produce RNG is at the pre-commercial stage with successful demonstration plants in Europe.

The gasification process can convert all organic components of the feedstock including lignin and some lignin/cellulosic materials to a resulting gas mixture called bio-syngas. The bio-syngas can then be methanated and cleaned to produce RNG.[83] Some studies advocate that anaerobic digestion will be the main source of RNG to 2020, with thermal gasification contributing onwards.[84] This projection is based on the availability and cost of thermal gasification technologies, prior use and acceptance by industry, and the need for further technology improvements.[85]

RNG feedstock and production sites are not always co-located with NGV fueling infrastructure. Since liquefied RNG is more easily transported, small-scale liquefaction is sometimes used to aid in distribution even if the demand is for gaseous product. Dedicated RNG pipelines require a point of consumption relatively close to the point of production and concentrations of fleets in a dense geographic area.[86] Adding RNG to the already established natural gas storage and distribution network enables utilities to offer renewable gas content to consumers. Infrastructure requirements may also include compressors to raise the pressure of the produced RNG to pipeline levels, pipelines to connect to the existing grid, site storage capacity to maintain delivery volumes in the event of a disruption or shutdown, and an on-site fueling station for fueling dedicated fleets.[87]

Feedstock Capacity and Price

Analysis of the potential organic feedstock inventories indicates that approximately 4.7 tcf of RNG is potentially available from domestic sources.[88] (See Figure 14-49.) Estimates of the potential supply are dependent on various assumptions including future waste streams, biomass availability, conversion technologies, and process yields. A more complete discussion of the potential feedstock inventory for RNG production is available in a study topic paper on the NPC website: Topic Paper #22, "Renewable Natural Gas for Transportation: An Overview of the Feedstock Capacity, Economics, and GHG Emission Reduction Benefits of RNG as a Low-Carbon Fuel."

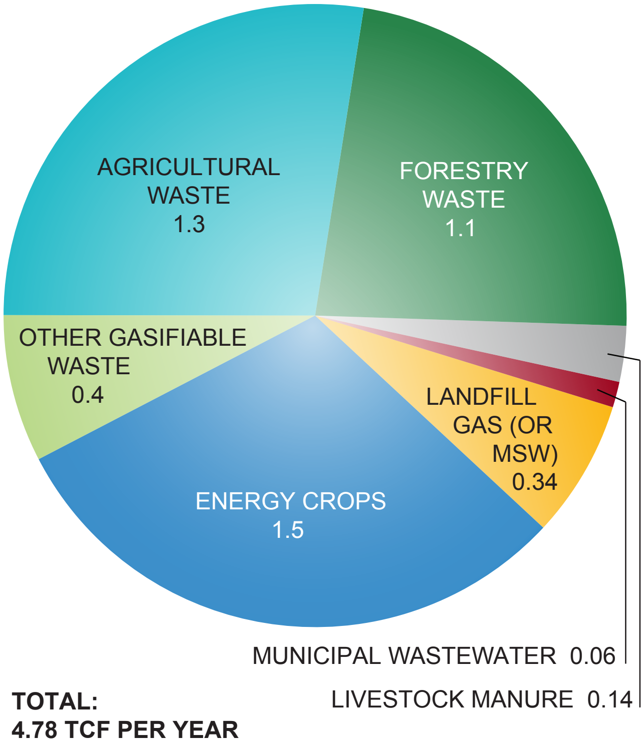

Figure 14-49. *Practical Potential RNG Feedstock Capacity, 2035–2050 Estimates (tcf per year)*

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[82] Max Ahman, "Biomethane in the Transport Sector – An Appraisal of the Forgotten Option," *Energy Policy* 38, no. 1 (January 2010): pages 208-217.

[83] Syngas may be burned directly in internal combustion engines, used to produce methanol and hydrogen, converted via the Fischer-Tropsch (FT) process into synthetic fuel or converted to methane through catalytic methanation.

[84] National Grid, *Renewable Gas – Vision for a Sustainable Gas Network,* white paper, July 2010, http://www.nationalgridus.com/non_html/NG_renewable_WP.pdf.

[85] Salim Abboud et al., *Potential Production of Methane from Canadian Wastes,* Alberta Research Council and Canadian Gas Association, October 2010, http://www.cga.ca/publications/documents/PotentialProductionofMethanefromCanadianWastes-ARCFINALReport-Oct72010.pdf.

[86] Marianne Mintz and Jim Wegrzyn, *Renewable Natural Gas: Current Status, Challenges and Issues: A Discussion Paper for Clean Cities Coalitions and Stakeholders to Develop Strategies for the Future,* U.S. Department of Energy, September 2009, http://www1.eere.energy.gov/cleancities/pdfs/renewable_natural_gas.pdf.

[87] Ibid.

[88] The 4.7 tcf represents about 20% of current U.S. natural gas consumption, or approximately 2.3 million barrels of oil per day.

The cost of RNG depends on biomass availability and cost, conversion processes, conversion yield, the costs of capital, delivery costs, distribution infrastructure, and other factors. Table 14-18 illustrates representative cost estimates and variables for the different feedstock pathways.

Utilizing the data ranges identified in Table 14-18, Figure 14-50 depicts RNG cost estimates for the fuel delivered to the natural gas pipeline. The delivered cost of RNG is composed of four components: (1) biomass costs as delivered to the conversion facility, (2) conversion costs to convert biogas or biomass feedstocks to pipeline quality natural gas, (3) delivery costs associated with transporting the fuel to the point of consumption including compressors, monitoring equipment, and interconnects to pipelines, and (4) other costs and co-product credits if applicable.[89]

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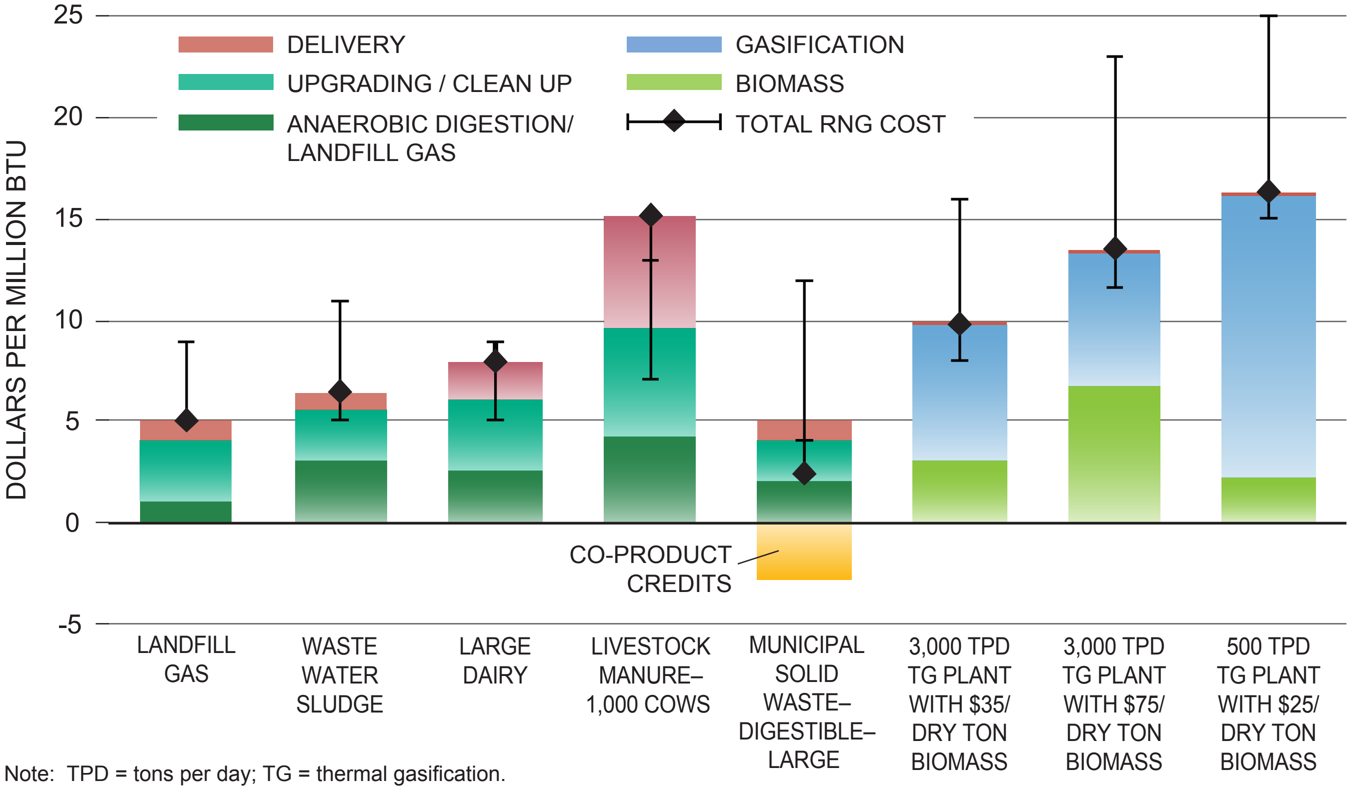
[89] Other costs and co-product credits could include carbon credits for avoided emissions, the economic value of any co-products (such as digestate, excess usable heat/power, etc.) and any additional costs. This model does not assume any value for co-products or carbon credits for this analysis and the category is primarily for future scenarios.

RNG Cost Summary	Biomass	Conversion (to Pipeline Quality RNG)			Delivery	Other/ Co-Products	RNG Cost Estimates (Delivered to Pipeline)	
Biomass/ Case	Biomass Cost ($/dry ton)	Digestion/ Gasification ($/ MMBTU/d input)	Upgrading and Cleanup ($/mmcfd input)	Yield (gge/ dry ton and % of Energy Input)	Pipeline Injection ($/MMBTU delivered)	Any other costs or co-product credits	$/MMBTU	$/GGE
Landfill Gas	Waste already collected. MSW may require sorting or cleaning.	LFG collection system costs ($0.9 average, range: $0.6–$1.2)	Biogas Upgrading and Cleanup ($0.5–$25). Costs depend on scale.	~85% of Energy Content in collected Landfill Gas	Requires compressors, connection, and monitoring equipment, and pipe (typically $50/ ft installed) to the pipeline injection point. ($0.2–$30 depending on scale.) For longer distances to pipeline, multiply by approx. (1 + miles/2). Urban costs per mile can be much higher than in agricultural areas.	Could get credits for tipping fees, carbon credits for avoided emissions, value of co-products including digestate, other non-RNG outputs, heat for district heating, excess power delivered to grid.	$5–$9	$0.6–$1.1
Livestock Manure – Large Dairy		Covered lagoon ($1–$7) or Anaerobic Digester ($2–$25)		Typically 48–64 (35–46%)			$5–$9	$0.6–$1.1
Livestock Manure – Medium							$7–$13	$0.8–$1.6
MSW*– Digestable – Large		Anaerobic Digester ($2–$25). Costs depend on scale and type.					$4–$12	$0.5–$1.5
Wastewater Sludge							$5–$11	$0.6–$1.4
Large Plant (ag waste, energy crops, &/or forest waste)	$30–$150	Thermochemical Conversion (e.g., Gasification and Methanation with Cleanup) ($5–$40/ MMBTU) Costs depend on scale.		Typically 70–95 (50%–70%)			$8–$20	$1.0–$2.5
Medium Plant (ag waste, energy crops, &/or forest waste)	$10–$50						$15–$25	$1.9–$3.1

* MSW = Municipal Solid Waste.

Table 14-18. *RNG Cost Summary*



Note: TPD = tons per day; TG = thermal gasification.

Figure 14-50. *RNG Cost Estimates Delivered to Pipeline*

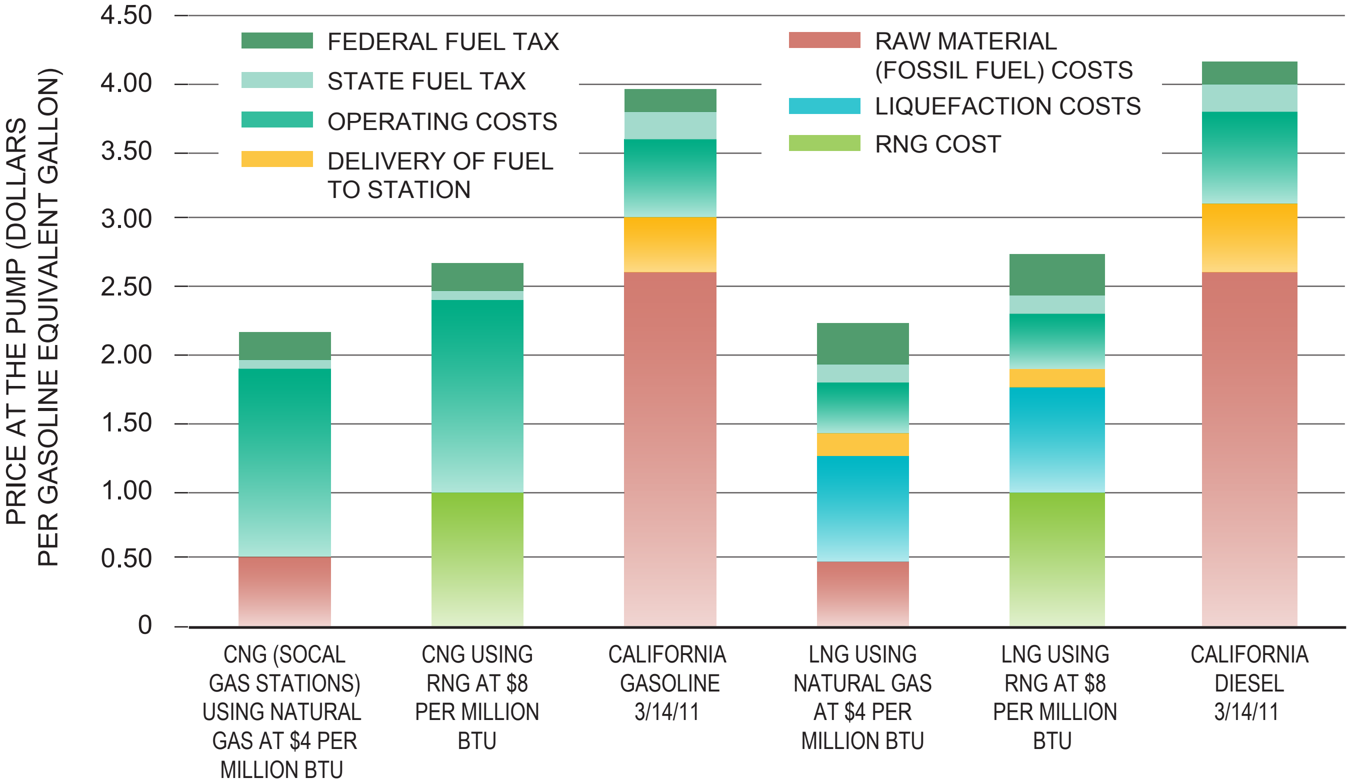


Figure 14-51. *Cost Comparison of RNG as a Transport Fuel*

While RNG is competitive with gasoline, diesel, and liquid biofuels, project developers are more likely to compare it to the retail price of natural gas. The lack of financial incentives for RNG makes it difficult to compete with lower-priced fossil natural gas.[90] (See Figure 14-51 for a cost comparison of RNG as a transport fuel.)

Greenhouse Gas and Environmental Attributes

RNG can offer significant GHG reductions compared to diesel, gasoline, natural gas, and liquid biofuels. There is the potential for emission reductions upstream or tank-to-wheels from the capture of methane emissions from landfills or dairies, and well-to-tank via the use of RNG as a petroleum substitute or in blended mixtures with fossil natural gas. The GHG emissions reduction benefit is dependent on the feedstock and is not inherent in the fuel itself.

The GHG benefits for RNG derived from landfill gas, dairy digester biogas, and manure have been well documented.[91] For example, RNG from landfill gas liquefied into LNG for HD transport applications has a well-to-wheels GHG savings of approximately 72–97% compared to diesel fuel pathways.[92] Table 14-19 depicts the emissions reductions identified in the literature to better reflect the range of cases and uncertainties.

Why RNG for Transportation

The potential for significant GHG emission reductions may be the most compelling reason for the deployment of RNG-fueled vehicles, but other factors support the proposition that RNG is well-suited for transportation:

- The use of RNG leverages the existing gas network to distribute or deliver a renewable fuel and enhances the diversity of the transportation energy mix.
- Spurred by California's Low Carbon Fuel Standard (LCFS) and the possibility of similar national standards, there is increasing interest in vehicle fuels with a low carbon footprint on a well-to-wheels basis. The prospect of a LCFS may be a persuasive argument for natural gas, particularly from low-carbon sources like RNG.[93]
- In the longer term, the cost efficient allocation of biomass resources is dependent on the development of alternative non bio-energy sources for heating and electricity. If cost efficient, nonbioenergy alternatives such as solar and wind power develop for heating and power applications, biomass derived fuels such as RNG may be the only low-carbon option for the transport sector.[94]
- NGV markets comprised of fleets looking to acquire renewable energy credits, meet LCFS requirements, or earn carbon credits based on the low carbon content of RNG may develop. The co-location of captive fleets such as refuse haulers or municipal vehicles with waste streams improve the economics of RNG projects as an interconnection to the natural gas grid may not be required.
- The use of RNG may expedite carbon finance markets for transportation as credits can be earned via projects to capture the biogas from feedstock sources and switching fuel from diesel or gasoline.

National Case Studies

Approximately 500 landfills, 120 dairies, 70 wastewater treatment systems, and 10 other livestock operations recover energy from biogas in the United States.[95] Projects range from small internal combustion engines or micro-turbines using biogas to generate power for site electricity, to multiple units able to export excess power to the grid. Although the majority of projects convert biogas

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[90] The Linde-Waste Management project at the Altamont Landfill is the largest RNG for transportation project in the United States. It is unique in that the market for the RNG fuel is built into the project as nearly 400 refuse haulers are fueled with RNG.

[91] Argonne National Laboratories has published models derived from GREET for CNG and LNG from landfill gas for a range of cases including different electricity sources, on-site compression or liquefaction, and off-site compression or liquefaction. CARB has carbon intensities for CNG and LNG from landfill gas and dairy digester biogas with differing cases of liquefaction efficiency. GHGenius biomethane results are available for CNG from not only landfill gas and manure but also for the anaerobic digestion of hay, switchgrass, wheat straw, and corn stover.

[92] M. Mintz et al., *Well-to-Wheels Analysis of Landfill Gas-Based Pathways and Their Addition to the GREET Model,* Report ANL/ESD/10-3, Argonne National Laboratory, May 2010, http://www.transportation.anl.gov/pdfs/TA/632.PDF.

[93] Ibid.

[94] Ahman, "Biomethane in the Transport Sector."

[95] Mintz and Wegrzyn, *Renewable Natural Gas.*

Source	RNG Fuel	Fuel % WTW GHG Savings	Notes
Landfill Gas (LFG)	CNG vs. Gasoline	80 – 101%	Argonne 2010 GREET analysis of various LFG cases. GREET 1.8d.1 default is 98%.
	LNG vs. Diesel	77 – 98%	Argonne 2010 GREET analysis of various LFG cases. GREET 1.8d.1 default is 97%.
Dairy Manure	CNG vs. Gasoline	70 – 90%	CARB 2009 GREET analysis: 85% better than gasoline.
	LNG vs. Diesel	70 – 81%	CARB CI data March 2011. 81% with 90% efficient liquefaction.
Anaerobic Digestion — Hay/Switchgrass/ Straw/Stover	CNG vs. Gasoline	75 – 81%	GHGenius 2009 Biomethane results.
Anaerobic Digestion – General	CNG vs. Gasoline	63 – 200%	UK study range. High end is liquid manure.
Thermochemical Conversion of Biomass		74 – 92%	Lacking solid studies. UC Davis 2006 has this range using life-cycle emissions model (LEM). California Energy Commission demonstration project cites 85%.

Table 14-19. *GHG Emissions Reductions Associated with Different Feedstock Pathways*

into electricity, a few use site-generated or grid electricity to purify the gas stream, upgrade it to pipeline-quality specifications, and pressurize it for injection into the natural gas grid or use it as a vehicle fuel.[96]

The largest commercial-scale landfill gas to RNG plant is located at the Altamont Landfill near Livermore, California. Operated by Waste Management-Linde, the plant has a daily capacity of 13,000 LNG gallons and fuels 400 refuse haulers powered by Cummins Westport ISL G engines. By displacing 2.5 million gallons of diesel, the RNG produced at Altamont eliminates over 30,000 tons of GHG emissions, 200 tons of NOx, and four tons of particulate matter per year.[97] The Frank R. Bowerman Landfill in Irvine, California, the second largest commercial-scale landfill gas to RNG plant, generates nearly 5,000 gallons of LNG per day to power Orange County Transit Authority's fleet of LNG powered buses and refuse trucks.

Smaller RNG for transportation projects include the Hilarides Dairy in Lindsay, California. The dairy received a $600,000 grant from the California Air Resources Board's Alternative Fuel Incentive Program, which subsidizes projects facilitating a greater use of non-petroleum fuels. Using an anaerobic-lagoon digester that processes the manure of nearly 10,000 cows, the project generates 226,000 cubic feet of biogas per day for electrical power and enough fuel to run two HD milk delivery trucks and five pickup trucks.[98]

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[96] The majority of biogas-to-energy projects generate electricity largely due to state and federal incentives.

[97] Linde Group, "Linde and Waste Management Receive California Governor's Award for Sustainable Facility," press release, November 16, 2010, http://www.the-linde-group.com/en/news_and_media/press_releases/news_2010_1117_2.html.

[98] California Environmental Protection Agency, "Dairy Trucks Powered By Cow Waste: New System Produces Fuel On-Site," Air Resources Board, news release, February 11, 2009, http://www.arb.ca.gov/newsrel/2009/nr021109b.htm.

Renewable Natural Gas Hurdles

RNG specific barriers include economic, regulatory, and technological hurdles, and an emerging knowledge of biomass feedstock availability and supply. The recent discoveries of natural gas shale resources and softening of natural gas prices have impacted the economics of RNG projects. Anaerobic digesters, biogas upgrading facilities, and liquefaction units require up-front capital investments that are difficult to align with the economics of an abundant, long-term supply of affordable conventional natural gas. In many areas, the costs for interconnect equipment to distribute RNG into the natural gas grid are prohibitive, further impacting the economic feasibility for a project.

In contrast to the demand for renewable electricity, a similar robust market for lower-carbon RNG does not currently exist. At present, the most significant demand for RNG is from power producers in Renewable Portfolio Standard (RPS) states that use the fuel in combined cycle plants to generate renewable electricity to satisfy RPS compliance requirements. A significant regulatory barrier to the increased use of RNG for transportation is the Investment Tax Credit, which incentivizes on-site power generation from RNG but does not provide any incentive to produce RNG for pipeline injection and transport applications.

Each state faces a different mix of regulatory barriers, making it difficult to generalize opportunities and constraints from a national perspective. The lack of a national, standardized specification for RNG injected into the pipeline system and the absence of uniform federal or state specifications for gas acceptance means that the developers of RNG projects must negotiate acceptance with each gas utility, thereby adding considerable time and cost.[99]

Regulatory mechanisms, including some air quality and environmental standards, may need to be revised to facilitate the production, distribution, and use of RNG. Requirements that prohibit the flow of landfill gas into natural gas pipelines, current debates on the volatile organic compound (VOC) emission factor for dairies, and standards governing on-site electrical power generation all hinder the use of RNG for transportation.[100]

The technology barriers for RNG are modest compared to other alternative fuels as it makes use of identical natural gas engines, pipeline infrastructure, liquefaction and compression technology, fueling stations, and storage as conventional natural gas. There is currently no common gas specification standard for RNG as a transport fuel, including composition analysis and allowable levels of trace compounds. The development of a market for biogas and RNG is driven by differing policy objectives that have to address the inherent uncertainty of both long-term emission reduction ambitions and the deployment of other renewable technologies in all sectors.

FINDINGS

1. The potential for a long-term and low-cost domestic supply of natural gas, supported by economically recoverable shale gas resources, may provide an economic driver for the increased use of natural gas for transportation.
   - The AEO2011 projected recoverable natural gas resources of 2,543 tcf with technically recoverable shale gas resources of 827 tcf.
   - Assuming continued development of domestic shale gas resources, the EIA projections suggest relatively low and stable natural gas prices compared to oil prices through 2035.
   - Estimates of infrastructure build out costs suggest that when refueling infrastructure is built and well utilized, its impact on dispensed fuel prices could be as low as $0.06 per GGE for LNG and $0.38 per GGE for CNG. However, the economics of infrastructure investment and the pace of development are some of the key challenges to expanded use of natural gas as transportation fuel.
   - Using AEO2010 Low, Reference, and High Oil Price Cases for Industrial Gas prices, the study extrapolated these to 2050 and incorporated

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[99] Mintz and Wegrzyn, *Renewable Natural Gas.*

[100] California's Hayden Rule was intended to prevent the pipeline injection of gas recovered from Class I hazardous waste landfills but has resulted in the utilities' refusal to accept gas from any landfill. The rule does not prohibit the injection of landfill gas-derived RNG into out-of-state pipelines and California customers purchasing CO_2 or low carbon fuel standard (LCFS) credits for the swapped gas.

infrastructure costs to develop estimates of dispensed natural gas fuel prices. These extrapolations indicate the price advantage for natural gas in relation to petroleum fuels could extend to as high as $3 per GGE by 2050 in the High Oil Price Case, while the Low Oil Price Case estimates suggest that there could be no fuel price advantage for natural gas.

2. There is an opportunity for LD and HD NGVs to become attractive to both retail and fleet consumers. The economic competitiveness of these vehicles is contingent on sustained low cost of natural gas as a transportation fuel coupled with continued application of technology to improve performance and reduce costs.
3. There are few technological barriers to market entry and expansion for either LD or HD NGVs. Technology developments can be used to extend the performance and economics of NGVs through improved fuel economy and lower cost.
   - Natural gas engines share common architecture with gasoline and diesel engines, with minor component specification changes required to operate on natural gas.
   - In HD applications, the prime path has been to convert diesel engines to operate as spark ignited natural gas engines. Recent developments have introduced engines that utilize the diesel cycle for higher efficiency but with added complexity.
   - Fuel storage systems for CNG and LNG are currently available that can accommodate the range requirements of HD and LD vehicles, but fuel storage systems represent a significant cost premium compared to gasoline or diesel. Improvements in fuel energy storage density would be beneficial to packaging and range extension if it can be achieved at reasonable cost.
4. Enhancements in internal combustion engines can generally be translated to natural gas engines.
   - In HD applications, improved air handling systems, friction reduction, and exhaust heat recovery would benefit natural gas engines as they do diesel engines.
   - Technical advances are required to enable LD direct injection operation on natural gas. These advances would enable fuel economy improvements taking advantage of the high octane rating of natural gas in highly boosted, downsized engines.
5. Build out of infrastructure is critical to support the increased use of natural gas. Infrastructure build out for HD vehicles is less complex than the development of wide-scale retail infrastructure for LD vehicle fleets.
   - There are approximately 10,000 diesel truck stops serving HD vehicles, and 160,000 retail gasoline outlets serving LD vehicle consumers.
   - The build out of infrastructure for HD vehicles can begin with private fuel stations at fleet depots and expand to public access stations along key freight corridors.
   - Infrastructure development for urban HD fleets can support continued fleet growth in LD applications such as taxis, shuttle buses, and private fleet vehicles.
   - The development of retail CNG stations will likely occur first in regions of dense population with a proximity to freight corridors. Dispensing technology for the incremental provision of CNG on existing retail fuel outlets has improved to support expansion without a need for a dedicated station build-out until demand increases.
   - LCNG stations could play a role in supporting early CNG fleets by enabling fuel availability at truck stops.
6. Natural gas contributes to lower GHG emissions compared to gasoline and diesel. For LD applications, the range of quoted reductions is 7 to 30% for North American sourced CNG. For HD vehicles, the results vary depending on the natural gas engine technology, but for North American sources of natural gas the range spans from 11 to 29%.
7. The GHG emission reduction benefits are dependent on the source of natural gas (domestic or imported), whether it is CNG or LNG, and the LD or HD technology within the vehicle.
8. The ability to develop and introduce bi-fuel LD and dual-fuel HD vehicles, which offer capability to run on gasoline or diesel fuel in the absence of available natural gas stations, offers consumer

flexibility that may be beneficial in a transitional market.

  - LD bi-fuel CNG-gasoline vehicles can be configured with a small gasoline tank such that consumers can bias operation to CNG and then revert to gasoline operation if access to refueling is limited.
  - Dual-fuel vehicles (CNG/LNG–diesel) offer similar flexibility in HD applications if they are able to revert to operation on pure diesel when natural gas tanks have been depleted.

9. While vehicle conversions represent a strategy for initial product availability, the role of the global OEMs will be increasingly important to increasing availability in North America and also to reduce the cost base of NGVs through streamlining of engineering, component, and production costs.
   - Much of the cost premium in today's NGVs is due to low-volume production and the inefficiencies of aftermarket conversions.
   - In Europe, there is a stronger emphasis on OEM-produced vehicles that assists with mitigating some of the cost premium compared to gasoline or diesel vehicles.
   - With concerted vehicle architecture consideration, CNG systems can be packaged in LD vehicles with minimal impact on cargo and passenger space, as demonstrated in some European OEM models.
   - An increasing number of HD OEMs are now offering natural gas truck products direct from the dealer, with full engineering and product support integration.
10. From an energy security perspective, LD and HD NGVs have the potential to provide an economic driver towards alternative fuel use, displacing oil with domestically sourced natural gas.
11. RNG derived from biogas and biomass feedstock sources can further improve the GHG emission reduction benefits of natural gas vehicles.
    - The use of RNG for transportation must overcome the economic, scale and efficiency hurdles of competing pathways such as on-site heating or electrical generation.
    - The technology barriers for RNG in transportation are modest as it makes use of existing natural gas infrastructure and technologies for natural gas engines.

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