Energy Research and Development Division
FINAL PROJECT REPORT

2015 NATURAL GAS VEHICLE RESEARCH ROADMAP

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Technology Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

The *2015 Natural Gas Vehicle Research Roadmap* is the final report for the Development of Natural Gas Vehicle Research Roadmap project (contract number 500-12-008). The information from this project contributes to the Energy Research and Development Division's Transportation Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

The California Energy Commission's *2015 Natural Gas Vehicle Research Roadmap* guides investments made by the Energy Commission in natural gas vehicle research and development to provide value to California utility ratepayers. Using natural gas transportation in California has the potential to reduce petroleum consumption, decrease vehicle emissions and provide fuel cost savings to California businesses and consumers.

The report updates the *2009 Natural Gas Vehicle Research Roadmap* and provides the framework and foundation for future investments. Changes between 2009 and 2014 are discussed to provide a context for the natural gas vehicle market and necessary research; The report includes research recommendations on 1) range and storage, 2) engine performance and availability, 3) vehicle emission and environmental performance and 4) analysis and information sharing. Specifically, low natural gas prices, increased supplies, and a changing regulatory landscape have impacted the natural gas vehicle market. These changes have also impacted traditionally fueled vehicles, changing the overall vehicle technology market.

The *2015 Natural Gas Vehicle Research Roadmap* stresses the need for continued investment and innovation in natural gas vehicle technology to ensure continued competitiveness and ratepayer benefits. Continued research on enhanced gas storage, engine and vehicle availability, advanced engine design, enhanced emission controls and hybridization represent key contributions necessary to advance the natural gas vehicle market. The roadmap also calls for coordinated investment among California stakeholders and the federal government to leverage investments and continue soliciting input on research priorities.

Keywords: California Energy Commission, natural gas vehicles, natural gas, alternative fuels, compressed natural gas, liquefied natural gas, natural gas fueling infrastructure, technology roadmap, research, PIER, NGVTF

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EXECUTIVE SUMMARY

The *2015 Natural Gas Vehicle Research Roadmap* informs natural gas vehicle research and development investments made by the California Energy Commission to promote ratepayer benefits for Californians. Specifically, using natural gas as a transportation fuel has demonstrated reductions in petroleum consumption, greenhouse gas emissions, local air pollution, and operating costs for businesses and consumers. The *2015 Natural Gas Vehicle Research Roadmap* updates the previous *2009 Roadmap* and seeks to 1) identify emerging opportunities and fundamental changes in the natural gas vehicle market and associated technologies and 2) reassess the priority of previously identified technologies given developments that have occurred over the last five years.

Between 2009 and 2014, numerous developments have influenced priorities for research specifically:

- A growing, stable, market for natural gas production and use
- Increased natural gas engine availability, performance, and reliability
- Significant regulatory and policy developments that increase requirements for emission reductions
- Performance and efficiency gains in conventional vehicle technologies

Favorable economics and increased availability have transitioned the natural gas vehicle market to one that requires more attention to remaining market barriers experienced by both new and existing technologies. The emergence of competitive engine and vehicle offerings, from passenger cars to heavy-duty trucks, fueled by the growing availability of low-price natural gas presents greater public benefits. The synergistic effects of growing market-scale vehicle and fueling infrastructure availability translate into opportunities for future growth of natural gas vehicle adoption.

To keep up with existing and emerging technologies and support increasingly stringent future regulations, natural gas vehicle technologies must experience significant levels of innovation in these key topics:

- Range, infrastructure and natural gas storage
- Engine performance and availability
- Vehicle emissions and environmental performance
- Analysis and information sharing

Each of these topics represents a market barrier to natural gas vehicle deployment and can be addressed through a variety of research and development activities. With increased opportunities for natural gas vehicles, it is vital for stakeholders to maintain progress in dynamic markets, invest in a broad selection of technologies to overcome new barriers for more growth, and coordinate efforts to ensure maximum impact.

As previous California Energy Commission documents have demonstrated, increased adoption of natural gas vehicles in California can reduce overall petroleum consumption, greenhouse gas emissions, and fueling costs for utility ratepayers. Specifically, this Roadmap recommends the following R&D actions be pursued in order to maximize those benefits:

- Decrease the cost of on-board natural gas storage and increase vehicle integration of storage
- Increase natural gas engine and vehicle availability, improve efficiency and maintain similar performance characteristics to gasoline and diesel alternatives.
- Advance technologies that continue to reduce NOx and greenhouse gas emissions.
- Continue supporting current, accurate, and timely information on natural gas vehicle technologies and availability.
- Continue coordination and collaboration between and among California and federal agencies with natural gas vehicle stakeholders to adapt to changing markets, customer needs, and technology developments.

Benefits to California

These recommendations will develop and help bring to market advanced transportation technologies that reduce air pollution and greenhouse gas emissions beyond applicable standards. As a transportation fuel, natural gas could offset over 750 million gallons of diesel per year by 2022, reducing greenhouse gas emissions by 4 million metric tons per year and saving the state approximately $1.35 billion in fueling costs annually.

CHAPTER 1: Introduction

California is a national leader in deploying natural gas vehicles and has made significant investments in research and technology development. To guide those investments, the California Energy Commission has commissioned a technology roadmap identifying research gaps and opportunities to help accelerate beneficial natural gas vehicle deployment. This Roadmap updates the *2009 Natural Gas Vehicle Research Roadmap*, and identifies emerging opportunities and fundamental changes in the natural gas vehicle (NGV) market and associated technologies, and updates the status of previously targeted technologies.

The *2015 Natural Gas Vehicle Research Roadmap (2015 NGVRR*) serves as a guiding document to showcase the natural gas vehicle research investments that can increase deploying natural gas vehicles to create value for California ratepayers. Specifically, the California Energy Commission recognizes that using natural gas as a transportation fuel can reduce petroleum consumption, greenhouse gas emissions, local air pollution, and operating costs for businesses and consumers. In the 2007 State Alternative Fuels Plan, the Energy Commission projected that using more natural gas in transportation in California can potentially:

- Offset more than 885 million gallons of gasoline and diesel per year by 2022
- Reduce 4.4 million metric tons of greenhouse gas emissions annually by 2022
- Save Californians about $1.35 billion annually in fueling costs.

Relatively low, stable prices for natural gas, greater natural gas vehicle availability, improved environmental performance, and increased use of renewable natural gas that point towards perhaps even greater opportunities for natural gas to create value for ratepayers. The *2015 NGVRR* provides background on developing the first roadmap, an overview of relevant legislation and directives that must be considered to properly scope applicable technologies and potential benefits, and the status of the research and development (R&D) priorities recommended in the 2009 report. This context and an overview of changes in the market and technology for natural gas vehicles are the foundation for revised and updated R&D opportunities to increase the benefits of more natural gas vehicles in California.

Enabling Legislation and Direction for Natural Gas Vehicle R&D in California

The NGVRR is based on and attempts to satisfy numerous legislative policies and priorities for California and provide direction for Energy Commission public funded investments. Several relevant pieces of legislation in California that have funded, informed and directed investments for natural gas vehicle technology development are:

- **Senate Bill 1250 (2006):** Allowed Public Interest Energy Research (PIER) funds to be used for advanced transportation technologies to reduce air pollution and greenhouse gas emissions beyond applicable standards as a benefit to natural gas ratepayers.

- **Senate Bill 1204 (2014):** Created the California Clean Truck, Bus and Off-Road Vehicle and Equipment Technology Program to fund zero and near-zero emission truck, bus, and off-road vehicle and equipment technologies and related projects
- **Assembly Bill 1007 (2007):** Directed the Energy Commission to develop a State Alternative Fuels Plan that presents strategies and actions California must take to increase using alternative transportation fuels including natural gas.
- **Assembly Bill 32 (2006):** Called for approximately 36 percent of the State's 2020 greenhouse gas reduction targets to come from the transportation sector.
- **Assembly Bill 118 (2007) :** Created the California Energy Commission's Alternative and Renewable Fuel and Vehicle Technology Program. The statute authorizes the Energy Commission to develop and deploy alternative and renewable fuels and advanced transportation technologies. This legislation was based on the State Alternative Fuels Plan developed under Assembly Bill 1007 to help attain the State's climate change policies. Assembly Bill 8 (2013) extended many of the provisions in AB118 through January 1, 2024.

Natural Gas Vehicle Research Roadmap Overview and History

The Energy Commission's *2009 Natural Gas Vehicle Research Roadmap* was developed to guide research and development investments made by the Energy Commission, its PIER Program and its stakeholders. Under Senate Bill 76, up to one-third of natural gas PIER funds could be used for public interest energy research, development, and deployment. The *2009 Roadmap* was developed by the California Institute for Energy and the Environment with input from the California Air Resources Board and stakeholders (Bevilacqua-Knight, Inc. 2009).

Natural Gas Vehicle Research Roadmap Scope

The technologies covered in this revision to the *2009 NGVRR* are limited to over-the-road applications that operate on the direct use of natural gas – compressed natural gas or liquefied natural gas – and their associated fueling infrastructure. The *2015 NGVRR* does not cover fuels that may be produced from natural gas (e.g. gas-to-liquids or hydrogen) or non-road natural gas vehicles (e.g. mining or agricultural applications). The technologies identified address specific market barriers for natural gas vehicles that may inhibit California natural gas ratepayers from reaching greater benefits. Technologies that do not provide explicit benefit to California ratepayers are not considered in the *2015 NGVRR*.

This roadmap also explores the potential for high horsepower natural gas operations such as marine and rail applications, to the extent of identifying opportunities to benefit natural gas ratepayers. It is generally recognized that these applications may have fairly unique R&D needs and deployment challenges as they often operate at a steady state and require infrastructure capacity and logistics to accommodate a much larger scale than over-the-road applications.

Upstream natural gas processing, extraction, and transmission issues are outside of the scope of this roadmap, as are hydrogen and electricity production pathways. Many of these topics are being addressed elsewhere through other processes and roadmaps. The Energy Commission is also developing a renewable natural gas roadmap as part of a separate effort, which will detail upstream technologies that facilitate the greater use of renewable natural gas in California.

Process for Developing Roadmap

The *2015 NGVRR* was developed through an inclusive process that solicited industry and public feedback. In addition to conducting numerous stakeholder interviews to determine the appropriate scope, the *2015 NGVRR* developers performed a comprehensive literature review to determine the status of current natural gas vehicle deployment barriers and identify needs for future natural gas vehicle deployment. This included a review of current and recently funded efforts supporting natural gas vehicles and associated technologies. The *2015 NGVRR* includes feedback from the 2014 Natural Gas Vehicle Technology Forum (described next) with the final report to include input from a 2015 public workshop held by the Energy Commission.

Natural Gas Vehicle Technology Forum

The National Renewable Energy Laboratory (NREL), in conjunction with the Energy Commission and U.S. Department of Energy (U.S. DOE), leads the annual Natural Gas Vehicle Technology Forum (NGVTF). The NGVTF was established in 2002 and continues to be a critical stakeholder forum to identify and discuss priority and high-impact R&D opportunities to advance the natural gas vehicle market. The NGVTF covers topics based on those identified in the *2015 NGVRR* while providing additional flexibility to address emerging or time-sensitive issues. Participation in the NGVTF is open and includes a variety of stakeholders to encourage broad-based discussions and solutions.

The Public Interest Energy Research Program and the Natural Gas Research, Development, and Demonstration Program

Under the administration of the Energy Commission the PIER program seeks to “develop, and help bring to market, energy technologies that provide increased environmental benefits, greater system reliability, and lower system costs” (California Senate Bill 1250, 2006). The PIER program has funded much of the natural gas vehicle R&D undertaken since completing the first *NGVRR (2009)*. It is expected that the topics outlined in this roadmap will be pursued primarily by the Energy Commission’s Natural Gas Research Program to complement the Alternative and Renewable Fuel and Vehicle Technology Program.

NGV Programs Put in Place by the Energy Commission (2009-2014)

Over the past five years, the Energy Commission has funded and partnered on significant research and development efforts related to natural gas vehicles. Table 1 provides an overview of the R&D priorities identified in the *2009 NGVRR* with highlights of those actions taken over the past five years. These items reflect priorities identified in the previous roadmap. Specific impacts are discussed on a number of these technologies in the following sections.

Table 1: 2009 Natural Gas Vehicle Research Roadmap Recommendations and R&D Efforts Pursued by CEC (2009-2014)

Engine Development and Vehicle Integration Actions
Develop NGV versions of off-road applications.
Develop engine technology optimized for hydrogen-natural gas blended fuel.
Develop NGV homogeneous charge compression ignition (HCCI) engine technology.
Develop legacy fleet engine controls and/or fueling infrastructure upgrades to accommodate fuel variability.
Research an improved composite tank safety device/installation protocol to avoid rupture in a localized fire.
Develop improved handling, reliability, and durability of LNG dispensing and on-board storage.
Provide global positioning system (GPS) guidance to NGV fueling station locations and details statewide.
Develop the next generation of home refueling for natural gas light-duty vehicles (LDVs).
Confirm NGV economic, carbon, and emissions net benefits.
Create a clearinghouse of NGV demand and supply information.

CHAPTER 2:
Natural Gas in Transportation 2009-2014: Changing Markets, New Opportunities

In the United States, the natural gas market has undergone a transformation in the past five years. Hydraulic fracturing and other advanced extraction techniques have made natural gas reserves economical, created price stability, and significantly increased supply projections for the near and long term. It is often observed that during roughly this same time period, natural gas and petroleum prices, which have traditionally trended in a similar direction, have decoupled. Sustained low prices for natural gas coupled with higher and more volatile gasoline and diesel prices have accelerated market adoption of natural gas vehicles, particularly in heavy-duty markets. Natural gas engine availability, performance, and reliability have also increased over the past five years from technology advances, encouraging more NGV.

At the same time, performance and fuel economy improvements in traditionally fueled vehicles (gasoline and diesel) present new challenges and opportunities for the increased use of NGVs. Emission and efficiency standards implemented in California and at the federal level have accelerated developing more efficient vehicles and enhanced emission controls. While these standards apply to all technologies, the result is a narrowing of some of the previous emission benefits inherent to natural gas vehicles.

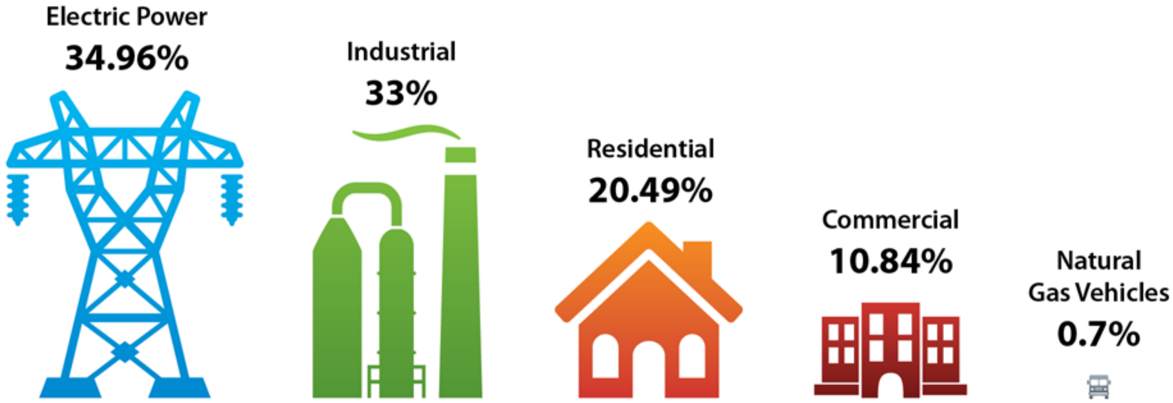
The change in market dynamics coupled with technology advances and new regulatory requirements sets the stage for reassessing R&D opportunities for natural gas vehicles to provide continued value to California's ratepayers.

Natural Gas Supply and Demand

Natural gas represents the largest source of energy in California, accounting for 2,456 trillion BTU or 32 percent of all of the energy used in the state. While the electric power and industrial sectors account for nearly two-thirds of this energy, Figure 1 shows only about 0.7 percent of natural gas demand comes from the transportation sector (EIA, 2015a).[1]

[1] Some of the natural gas sales made to commercial customers include natural gas used as a transportation fuel.

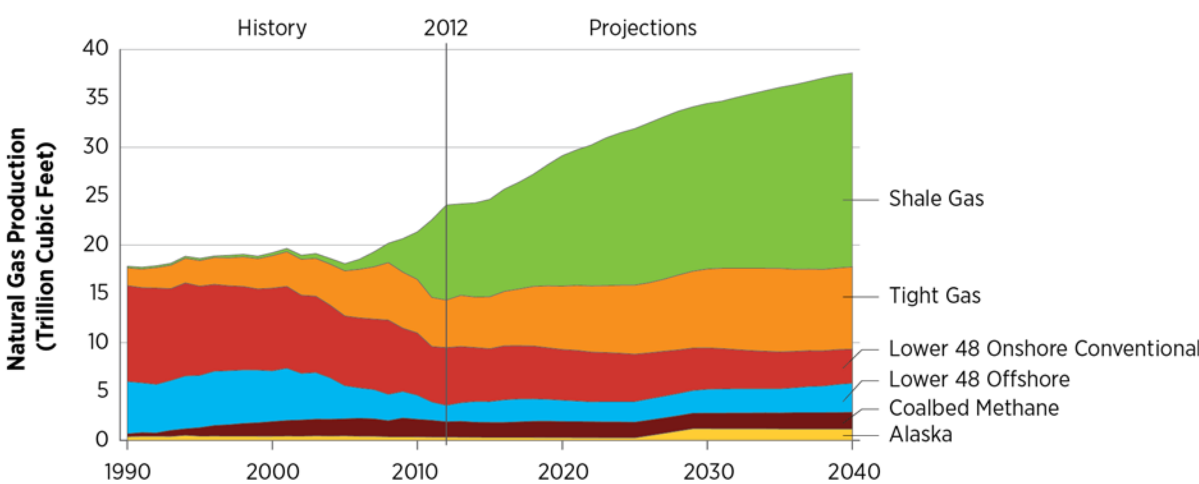
Figure 1: Natural Gas Demand in California by Sector in 2012



Source: U.S. Energy Information Administration (2015)

Natural gas is a domestically produced resource that is extracted from numerous regions in the United States. Dramatic increases in shale gas extraction have vastly expanded estimates of the nation's recoverable gas in the near- to mid-term (Figure 2). The most recent estimate from the U.S. Energy Information Administration projects that by 2040, the nation's annual natural gas production will increase to 37.5 trillion cubic feet, an increase of 82 percent over 2009 production levels (EIA, 2014).

Figure 2: Historical and Projected U.S. Natural Gas Production (1990—2040)



Source: EIA, 2014

Natural gas is used in two forms for transportation purposes – as a compressed gas and as a super-cooled liquid. Compressed natural gas (CNG) is used for a variety of purposes ranging from passenger vehicles to Class 8 vehicles such as transit buses, and can be substituted for either gasoline or diesel fuel. Liquefied natural gas (LNG) is more likely a replacement for diesel operations and typically used for larger vehicles such as Class 8 trucks where driving range and energy density are particularly critical. LNG is also of interest as a viable fuel for rail, marine, and other high horsepower operations.

Natural gas can also be developed from renewable sources as renewable natural gas (RNG) or biomethane. Renewable natural gas is produced through natural processes from a variety of sources including landfills, wastewater treatment plants, and dairies and is upgraded and purified to meet certain specifications (depending on the use and transport mode). Renewable natural gas can be used as a direct replacement for extracted natural gas in vehicle fueling or can be blended with traditional supplies. Unlike fossil-based natural gas, some renewable natural gas pathways qualify as an advanced cellulosic biofuel under the federal Renewable Fuel Standard, also known as the RFS (EPA 2014).[2]

Natural Gas Prices

Increased natural gas production has kept the natural gas commodity prices relatively low over the past few years. The "citygate" price of natural gas in California, the price at which utilities receive gas from pipeline or transmission companies, declined by more than 10 percent between 2009 and 2012, which was preceded by a decrease of more than 50 percent between 2008 and 2009 (EIA 2015b). Figure 3 shows natural gas citygate prices as cost per gasoline gallon equivalent (GGE) to provide a benchmark to gasoline.

Figure 3: California Natural Gas Citygate Prices – 1989-2014 (Gasoline Gallon Equivalence)[3]

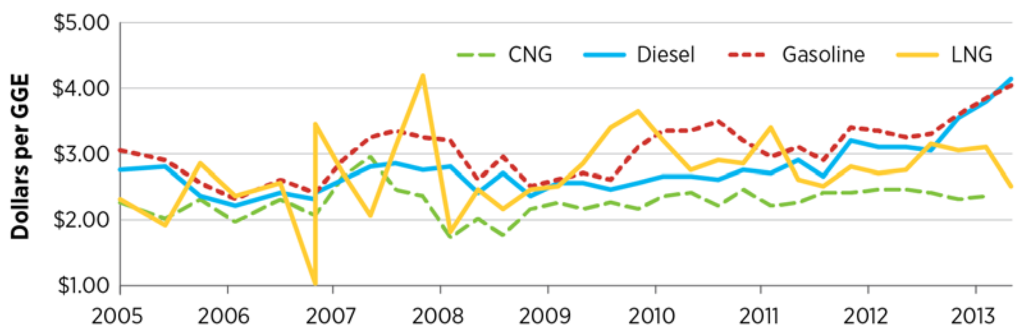
Source: EIA 2015b

[2] CNG and LNG produced from biogas from agricultural digesters, landfills, municipal wastewater treatment facilities, and separated municipal solid waste digesters are eligible for a Renewable Fuel Standard credit. Additionally, biogas produced along these pathways for electricity generation used for electric vehicles is also eligible.

[3] Citygate prices are presented in gasoline gallon equivalents for context into the vehicle market and are typically presented in units of thousand cubic feet (MCF) of natural gas. It is also important to note that this price only represents a portion of a gasoline or diesel gallon equivalent of CNG or LNG.

Overall, CNG prices in California have been relatively stable for the past five years while available data suggest that LNG prices have displayed more volatility.[4] Figure 4 shows prices for CNG, LNG, gasoline and diesel set at gasoline gallon energy equivalence provide a uniform comparison between 2005 and 2014 (DOE, 2015a). It is important to note that the significant drop in natural gas prices in the past five years has not directly correlated to lower public prices for CNG and LNG.[5] This is due to a number of factors including the amortization of capital equipment costs for fueling infrastructure, infrastructure utilization costs that are sensitive to fueling volumes, and the electricity used for compression or liquefaction.

Figure 4: Historical Prices for CNG, LNG, Gasoline and Diesel in California



Source: Derived from DOE, 2015a.

In late 2014, crude oil prices decreased dramatically lowering gasoline and diesel prices and decreasing the price differential between petroleum and natural gas-based fuels. This decline in crude oil price is a result of numerous factors including increased U.S. and global production and supply and can, in part, be attributed to the same enhanced extraction techniques that have enabled greater natural gas production and reserve projections. It is unclear how long the trend of relatively low oil prices will persist and what the long-term impacts will be on adopting natural gas vehicles, however commodity prices may not afford the same economic benefits as have been historically.

Natural Gas Fueling Station Availability

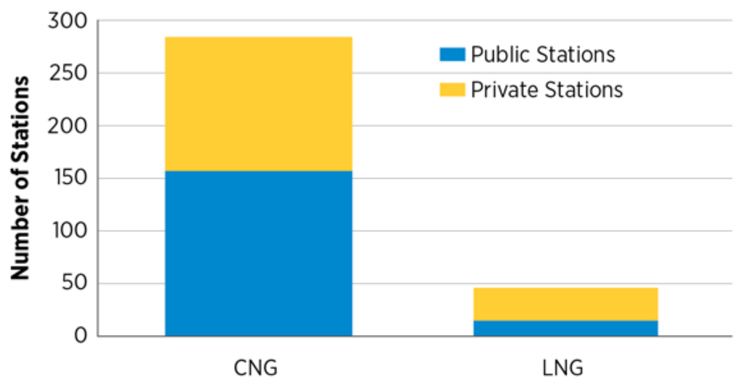
At the end of 2014, California had 330 compressed and liquefied natural gas fueling stations to support approximately 25,000 registered natural gas vehicles as shown in Figure 5 (DOE, 2015b). While many of these stations are open for public access, a number of them only provide limited access or exclusive access to a private vehicle fleet(s). LNG infrastructure in particular has limited public access, with only one-third of the LNG stations in California open to the

[4] It is possible that limited data availability for LNG prices may account for exaggerated volatility. One reason for limited data availability is a general lack of public stations and the lack of availability of public information around LNG contract pricing.

[5] This may not necessarily be the case for fuel contract agreements with private fleets

public.[6] Most of the CNG stations in California offer 3,600 psi (pounds per square inch) gas compression service while 15 stations offer only 3,000 psi service.[7] Of the 43 LNG stations in California, 23 are L/CNG stations providing both liquefied and compressed natural gas (DOE, 2015b). An increasing number of stations are offering RNG as a marketed variation of CNG, providing additional options for consumers and businesses.

Figure 5: Public and Private Natural Gas Fueling Stations in California (December 2014)



Source: DOE, 2015b.

CNG stations can also be fast-fill or time-fill configurations, which can exist independently or in combination to provide flexibility. Fast-fill stations account for the majority of California's CNG stations and provide fill performance similar to a traditional gasoline or diesel-fueling dispenser. Time-fill stations provide a slower rate of fill and are often employed in operations where a vehicle is parked for sustained periods of time, such as a fleet facility. Time-fill stations account for about 80 of the CNG stations (DOE, 2015b).

The availability of natural gas fueling infrastructure has shown relatively steady growth in California. In 2009, there were 191 CNG stations and 25 LNG stations. By 2014, the number of CNG and LNG stations had increased to 284 and 46 stations, respectively, which is shown in Figure 6 (DOE, 2015b).[8] For perspective, California has nearly 10,000 retail gasoline stations, a number that has been declining in recent years (CEC, 2012).

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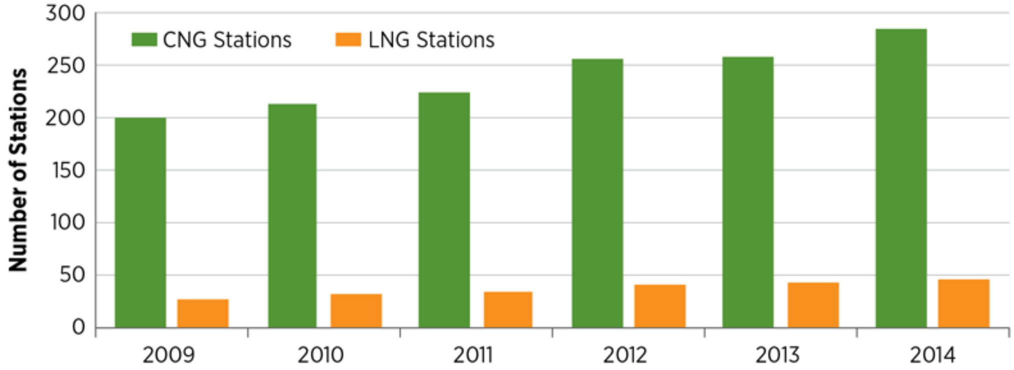
[6] L/CNG stations are classified as LNG stations for the purpose of Figure 5.

[7] The maximum pressure service offered by a CNG station indicates relative fill time as well as the maximum compression that a station can achieve in a vehicle (and accordingly having an impact on vehicle range).

[8] Additional estimates for natural gas fueling stations exist to include utility and other private stations, however the methodology for collecting this data and site verification are not clearly stated and accordingly not included in this report.

Figure 6: Natural Gas Fueling Stations in California (2009—2014)

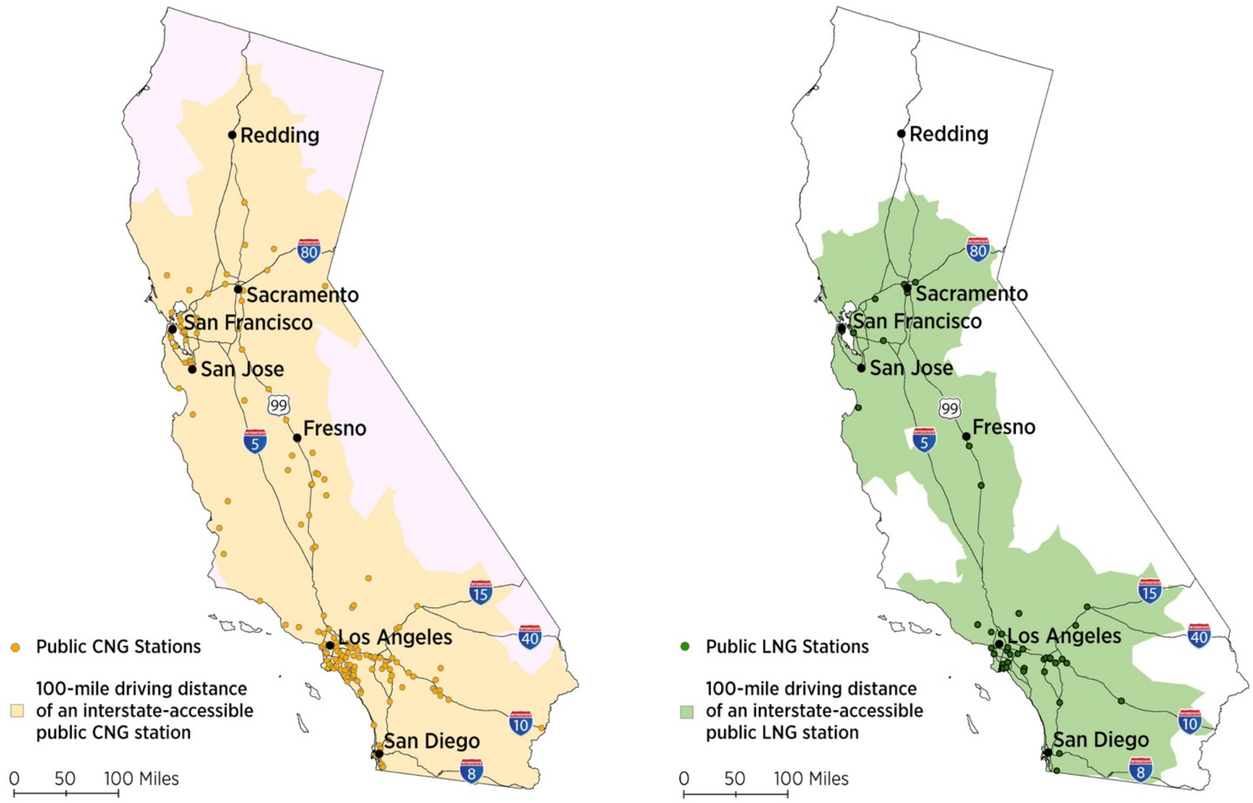


Source: U.S. Department of Energy Alternative Fuels Data Center

While California has the largest number of both CNG and LNG stations in the country, it ranks 13th and 3rd among states in the number of CNG and LNG stations per capita, respectively. Much of the natural gas fueling infrastructure in California is concentrated near the greater Los Angeles and San Francisco Bay areas; however, most parts of the state are within 100 miles of public CNG fueling (Figure 7).[9] From a practical perspective, the availability of fueling infrastructure can be viewed either as a corridor that facilitates intrastate and interstate transportation or as a hub that facilitates return-to-base or home trips. Public access fueling corridors exist in the central and southern parts of California for LNG and across most of the state for CNG. CNG is available at least every 100 miles at a public station between Redding and San Diego and there is a notable presence of public CNG access along Highway 99, which connects a number of communities in California's Central Valley. LNG is publicly available primarily in the greater Los Angeles area as well as the San Joaquin Valley, and Sacramento with two routes connecting those corridors. While these maps help to provide an overview of public fueling stations within California, they do not account for private fueling facilities or stations in neighboring states that may facilitate interstate operations.

[9] 100 miles was chosen for illustrative purposes only. Individual consumers, local fleets, and long-haul operations will all have different requirements, which may not allow for this to be practical.

Figure 7: Public Natural Gas Fueling Corridors in California (December 2014)

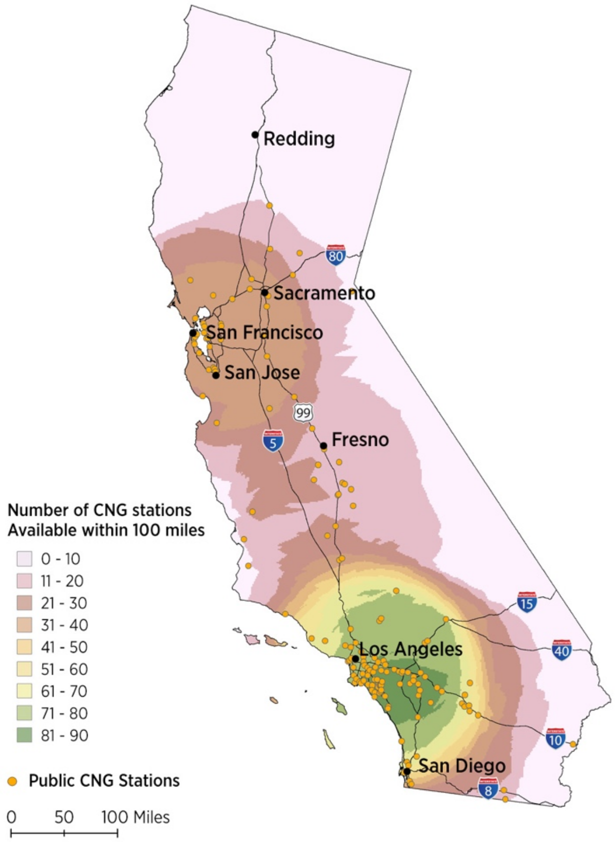


Source: Data derived from the U.S. Department of Energy Alternative Fuels Data Center

Natural Gas Fueling Hubs in California

The current economics and infrastructure availability of CNG facilitates both return-to-base operations and home trips, which in most cases require a localized concentration of infrastructure for basic convenience and refueling availability (Figure 8). The Los Angeles metro area has the greatest concentration of stations of any part of the state.

Figure 8: Density of CNG Fueling Infrastructure in California (December 2014)



Source: Data derived from the U.S. Department of Energy Alternative Fuels Data Center

Natural Gas Vehicle Market in California

As with other alternative fuels, a key indicator of fueling infrastructure viability is the number of vehicles capable of running on the alternative fuel. There are three types of natural gas vehicle technologies that allow for varying levels of fueling flexibility: 1) a dedicated natural gas vehicle that is only capable on running on CNG or LNG; 2) a bi-fuel vehicle that can run on either natural gas or gasoline independently; and 3) a dual-fuel vehicle that runs on natural gas but also requires diesel fuel for ignition.[10]

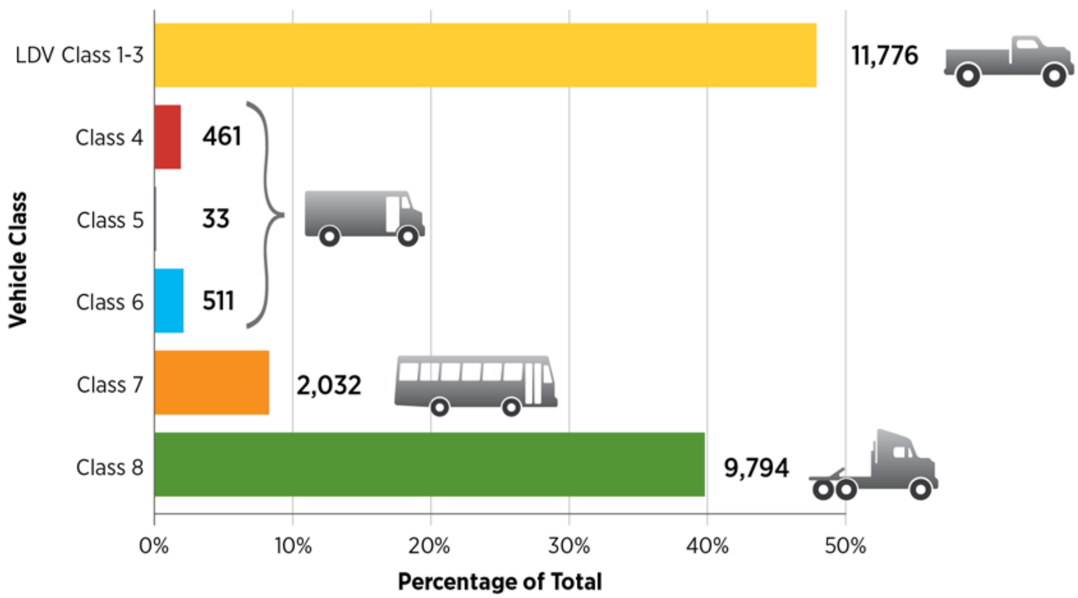
The driving range of a vehicle will often be correlated to the type of natural gas fueling system – a dedicated CNG vehicle typically has the lowest range of these options and likely has the

[10] The Energy Commission has also funded research efforts for hybrid natural gas vehicle technology, which pairs electric motors and energy storage with traditional combustion technologies for more efficient operation across the drive cycle. These vehicles are not currently commercially available.

greatest need for fueling infrastructure. Bi-fuel vehicles can operate on multiple fuels independently and create additional options for refueling and offer a greater "effective range." While bi-fuel operations provide an opportunity for drivers to choose petroleum or natural gas fuels, CNG and LNG prices can provide an economic incentive to use natural gas when possible.

By the end of 2013, roughly 24,600 natural gas vehicles were registered in California; about half of those fall into medium (Class 4-6) and heavy-duty vehicle classes (Class 7-8), and the remaining are light-duty vehicles (LDV Class 1-3) (Figure 9). Light-duty vehicles, and Class 8 trucks make up the largest portion of California's NGV fleet by a substantial margin (R.L. Polk VIO_2014). It should be noted that these figures do not include undocumented aftermarket conversions.

Figure 9: Market Share of Natural Gas Vehicles in California (2013)



Source: R.L. Polk VIO_2014

Wide disparities in fuel consumption across the vehicle categories are important when considering ratepayer benefits. For example, a passenger car uses about 500 GGEs per year, while Class 8 trucks use more than 12,000 GGEs annually.

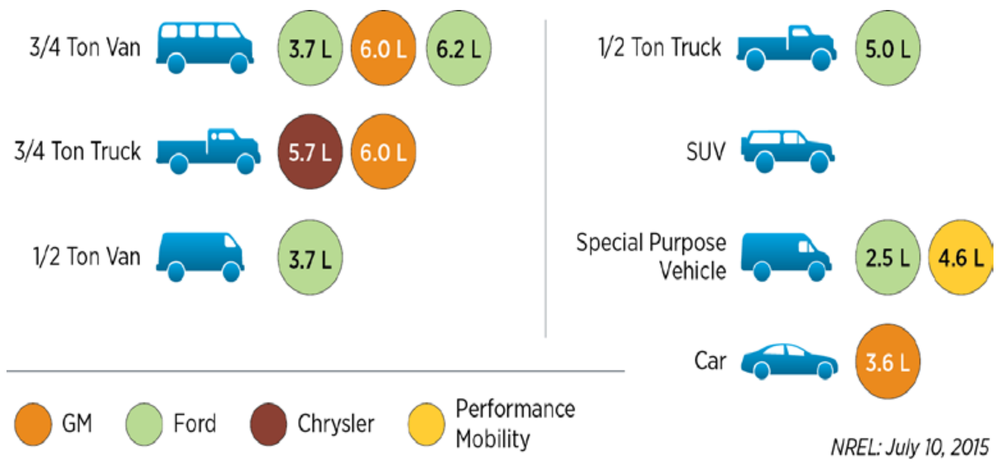
Natural Gas Vehicle Technology Advances

In the past five years, a number of new natural gas vehicles, engines, and fueling technologies have made their way into the market, and several significant product offerings are expected to become available in the coming year.

Light-Duty Vehicles

Several light-duty original equipment manufacturers (OEMs) have expanded their offerings in the natural gas vehicle market, catering primarily to fleet markets (more than 1/2 ton with more than 5.0-liter displacement). Figure 10 illustrates offerings that are currently available for purchase as OEM warrantied options.[11] This warranty does not include third-party vehicle conversions that are not warranted through the OEM or certified by the California Air Resources Board (ARB). While General Motors has announced it will offer its Impala as a bi-fuel CNG vehicle beginning in model-year 2015, there is a notable gap in consumer vehicle availability. Notably, Honda announced in June 2015 that it would discontinue sales of the Honda Civic Natural Gas, which had been available since 1998 and accounted for approximately 16,000 NGV sales nationwide (Ramsey, 2015) . The information suggests a broader shift towards accommodating fleet operations with limited options for consumer vehicles.

Figure 10: Light-Duty Natural Gas Vehicle and Engine Availability (by Displacement in Liters)[12]



Medium and Heavy-Duty Vehicles

Significant strides have been made in medium and heavy-duty natural gas vehicle and engine availability, and additional new engine(s) are expected to be released in late 2015 or early 2016. Specifically, Cummins-Westport's spark-ignited 6.7-liter CNG engine is expected to fill a current gap in heavy-duty engine availability and open up additional market opportunities (the engine is based on the Cummins ISB 6.7 that is a successor to the B 5.9 found in a wide variety of vehicles including Dodge/Ram diesel trucks). There is a noticeable gap in natural gas engine

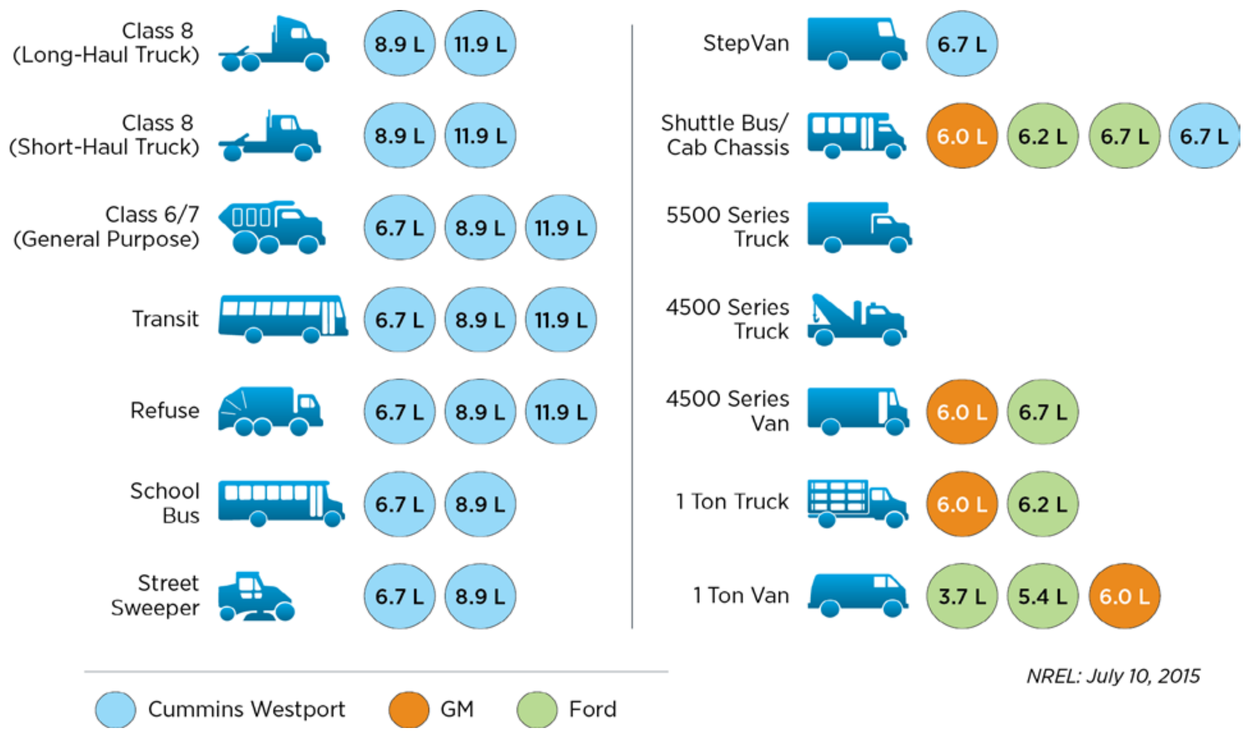
[11] Ford vehicles come with natural gas ready engines, which are fully converted through certified third parties through its Qualified Vehicle Modifier program.

[12] This chart represents the author's best estimate of vehicle and engine availability as of the anticipated date of final report publication (December 2015) and may be subject to further refinement prior to that date.

availability for displacements beyond 12L. While a number of engines have been announced, they have yet to be introduced into the market.

Since the *2009 NGVRR*, the Energy Commission has worked collaboratively with the U.S. DOE, South Coast Air Quality Management District (SCAQMD), NREL and other stakeholders to develop five high-performance, low emission natural gas engines that are becoming commercially available. Current engine offerings for medium and heavy-duty natural gas vehicles are still relatively limited in overall availability (Figure 11). It should be noted that medium and heavy-duty vehicles are often heavily tailored to specific applications and vocation and the availability for an engine in the chart below does not ensure that it is an appropriate fit for all applications and operating environments.

Figure 11: Medium and Heavy-Duty Natural Gas Vehicle and Engine Availability (by Displacement in Liters) [13]



Regulatory Environment for Natural Gas Vehicles

Since 2009, there have been a number of regulatory changes within the State of California as well as at the national level that are primarily directed at reducing vehicle emissions and/or increasing vehicle fuel efficiency. As has been the case with prior regulations, these changes are expected to have significant impacts on the technologies used by manufacturers and can help to

[13] This chart represents the author's best estimate of vehicle and engine availability as of the anticipated date of final report publication (December 2015) and may be subject to further refinement prior to that date.

guide NGV R&D investments. Perhaps as significantly, regulations also effect narrowing the gap in emission performance between natural gas and its gasoline and diesel counterparts through advanced engine, exhaust aftertreatment, and hybridization technologies. Further market expansion for high-fuel-consuming vehicles, which provide larger economic petroleum (i.e., diesel) displacement opportunities, brings attention to current efficiency challenges with spark-ignited natural gas engines. The combination of required greenhouse gas and criteria pollutant emission reductions presents a challenging environment for air quality planners as well as vehicle technology providers and integrators. These combined objectives must be considered simultaneously to lower overall costs and make sure improvements are made on both air quality and climate goals.

Light-Duty Vehicles

For vehicle model years 2012—2016 and 2017—2025, federal fuel economy standards have been set that mirror those established by the California Air Resources Board, and now provides a uniform national standard of average fleet requirements. These standards have also introduced greenhouse gas emissions as the key measure of a vehicle's fuel efficiency. Recognizing additional benefits to using natural gas in transportation, current natural gas vehicles receive a significant multiplier when calculating fuel economy for the Corporate Average Fuel Economy (CAFE) standards (e.g. a CNG car that averaged 15 miles per gallon would be viewed the same as a gasoline vehicle that gets 100 miles to the gallon). Going forward, federal CAFE requirements provide a multiplier of 1.6 for natural gas vehicles in model year 2017; this ramps down to 1.3 by 2021, after which it is phased out (Federal Register 2012).[14] To meet early efficiency and emission targets, light-duty car manufacturers have turned to technologies such as light weighting, hybridization and electrification, engine downsizing, and new combustion strategies such as gasoline direct injection. These technologies have been almost exclusively applied to gasoline-powered vehicles. California and nine other states have also adopted zero-emission vehicle targets that will influence the technology used in the light-duty vehicle market.

Medium- and Heavy-Duty Vehicles

In 2011, the U.S. Environmental Protection Agency (EPA) finalized rules for the first-ever heavy-duty vehicle efficiency standards for model years 2014—2018. Earlier in 2014, the U.S. EPA announced that the program would continue with new standards that cover model years 2019—2025, which also brings them in line with the timing for light-duty vehicle efficiency standards. It is expected that these standards will require significant reductions in greenhouse gas emissions, which suggests the need for strategies similar to those for light-duty vehicles. Heavy-duty natural gas vehicles will likely be able to benefit from many of the technologies adopted for heavy-duty diesel vehicles.

These fuel efficiency rules are in addition to air quality regulations, which present increasing technology challenges to comply for critical air basins in California. California has long been at the forefront of taking action to improve air quality. In its 2012 "Vision for Clean Air," the ARB

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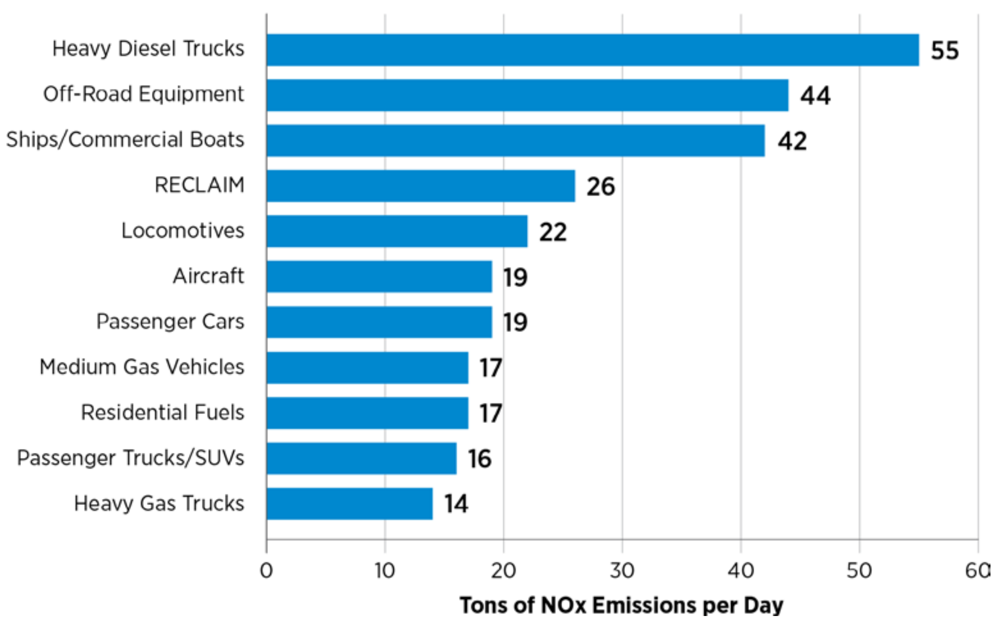
[14] Both dedicated and bi-fuel natural gas vehicles are eligible for these credits.

stipulates that by 2023 an 80 percent reduction in nitrogen oxide (NO_x) emissions over 2010 levels are necessary to meet federal ozone standards of 84 parts per billion (ppb). In December of 2014, the U.S. EPA announced a rulemaking that will consider lowering this standard to between 65 and 70 ppb, while seeking further comment on setting the standard at 60 ppb. By 2031, ARB expects reductions in NO_x of about 90 percent below 2010 levels are required to attain the ozone standard in the South Coast Air Basin, and a similar magnitude of emission reductions necessary in the San Joaquin Valley. Current ARB standards are 0.2 grams of NO_x per brake horsepower-hour (g/bhp-hr) with the option to certify optional reductions as low as 0.02 g/bhp-hr.

Regardless of the outcome of the rulemaking, NO_x emissions must continue to be reduced. Mobile sources are the largest contributor of NO_x in California, with a majority of these emissions attributed to heavy-duty vehicles, so a significant portion of the necessary reductions must come from heavy-duty vehicles. Figure 12 illustrates projected NO_x emissions in the South Coast Air Quality Management District (SCAQMD) by source in 2023. With targeted technology advancements, natural gas vehicles are well positioned to continue to lead the charge toward greater NO_x reductions. Additional technology developments are necessary to combine progress on lower NO_x reductions with higher efficiency for lower greenhouse gas emissions, which otherwise conflict. This includes higher efficiency in actual vehicle operation.

Figure 12: Projected Sources of NO_x Emissions in South Coast Air Basin by 2023 (tons/day)



Source: California Air Resources Board et al., 2012.

High-Horsepower Opportunities for Natural Gas

Favorable economics for natural gas as well as international and domestic emission regulations have increased interest in what are called "high-horsepower" applications such as the marine and rail sectors. While the *2015 NGVRR* is focused on over-the-road applications, there is an opportunity to expand R&D efforts into this emerging area for natural gas.

While much of marine and rail operations that initiate or terminate in California are interstate or international in nature, commercial marine vessels and locomotives are projected to be the third and fifth largest sources of NO_x in the SCAQMD by 2023 (Vision for Clean Air, 2012). Additionally, health concerns surrounding the relatively high sulfur content of heavy fuel oil, which is used in some marine applications, have led to more stringent regulation of marine emissions. Some efforts have explored hybridization of the primary power source and reducing auxiliary loads for marine applications; however the scale and horsepower required by these modes also suggest a broader opportunity for natural gas to displace the current use of diesel and heavy fuel oil.[15]

It is worthwhile to point out possible synergies between localized marine and rail operations that can use natural gas. Harbor craft and switching locomotives have similar operating characteristics and typically use the same or very similar engine designs. The combination of these two applications in a given port can also provide more attractive economics to infrastructure investments by providing a larger market for LNG, and in some cases CNG, fuel.[16]

Marine Applications of Natural Gas

With numerous high-volume ports in California – the Ports of Los Angeles and Long Beach account for nearly one-third of all container traffic in the United States – and the relatively large quantities of fuel used, marine applications for natural gas can create value to California ratepayers through emission reductions and petroleum displacement. This is further sparked by economic benefits and increasing regulations on marine applications, which have rudimentary emission controls compared to compliant over-the-road vehicles.

Ocean-going vessels, which can be rated at greater than 100,000 horsepower, are significant consumers of fuel. However, these vessels spend a relatively short amount of time running at full load within California waters, which limits the ability to achieve localized benefits within the state.[17] In the Port of Long Beach's 2013 Air Emissions Inventory, ocean-going vessels accounted for about 59 percent of NO_x emissions and 35 percent of greenhouse gas emissions at the Port, demonstrating the size of the opportunity for emission reductions (Port of Long Beach, 2013).

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[15] CNG is also being used in some high horsepower applications such as natural gas extraction and rail applications, but to a lesser extent.

[16] Switch locomotives are part of the North American freight rail fleet operations, and though they tend to operate within a region longer than interstate line haul locomotives, they will likely have to operate as dual fuel locomotives until the national rail network ultimately transitions to natural gas.

[17] SCAQMD measures emission impacts for marine vessels out to a distance of 100 nautical miles from California's coastlines.

Commercial harbor craft are significantly smaller in scale, but they provide a captive fleet that potentially supports more direct air quality benefits for California ratepayers. These vessels range from between a few hundred horsepower to more than 3,000 horsepower and serve a variety of purposes in managing operations at the ports. In 2013, harbor craft accounted for about 9 percent of NO_x emissions and 5 percent of greenhouse gas emissions at the Port of Long Beach (2013 Emissions Inventory, 2013).

Several efforts are currently underway to deploy LNG in marine vessels in the United States. Initial ocean-going LNG marine vessels are expected to be container ships, with the first expected to begin operation in 2015 as a retrofit. LNG transport vessels have also been discussed, which may require that they be co-located with liquefaction terminals. Other fuel delivery options being discussed include using bunker fueling operations or bringing in LNG via truck. It is worth noting that dual-fuel applications have been discussed for natural gas use in marine vessels.

In addition to using fuel for transport, cargo ships also spend a significant time docked at ports (about 40—70 hours) and require off-board auxiliary power. Using natural gas in one or both of these operations presents opportunities for more direct economic and health benefits and can possibly address some of the infrastructure scale challenges for initial applications. However, using natural gas in cargo applications is a challenge since currently the most commonly used fuel, heavy fuel oil, is often much less expensive than diesel fuel and does not provide the same cost savings as applications where natural gas is displacing diesel.[18]

Rail Applications of Natural Gas

Similar to marine applications, rail operations are fuel intensive and diesel costs can make up a substantial portion of a railroad's operating costs. The U.S. Energy Information Administration estimated that in 2012, fuels costs made up 23% of freight railroad budgets (Chase, 2014). LNG-powered locomotives are currently under research with small-scale demonstrations to determine the value of lower fuel costs and better environmental performance. Switch and medium-horsepower locomotives and others in California may provide immediate benefits and also seed activities for much larger-scale cross-country operation. The *2015 NGVRR* looks at opportunities for the three classes of locomotives: switch (1,006—2,300 HP), medium horsepower (2,301—4,000 HP), and interstate (greater than 4,000 HP) locomotives. A 2009 report issued by the ARB cites estimated annual locomotive diesel fuel consumption by Union Pacific and BNSF Railway at about 150 million gallons per year within California. The ARB has updated the previous fuel consumption estimates to more than 200 million gallons annually. Union Pacific and BNSF operate about 400 intrastate switch and medium horsepower locomotives that consume about ten percent or 20 million gallons or more of diesel fuel per year. The 2009 report concluded that four interstate locomotives carried a comparable load to

[18] It should be noted marine fuel is limited to 0.1 percent sulfur by California (out to 24 nm) and nationally (out to 200 nm). This requirement is typically met with the use of distillate fuel. Accordingly ships often carry multiple fuels, which present an opportunity for a dual-fuel natural gas application.

280 trucks but required about one-fourth of the fuel, providing substantial benefits in comparably energy efficiency (CARB 2009).

Natural gas use in rail operations has been discussed, researched and demonstrated numerous times over the past 75 years and has previously been demonstrated in California with small switch locomotives at a relatively small scale. In the 1990s BNSF deployed four LNG-fueled switching locomotives in Los Angeles as part of a demonstration; these were the only LNG-fueled locomotives operating in the United States during that time and they have since been decommissioned (CARB, 2009).

Attractive economics for natural gas and the recently implemented Tier 3 and Tier 4 regulations by the U.S. EPA have caused a number of railroads and locomotive manufacturers to reexamine potential opportunities for natural gas-powered rail operations. BNSF has recently tested a natural gas-diesel dual fueled six-axle locomotive, suggesting a renewed interest in interstate applications for natural gas-powered rail operations. These particular locomotives utilize dual-fuel configurations with varying mixtures of natural gas (between 60 percent and 80 percent) and diesel needed to operate within the compression ignition system (Vantuono, 2014). Other companies have also explored spark ignition engines, which allow for the use of 100 percent natural gas. Caterpillar and Westport have announced their intent to work jointly on the development adapting Westport's high-pressure direction injection engine to high-horsepower applications, with the goal of achieving U.S. EPA's current new Tier 4 locomotive emission standards (Westport, 2012). Specific to California, in 2013 SCAQMD announced funding for the development an LNG passenger locomotive to be piloted by Metrolink. The critical issues to consider on whether to initiate larger scale use of LNG interstate line haul locomotives on the North American freight rail network are: locomotive modification and tender costs, tender fueling range and time to implement federal standards, and potential train operational impacts (i.e., train delays).

Recent incidents in transporting oil by rail have led to efforts to reevaluate safety standards for rail car design and operation. CNG and LNG locomotives and the attached fuel tenders have been included in these discussions, causing some delay in technology developments until standards are finalized.

CHAPTER 3: Natural Gas Vehicle Research and Development Gaps and Market Barriers

Given the current status of the market for natural gas for transportation, technology advances made in the last five years, and new regulations for light-, medium-, and heavy-duty vehicles, the following R&D priority areas have been identified to address market barriers:

- Range and natural gas storage
- Engine performance and availability
- Vehicle emission and environmental performance
- Analysis and information sharing.

While there is overlap among these categories, these topics cover key issues that can enable natural gas vehicle technology to provide greater value to California ratepayers.

Range, Infrastructure and Natural Gas Storage

Range, and the associated challenges with on-board storage of fuel, continues to be a significant barrier for natural gas vehicles across all vehicle classes. These challenges can be attributed to several factors:

1. Storage capacity, size, weight, shape and cost of compressed natural gas cylinders
2. Size, weight, energy density, cost and possible venting of liquefied natural gas storage vessels
3. Availability, cost and convenience of fueling infrastructure
4. Relative engine efficiency and performance.

Each of these areas presents R&D opportunities to increase the distance that NGVs can travel. Increased availability of CNG and LNG can offset the range issue somewhat; however, limited range will continue to be a market constraint without major advances in on-board storage.

Compressed Natural Gas Storage

In light-duty vehicles, increased range comes at the expense of cargo space and functionality, either in the trunk of a vehicle or in the cargo space of a van or truck. For example, a 2014 Honda Civic natural gas vehicle has the capacity to hold 8 gasoline gallon equivalents (GGE) in a cylinder that is located in the trunk, while gasoline models can hold 13.2 gallons in a tank that is built into the vehicle chassis. For medium- and heavy-duty vehicles, increased natural gas range comes with a trade-off between storage, weight, and cost. For many of these larger vehicles, additional weight and space needed for fuel storage comes at the direct expense of revenue from cargo and may also limit other fuel economy measures that can be implemented. Natural gas storage has been the subject of a number of projects supported by the U.S. DOE

Advanced Research Project Agency-Energy (ARPA-E), yet substantial R&D is still necessary to commercialize targeted technologies after the prescribed three-year project periods expire. This specific example highlights a broader opportunity to coordinate R&D between California and federal activities to move technologies from high-risk R&D to technology commercialization to technology deployment.

Develop Low-Pressure, High-Density Natural Gas Storage Vessels

This research is continued from the *2009 NGVRR*. Current natural gas storage vessels require off-board compression and constitute a major part of the incremental cost, space requirement, and weight of an NGV. Additionally, compressing gas from pipeline pressure, which can be as low as 0.5 psi in residential locations, increases the required capital equipment and electricity costs for CNG fueling. Because of this, the availability of a low-pressure, high-density storage vessel can enable more cost-effective small-scale refueling options without sacrificing range and may also lead to lower fuel production/compression costs at current commercial fueling stations. Lower pressures also create an opportunity to shape tanks in a way that could conform to greater placement options in a vehicle and could create opportunities for lower-cost home refueling devices. It should be noted that conformable tank designs have also been explored for high-pressure applications, which are included in the recommendation to increase vehicle/storage integration.

Advanced storage technology offers the dual opportunity to use lower pressures and enhances range otherwise limited by current high-pressure cylinders. Unlike traditional cylinders, which have a hollow interior, adsorbed natural gas storage uses a lattice-like structure to store natural gas at higher densities but at relatively low pressures. While there have been a number of research projects to examine various materials for adsorbed storage, barriers still exist to commercially viable solutions. Adsorbent storage may require high-quality methane to maintain high storage capacity over its lifetime. While pipeline natural gas meets certain specifications, CARB rules specify that it can include up to 12 percent of other molecules by volume that could affect the viability and durability of adsorptive technology. Durability with real world components (e.g. mercaptan) or some limits to fuel quality may be necessary targets for development and demonstration of effective storage capacity.

Work funded by ARPA-E through its Methane Opportunities for Vehicular Energy (MOVE) Program examined various materials and geometric configurations of storage lattices (Table 2). This was complemented by an effort to develop modeling and screening techniques for low-pressure adsorbent materials and validate these models with real-world results. While a number of these projects were able to meet individual performance metrics, such as energy density, durability, cost, and fueling rates, no single technology has been able to meet all of the targets. Further efforts are necessary to identify and develop a commercial product that can deliver across the suite of required performance characteristics. Future research in this area should leverage lessons learned from various projects to avoid duplication and seek to resolve remaining technical challenges.

Table 2: ARPA-E MOVE Sorbent Technical Targets

ARPA-E Sorbent Storage Technical Targets	
Storage Cost	< $150/gge
Storage Capacity	10 gge
Maximum Operating Pressure	< 6.5 MPa
Minimum Operating Pressure	> 0.58 MPa
Compressor Cost	$1,000/(gge/h)
Energy Density	> 9.2 MJ/L
Sorbent Cost	< $10/kg
Desorption Rate	0.2 kg/(L*h)
Lifetime	1,000 cycles
Desorption Temperature	< 85°C
Temperature Tolerance	-40°C to 85°C
Impurity Tolerance	Pipeline Natural Gas

Source: ARPA-E, 2012a

Develop Certification Procedures for Natural Gas Conformable Storage Tanks

Given the research that has been directed toward adsorbed storage and conformable tanks, testing and certification procedures are necessary to enable their use in vehicles. Certification is currently under the jurisdiction of the U.S. Department of Transportation; however it is often left to states to ensure compliance. California has the opportunity to partner with the U.S. Department of Transportation to develop testing and certification procedures that will promote the safe and cost-effective use of adsorptive and/or conformable, on-board natural gas storage tanks.

Increase Natural Gas Storage and Enhance Vehicle Integration

Options for integrating CNG cylinders into various vehicle designs are limited from the size and shape of the cylinders. The effect of this is two-fold: this can limit the available total natural gas storage available in a vehicle, and it often requires a cylinder to be installed in a position that would otherwise be used for cargo, limiting vehicle utility. One option for the Ford F-250 has the natural gas cylinder installed underneath the truck bed, which frees up storage space, but this is the exception to most installations. For other applications such as transit buses, cylinders are mounted on the roof of the vehicle, but this is not practical and/or permitted in other applications. Current passenger NGV designs in more mature NGV markets, such as Europe, provide for compressed gas storage in multiple locations that often do not require significant sacrifices in cargo space. The lack of these options in the United States is often attributed to relatively low sales volumes, which prevent original equipment manufacturers (OEMs) from being able to justify dedicating engineering resources to NGVs. Cost sharing to underwrite the costs of vehicle design and certification, as well as a market study or needs assessment to determine where greater cylinder integration would add value, can help to encourage better NGV design in the United States. There may be synergies between the challenges for integrating fuel storage with natural gas vehicles and with hydrogen fuel cell electric vehicles. Increased OEM efforts on gas storage technologies can likely provide mutual benefits. It should also be noted that more customization in cylinder design could come at the expense of economies of scale and impede cost reductions.

The opportunity for conformable, high-pressure storage also presents an opportunity for increased vehicle/storage integration. A number of configurations were explored in ARPA-E's MOVE program to increase the use of available space in a vehicle for pressurized gas storage. The strategies of increasing integrating current CNG cylinder designs with exploring more conformable geometries for high pressure (3,600 psi) gas storage should be pursued in tandem, and require potentially different approaches.

Develop Low-Cost Carbon and Glass Fiber Storage

Numerous CNG cylinders in use today are made of high-strength steel, which provides an economic but relatively heavy solution. More advanced Type-2, Type-3, and Type-4 cylinders utilize carbon or glass fiber, providing a weight reduction of almost 80 percent on a storage capacity basis. The cost of these tanks, however, is significantly more than their steel counterparts as demonstrated in Figure 13 (NPC 2012). While Type-1 tanks make up a large majority of current pressure vessels, it is expected that there will be a substantial increase in more advanced technology.

Applications such as aviation and high-end automotive chassis use advanced fiber-based systems and have seen continuous improvement in both cost and performance. Dedicated research for fiber-based gas storage with reduced gas permeation will help advance more cost-effective lightweight gas storage options. This research effort can also be combined with conformable storage to allow for lighter, cheaper, and more adaptable CNG cylinders. Work could be pursued in conjunction with the advanced composites hub of the National Network for Manufacturing Innovation, particularly as advanced, bio-based materials become more available.

Low-cost fiber-based storage R&D efforts can also be leveraged with existing research in the area of carbon figer based hydrogen storage, which provides higher-pressure storage for smaller molecules (which result in smaller tanks). Proceeding along this route also opens up the possibility for storage pressures greater than 3,600 psi as hydrogen is often stored at pressure of up to 10,000 psi. Higher storage pressures for natural gas would increase range with the likely tradeoff being increased cost.

Figure 13: Natural Gas Cylinder Storage Technologies

Cylinder Type	Most Commonly Used Materials	Indicative Cost (U.S. $/Liter)	Indicative Weight (Kg/Liter)
Type 1	Steel	$3 to $5	0.9 to 1.3
Type 2	Steel with Glass Fiber	$5 to $7	0.8 to 1.0
Type 3	Aluminum with Glass and/ or Carbon	$9 to $14	0.4 to 0.5
Type 4	Carbon Fiber with High-density polyethylene Liner	$11 to $18	0.3 to 0.4

Sources: CompositeMarketReports.com, CompositeWorld.com. Chart adapted from NPC (2012)

Infrastructure Cost and Availability

As discussed in Chapter 2, California has a relatively robust commercial natural gas fueling infrastructure; however, station count numbers fall far short of those for diesel and gasoline. CNG and LNG station costs are also much higher given the requirement for expensive on-site storage and compression (in the case of CNG). CNG fueling infrastructure can also cost anywhere from $45,000 to $1.8 million depending on the necessary level of service, while LNG stations range in cost from $1 million to $4 million (DOE, 2015c). Amortizing capital expenditure can dominate costs for underutilized resources, so infrastructure builders need a certain demand base before making the investment and typically see significant improvements in station economics as demand increases. Increased availability of stations, opportunities for home refueling, and decreased operational and capital costs can help to foster a more competitive natural gas vehicle market. Furthermore, by increasing the efficiency of fueling station operations, there is an opportunity to reduce operating costs and environmental impacts from compression (which is a direct function of electricity costs).

Develop Cost-Effective Home Refueling Technologies

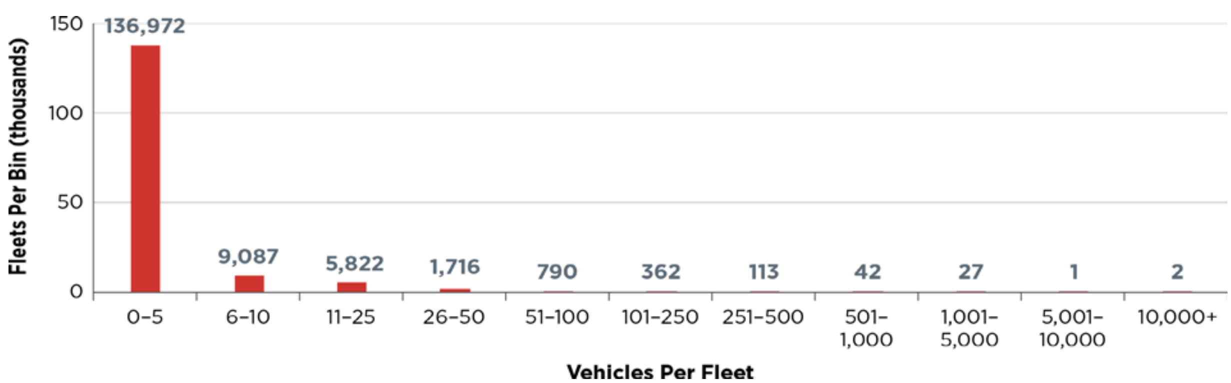
The majority of California residences have natural gas service installed, positioning home refueling technologies as an opportunity to provide greater access to natural gas and increase the overall convenience of owning an NGV. While home refueling appliances are available, they are relatively expensive (about $5,000) and have relatively long fill times (ARPA-E, 2012b). In

2012, GE announced an effort to develop a home refueling appliance that would chill the gas to provide for lower-cost fills. This effort has since been cancelled and a more cost-effective natural gas home refueling solutions is required (ARPA-E, 2012b). Home refueling provides the most benefit to commuters and small fleets, expanding market opportunities for passenger and personal-use vehicles. Home refueling can also allow NGVs to offer similar convenience at similar overall incremental cost of plug-in electric vehicles. Given a general lack of success of previous efforts to align home refueling with current high-pressure on-board storage, the success of home-refueling technologies may be coupled to the development of low-pressure storage as described earlier. It should be possible for low-cost refueling equipment to partially fill high-pressure cylinders overnight enough to meet typical daily range requirements. This effort would complement bi-fuel vehicle configurations that a number of OEMs are pursuing.

Develop Small or Modular Fueling Facilities

In California, a majority of CNG fleets have fewer than five vehicles as shown in Figure 14 (R.L. Polk VIO_2014). Given the relatively high costs of CNG and LNG fueling infrastructure, these smaller fleets likely rely on public infrastructure. Current fueling solutions are in many cases too expensive and large in scale to justify on-site fueling. GE currently offers its "CNG-in-a-box" solution for approximately $750,000 per unit (Piellisch, 2013), which provides 1.0-6.3 gge/min (GE Oil & Gas, 2013). By developing similar modular and small- to medium-sized CNG fueling components, more fleets can leverage the convenience and economics of on-site fueling. Such a technology would primarily serve small fleets and be scaled between a home refueling unit and the "CNG-in-a-box" solution. From the standpoint of public benefits, these fleets also will typically displace more gasoline/diesel usage than typical consumer vehicle.

Figure 14: California Medium- and Heavy-Duty CNG Vehicle Fleets by Number of Vehicles



Source: R.L. Polk VIO_2014

Increase Fueling Station Operational Efficiency

On-site storage of natural gas is used to enhance the fueling experience by providing reduced fill times and increased capacity to provide back-to-back fills. On-site storage also presents some challenges, as there is a limited ability to use the full storage capacity of a given cylinder due to inherent pressure requirements for fueling operations. It is estimated that only 30 percent of storage capacity is actually used in fueling operations. A better use (via operational or design improvements) of on-site storage management and compression presents opportunities to improve both fueling station economics and performance. Similar to needs for lower-cost on-board natural gas storage, more efficient and economic storage vessels at fueling facilities can help to lower overall operating costs and also provide resiliency benefits such as in an emergency or disaster. Furthermore, additional measures such as improved station and compressor design can help to improve the operations profile of natural gas fueling stations.

Maximize Cylinder Utilization and Improve Fill Quality

Because natural gas is compressed from low pipeline pressures to high (typically 3,600 psi) pressures, CNG is often hot by the time it reaches the fuel cylinders and further heated as it is compressed within the cylinder itself. Implementing technology on the dispensing side, as well as in the storage vessel itself, to compensate for temperature increases while increasing fueling rates can increase CNG vehicle range by improving the utilization of vehicle compressed gas storage. R&D is needed to develop technologies to facilitate and verify better fills in a safe manner. Improved fills can be accomplished at the refueling station, via communication between fueling equipment and vehicles as described below, or through algorithms that dynamically measure fills and tank conditions. Cylinder valve and pressure-relief device technology presents another opportunity to provide for a fuller, faster fill.

Promote "Smart" Cylinders and Refueling Stations to Enhance Monitoring Capabilities

Developing sensors, communication protocols, and software for communication between storage cylinders and refueling equipment can also enhance vehicle operation and safety. In addition to adjusting operational variables, such as those described for temperature compensation, communications built into cylinders can help to convey valuable safety data to drivers and maintenance technicians such as remaining cylinder lifetime, presence/pressure of fuel in a given cylinder, and any damage that may have occurred due to an accident or abnormal operation. Some of these technologies may be adapted from hydrogen fueling equipment and storage containers to provide for shared economies and standards. In either case, developing these technologies must be done to ensure that additional control and monitoring avoids the opportunity for additional error.

Vehicle and Engine Performance and Availability

Significant investment and progress has been made in natural gas engine development and commercialization over the past several years. For heavy-duty vehicle classes and vocations in particular, this has led to greater vehicle availability and adoption; however, there remain opportunities for engine development to meet advanced requirements and continued vehicle integration in this space. For medium- and heavy-duty vehicles, it will be important to continue down the pathway of greater fuel efficiency and emission reductions to meet increasingly stringent requirements while maintaining or improving performance characteristics. In addition, the relative efficiency penalty of natural gas engines compared with diesel engines may justify research on strategies such as hybridization and advanced combustion strategies that can best take advantage of the beneficial properties of natural gas. Extending these objectives into the light-duty sector may depend on achieving economies of scale for NGVs relative to gasoline vehicles.

Vehicle and Engine Development

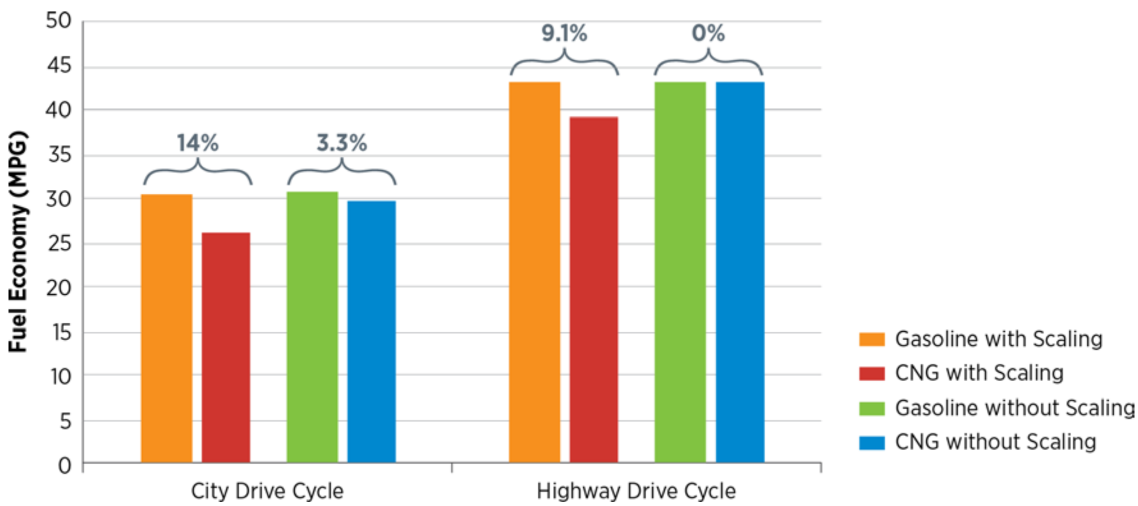
Vehicle technology and engine development for conventional and natural gas vehicles have advanced substantially in recent years as consumer demand and regulatory requirements have changed. This is evidenced by both greater availability of medium- and heavy-duty engines and increased integration of natural gas engines and storage into existing platforms.

Invest in Light-Duty Engine Development and Direct Injection Engines

As light-duty vehicle manufacturers continue to drive up vehicle efficiency, engines are increasingly shifting to gasoline direct-injection (GDI) technologies and reduced displacement (referred to as 'downsizing', which is often combined with turbocharging to maintain performance). Both GDI and the trend to downsize/turbocharge have significant implications for NGVs because they present challenges in vehicle performance and technology integration.

Previous research has suggested a loss of 2 percent to 12 percent in vehicle efficiency for a light-duty natural gas engine over a gasoline counterpart (Kwon and Rousseau, 2012).[19] Figure 15 illustrates the fuel economy performance of gasoline and natural gas when compared across identical light-duty engine models and when the natural gas engine has been increased in size (displacement) to provide comparable performance. This relative efficiency gap may increase unless new engine designs and technologies are able to effectively use natural gas.

Figure 15: Relative Fuel Economy Between Natural Gas and Gasoline Vehicles



Source: Kwon and Rousseau (2012)

Some unique technology challenges must be addressed for NGVs to keep pace with gasoline engine technology developments. Specifically, injection system technology, modeling, and design must be tailored to accommodate the pressures provided by on-board natural gas

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[19] The lower end of the range examines the same natural gas and gasoline engine, whereas the higher number of 12 percent represents a natural gas engine that has been increased in size (displacement) to match the performance of the gasoline engine.

storage and required for natural gas direct injection, which shows promise for bridging current performance and efficiency gaps. It is also possible that shifts to GDI engines will create a necessity to manage increased sub-micron particulate emissions, requiring additional research into combustion strategies and aftertreatment. There are a variety of challenges of integrating natural gas into GDI engines. While there are likely a number of factors that went into the decision, it is noteworthy that the gasoline-powered 2015 Chevrolet Impala has a GDI engine while port injection is used in the natural gas-powered model. Other opportunities include exploring using Miller and Atkinson cycles in light-duty engines.

Continue Research in Medium- and Heavy-Duty Engine Development

Over the past few years, developing medium- and heavy-duty engine has received considerable support from the Energy Commission, SCAQMD, U.S. DOE, and NREL resulting in a number of new engine sizes, designs, and performance improvements. In addition to the previous models mentioned, it is expected that Cummins Westport will offer a 6.7-liter ISB6.7G in limited numbers in 2015 with full production beginning in 2016 (Cummins Westport, 2015). It is notable that several efforts to develop larger engines, such as Cummins' 15-liter SESI and Volvo's 13-liter HPDI natural gas engines, have been put on hold. This leaves a gap in availability for natural gas engines larger than 11.9 liters.

Going forward, continued efficiency, performance, and emission improvements will be necessary for medium- and heavy-duty NGVs. These improvements will be driven by fuel economy standards and the increasing pressure to decrease NO_x emissions to meet air quality requirements in California's air basins (potentially down to .02 g/bhp-hr). Both objectives will likely require higher levels of exhaust gas recirculation, advanced ignition and fuel injection (port and DI) systems, and downsized engines with higher boosting. It will be critical to continue to encourage the development of new medium- and heavy-duty engines with a particular emphasis on emission performance. Increasingly this work must be incorporated with advanced aftertreatment technologies for natural gas. In dual-fuel applications, recent work completed by the Southwest Research Institute demonstrated advanced timing and specialized fuel injectors for operations that use natural gas for a majority of operations suggesting targeted research needs for this natural gas application.

Similar to light-duty vehicles, it will be increasingly important to reduce the efficiency gap between natural gas and diesel engines that limits greenhouse gas benefits. Data collected by NREL from refuse haulers suggest as much as a 15 percent to 20 percent fuel efficiency penalty depending duty cycle (Kelly, 2015). Some of these penalties can be addressed through integrating existing hybridization technologies and strategies along with an overall increase in the electrifying engine subsystems. Additional research is required to identify the technology opportunities to reduce and ideally eliminate this performance gap, including natural gas optimization for gasoline-based engines, hybridization strategies, and avoiding losses that result from throttling in diesel-based engines.

As mentioned in the *2009 NGVRR*, longer-term engine technologies that continue to show promise include homogenous charge compression engines and low temperature combustion technologies such as reactivity controlled compression ignition. Reactivity controlled compression ignition in particular has demonstrated the ability to produce an indicated mean effective pressure of almost double what gasoline is capable of (Walker, et al., 2014).[20] Other technologies such as cam-less engine and waste heat recovery and advanced ignition systems (as mentioned earlier) will also be key to meeting future performance and emission targets. While natural gas may not drive the development of these technologies, it will be important to verify where natural gas characteristics provide benefits with RD&D on advanced engine technologies and emission control. Low temperature combustion strategies will also require significant research into advanced catalysts and aftertreatment that may support unique opportunities for natural gas.

The benefits of increased efficiency in medium and heavy-duty vehicles also directly carry over to the performance of California's freight industry. In 2015, an effort to develop a California Sustainable Freight Action Plan was initiated to improve freight efficiency, transition to zero-emission technologies, and increase competitiveness of California's freight system. The undertaking involved numerous California agencies and stakeholders and presents opportunities for natural gas vehicles to be considered as contributing towards the initiatives objectives.

Exploit Natural Gas Properties and Address Fuel Quality Discrepancies[21]

The *2009 NGVRR* addressed flexible engine controls to address varying fuel quality. A number of vehicle OEMs and trade associations have stated the desire to have separate natural gas fuel quality specification for vehicle use indicating that current pipeline gas specifications are not conducive to efficient use in internal combustion engines. The conversation around fuel specifications will become increasingly important as engine designs may need to become more adaptive to the fuel that they are burning to meet regulatory requirements. Natural gas has several properties that are ideal for tailored engine design, such as a high-octane value, which allows for greater compression ratios and higher boosting. Given the relatively small market share of natural gas being used in transportation, it is unlikely that fuel composition standards will be enacted that are optimized around vehicle engine performance and the demand for engine controls to deal with real-time fuel characteristics. On-board technologies can help to compensate for varying fuel quality/content issues, while off-board solutions are likely best suited to address contamination and oil carryover issues.

Several research opportunities in this topic exist including quantifying the impact of methane properties on combustion strategies, identifying on-board controls to compensate for varying fuel quality specifications (identified in the *2009 NGVRR*) and understanding the efficiency

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[20] Research by the University of Wisconsin demonstrated an indicated mean effective pressure of 13 bar for natural gas in a reactivity controlled compression ignition engine, while the gasoline equivalent produced an indicated mean effective pressure of 7 bar.

[21] Fuel quality is also an issue for renewable natural gas, but the issue exists upstream in ensuring that various renewable methane feedstock pathways produce methane that meets pipeline specifications.

impacts of these controls, developing natural gas fuel specifications for internal combustion engines (such as a fuel-specific anti-knock index, octane rating, and limits on contamination), and developing off-board equipment that can remove contaminants and/or provide consistent and appropriate levels of fuel quality. Developing this technology has the potential to enhance vehicle performance and it can also enable various adsorbent storage technologies that may be sensitive to impurities found in pipeline and natural gas that has been run through a compressor.

Vehicle Emission and Environmental Performance

As California and federal fuel economy and emission standards are implemented, natural gas vehicles may no longer be able to rely on some of their inherent "clean-burning" advantages over diesel and gasoline. Advanced aftertreatment and engine technologies for gasoline and diesel vehicles have been employed to meet more stringent performance standards, which has begun to level the playing field in emission performance (and has also reduced the cost differential of natural gas relative to conventional technologies). As discussed in the previous section on advanced engine design, there will be increasing pressure to reduce NO_x emissions, increase overall fuel economy (to eliminate any fuel efficiency penalty with natural gas), and avoid emissions not currently regulated. That may prove to be problematic with methane and ammonia. Furthermore, the integrating natural gas with zero emission strategies, such as vehicle electrification for part of the drive cycle, may yield additional benefits for ratepayers.

Develop Optimized Emission Controls for Natural Gas

While heavy-duty diesel vehicles have had to undergo significant modifications to their aftertreatment systems and emission controls (e.g., diesel particulate filters and selective catalyst reduction) to meet regulatory requirements, natural gas vehicles have been able to meet and surpass standards with less costly technologies already available for light-duty vehicles. This has narrowed the incremental costs of natural gas vehicles, but significant development of advanced emission control strategies will likely be necessary to meet future regulatory requirements. Furthermore, advanced engine and emission control technologies being developed for gasoline and diesel vehicles may not be suitable for natural gas. Finally, with increased emphasis on greenhouse gas reduction and methane's potency in the atmosphere, controls for unburned methane will likely be necessary for improved greenhouse gas benefits. It is recommended that a significant investment be made to identify and develop advanced emission controls and aftertreatment systems that will allow for natural gas vehicles to offer superior or equivalent performance while remaining cost competitive.

Address LNG Storage Tank Venting on Vehicles

LNG on-board storage may lead to venting due to pressure build-up as LNG warms up. This venting is not an issue for vehicles with sufficient operation (i.e., they use a full tank of fuel during their route or have a relatively high usage rate). However, defueling may be required for vehicles taken out of service. Technology or vehicle operation improvements may be needed in order to conserve fuel and minimize methane emissions. Without technologies such as these and other vehicle-use methane reductions, LNG may not provide a full measure of greenhouse gas benefits over diesel technologies. Another strategy to address this is to utilize cold (i.e. unsaturated) LNG, which can increase the hold time of the fuel in a storage tank.

Promote Further Development of Vehicle Hybridization and Electrification Technologies

While already the topic of a previous solicitation by the Energy Commission, hybridization of natural gas vehicles may prove to be beneficial for certain vehicle classes to meet current and future regulation of greenhouse gases, criteria pollutants, and overall fuel economy. Some hybridization strategies could help to provide a more balanced drive cycle as well as increase vehicle range, but minimizing the costs of expensive energy storage technologies (compressed or liquefied gas and batteries, ultra capacitors, hydraulic storage, or flywheels) presents a challenge.

Current commercial hybrid technologies for light-duty vehicles often use DI gasoline engines, which raises some of the earlier issues discussed around integration with engine technologies. Research to identify strategies and technologies that will enable high efficiency CNG hybrids will be necessary to compete with gasoline technologies. Furthermore, incremental costs of hybridization will need to be minimized so as to not exacerbate vehicle economics.

For medium heavy-duty vehicles, the appropriate hybridization technology is likely to be more tied to the size and application of the vehicle and its duty cycle. Current demonstrations are exploring battery electric and electrification via catenary cables for large vehicles, and other technologies such as hydraulic launch-assist are available. R&D is necessary for the optimizing and integrating these types of technologies with CNG and LNG powertrains and vehicle systems. Weight considerations for heavy-duty vehicles will also be an important consideration when considering vehicle hybridization.

Analysis and Information Sharing

In addition to technical topics, there are a number of analytical and collaborative undertakings that can inform and enhance the deployment of natural gas vehicles. The following recommendations highlight opportunities to better inform decision-making and leverage efforts to maximize the outcome of investments made by the California Energy Commission.

Determine the Best Use of Natural Gas in Transportation

The recent natural gas boom has created increasing demand for a number of competing end uses for this resource. Within transportation, natural gas is a direct or indirect feedstock for nearly all alternative fuels: biofuels, dimethyl ether (DME), electricity, and hydrogen, as well as CNG and LNG. While there are merits to each of these approaches (collectively and individually), there is not a clear understanding of how to prioritize the use of natural gas along these pathways and among various vehicle classes in order to achieve current and future policy objectives. A study assessing the relative merits of each of these pathways and the various applications would provide insight into future R&D investment, policy, and regulatory proceedings.

Update Emission Data on Natural Gas Vehicles

With recent technology advancements and greater availability of natural gas, there has been a concerted effort to understand the upstream emissions from extraction in order to update life-cycle assessments. While this activity is important to understanding the implications of policies and technology investments, current real-world (non-certification) comparisons between natural gas and diesel vehicle emissions pre-date recent vehicle emission standards.[22] This provides a significant gap in the overall understanding of NGV emission footprints relative to that of gasoline and diesel technologies (or other alternatives). These data can be helpful in guiding state implementation plans in regions where natural gas vehicles are being considered as an air quality strategy as well as determining life-cycle greenhouse gas emission footprints. Collecting real-world emission data for current natural gas vehicles relative to their gasoline and diesel counterparts across various vocations and real world drive cycle patterns can help guide future decisions and investments.

Continue and Enhance Coordinated NGV Research and Support the NGVTF

As described earlier, the Natural Gas Vehicle Technology Forum provides an opportunity to gather regular input from diverse stakeholders on issues pertaining to natural gas vehicle technologies. The NGVTF continues to be effective at identifying and addressing emerging issues, promoting coordination between California and federal agencies on R&D, and providing input into solicitations that address R&D gaps identified in the NGVRR.

It will be important to focus beyond the NGVTF to coordinate NGV research between the Energy Commission, ARB, SCAQMD, and the U.S. DOE (including ARPA-E). The Energy Commission, SCAQMD, and U.S. DOE have had notable success in developing advanced natural gas engines over the past few years and there may be continued opportunities to further and expand this work. ARPA-E focuses on early-stage technologies and limits programs to 3 years in duration. The Energy Commission has an opportunity to partner with ARPA-E to develop a more robust R&D continuum that can leverage federal investments and increase the likelihood that beneficial and promising technologies will come to market. Similar opportunities may also exist in high-horsepower applications as discussed in Chapter 2.

Identify Market Impact of Technology Developments

While the *2015 NGVRR* identifies and prioritizes technology gaps in natural gas vehicle technologies, it does not delve into a level of detail to analyze projected market impact for each of the recommended steps. It is recommended that a more detailed technical analysis of the priority R&D recommendations be conducted to validate the qualitative prioritization presented and provide maximum value to California ratepayers.

Continue to Enhance Publically Available Information on Natural Gas Vehicles

There are inconsistencies in CNG and LNG station availability data sources, which may be attributed to incomplete information about private fueling sites. Other issues with CNG

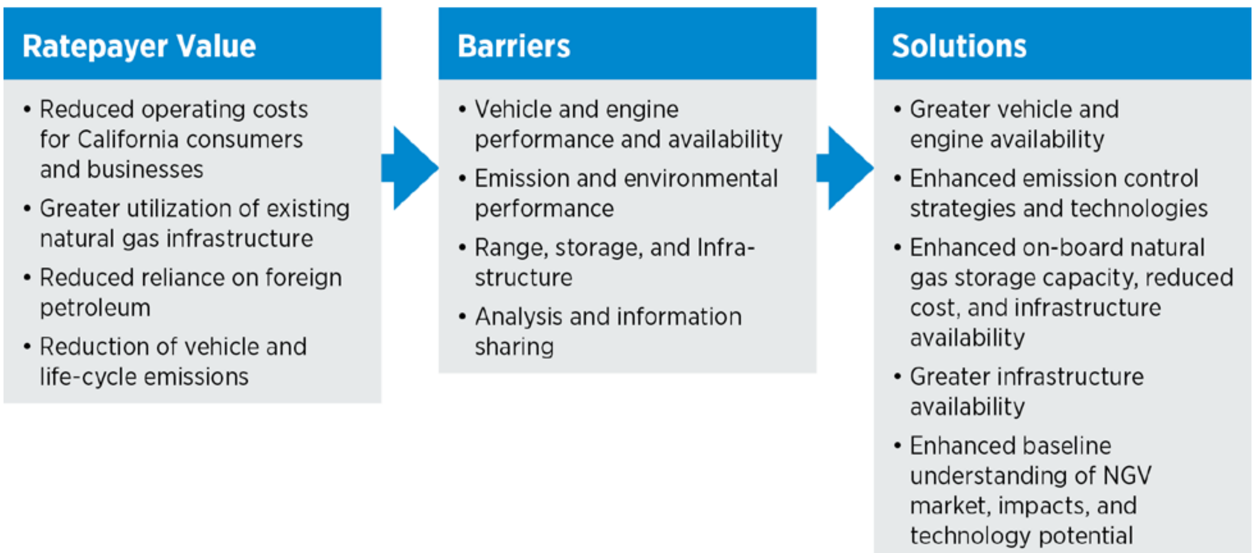
[22] A similar gap likely exists for comparisons between natural gas and gasoline engines, however emission standards have not changed as dramatically for gasoline as diesel in recent years.

cylinder and vehicle inspection data also exist. The difficulty in tracking these market adoption numbers can create difficulties in creating informed policy and maximizing R&D investments. A more thorough investigation and documentation of the NGV market in California, particularly vehicles that have been repurposed for natural gas, can help to better inform decision makers in beneficially growing the market.

CHAPTER 4:
Prioritizing R&D Recommendations

The previous section details a number of R&D opportunities that can help to advance deploying natural gas vehicles. These opportunities have varying impacts, costs, and development timelines requiring that they be prioritized and sequenced. The following prioritization and sequencing of the recommended strategies in Chapter 3 is based on the ability to create value for California ratepayers, which is otherwise being inhibited by barriers requiring technology, market, or knowledge solutions (Figure 16).

Figure 16: Natural Gas Vehicle Ratepayer Value Proposition, Barriers, and Technology Solutions



Figures 17 through 20 highlight identified R&D categories to provide a relative level of required investment, a ranking of priority or market impact based on ratepayer benefit, and the expected timeframe anticipated for a research project to have market impact. The timeframe does not indicate the relative urgency of a particula item, rather that is indicated by priority. It should also be noted that the prioritization is largely qualitative and that further investigation may be warranted on each of these topics to further quantify costs and benefits.

Figure 17: Natural Gas Vehicle Research Roadmap Recommendations and Timing – Range and Storage

Range, Storage, and Infrastructure — R&D Objective: *Enhanced on-board natural gas storage capacity, reduced cost, and infrastructure availability*

	Short (0–1 year)	Medium (1-5 years)	Long (5-10 years)
Increase Natural Gas Storage and Enhance Vehicle Integration			
Investment Needed: ***>$1 million*** Priority/Impact: ***High***	• Identify technologies, strategies, and barriers to improve CNG storage integration	• Underwrite cost of vehicle design and engineering for better CNG storage integration • Initial vehicle models become available	• Incorporate low pressure natural gas storage into vehicles • Enable large-scale integration of compressed gas cylinders into vehicle designs
Develop Low-Cost Carbon and Glass Fiber Storage			
Investment Needed: ***>$1 million*** Priority/Impact: ***High***	• Identify collaboration opportunities with the National Network for Manufacturing Innovation	• Fund dedicated research center(s) for the development of low-cost manufacturing of lightweight gas storage cylinders • Certify and integrate advanced fiber-based storage vessels into vehicles	• Develop bio-based materials for storage containers
Maximize Cylinder Utilization and Improve Fill Quality			
Investment Needed: ***$1 million*** Priority/Impact: ***High***	• Develop algorithms in fueling dispensers and on-board vehicles to adjust for temperature changes during fueling to ensure a greater fill	• Conduct research on sensor, pressure relief devices, and valve technologies that can enable greater CNG fill capacity	

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Range, Storage, and Infrastructure — R&D Objective: *Enhanced on-board natural gas storage capacity, reduced cost, and infrastructure availability*	Short (0–1 year)	Medium (1-5 years)	Long (5-10 years)
Develop Low-Pressure, High-Density Natural Gas Storage Vessels			
Investment Needed: ***>$1 million*** Priority/Impact: ***Medium***	• Complete ARPA-E projects to allow for further technology assessments	• Resolve fuel compatiability and durability issues with adsorbents.	• Enable commercially viable adsorbent storage as multiple performance targets are met • Begin to integrate commercially viable adsorbent storage products into vehicles
Develop Small or Modular Fueling Facilities			
Investment Needed: ***>$1 million*** Priority/Impact: ***Medium***		• Develop small-scale (1-5 vehicles) refueling facility technologies • Develop modular fueling infrastructure technology that can be scaled as demand increases	
Promote "Smart" Cylinders and Refueling Stations to Enhance Monitoring Capabilities			
Investment Needed: ***$1 million*** Priority/Impact: ***Medium***		• Develop algorithms, sensing, and communications technology in fueling dispensers, natural gas storage containers, and vehicles to communicate critical operating and safety information. • Some of these technologies may also enhance fill quality as noted previously	

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Range, Storage, and Infrastructure — R&D Objective: *Enhanced on-board natural gas storage capacity, reduced cost, and infrastructure availability*			
	Short (0–1 year)	Medium (1-5 years)	Long (5-10 years)
Develop Certification Procedures for Natural Gas Conformable Storage Tanks			
Investment Needed: ***<$1 million*** Priority/Impact: ***Low***		• Identify protocols needed for conformable tank certification • Develop technology and procedures for conformable tank certification	
Develop Cost-Effective Home Refueling Technologies			
Investment Needed: ***>$1 million*** Priority/Impact: ***Low***		• Develop home refueling technologies that can be cost competitive with home electric vehicle charging	
Increase Fueling Station Operational Efficiency			
Investment Needed: ***<$1 million*** Priority/Impact: ***Low***	• Fund and identify opportunities for greater fueling infrastructure efficiency via on-site storage and improved operation		

Figure 18: Natural Gas Vehicle Research Roadmap Recommendations and Timing – Vehicle and Engine Performance and Availability

Vehicle and Engine Performance and Availability — R&D Objective: *Greater Vehicle and Engine Availability*

	Short (0–1 year)	Medium (1-5 years)	Long (5-10 years)
Continue Research in Medium- and Heavy-Duty Engine Development			
Investment Needed: ***>$1 million*** Priority/Impact: ***High***	• Assess R&D and market needs for LNG engines in heavy-duty applications given recent delays • Coordinate with the California Department of Transportation, Air Resources Board, and other state agencies to identify opportunities for natural gas vehicles in the development of the statewide freight efficiency plan	• Continue the development of low NOx engines and technologies such as exhaust gas recirculation, ignition, and fuel injection • Continue integration of engines into medium- and heavy-duty vehicle applications • Pursue R&D in medium- and heavy-duty natural gas engines that can reduce fuel economy penalties relative to diesel	• Support the development of HCCI and RCCI engines to ensure that they are compatible with natural gas and provide comparable or superior performance to diesel
Invest in Light-Duty Engine Development and Direct Injection Engines			
Investment Needed: ***>$1 million*** Priority/Impact: ***Medium***	• Identify needs for additional engines and emission controls when using natural gas in high-efficiency engines	• Develop solutions for natural gas to be used in direct injection engines such as fuel injection and ignition technologies • Underwrite costs to develop additional high-efficiency natural gas engines such as Atkinson and Miller cycle technology	
Exploit Natural Gas Properties and Address Fuel Quality Discrepancies			
Investment Needed: ***>$1 million*** Priority/Impact: ***Medium***		• Identify optimal control strategies for the operation of natural gas in current engine designs and applications	• Develop clean sheet natural gas engines with specific design and control strategies

Figure 19: Natural Gas Vehicle Research Roadmap Recommendations and Timing – Emissions and Environmental Performance

Emission and Environmental Performance – R&D Objective: *Enhanced Emission Control Strategies and Technologies*

	Short (0–1 year)	Medium (1-5 years)	Long (5-10 years)
Promote Further Development of Vehicle Hybridization and Electrification Technologies			
Investment Needed: ***>$1 million*** Priority/Impact: ***Medium***	• Identify niche markets and portions of a given vehicle's drive cycle that would benefit from the hybridization of natural gas powertrains	• Support the incorporation of hybridization technologies into light-, medium-, and heavy-duty vehicle and engine development	
Develop Optimized Emission Controls for Natural Gas			
Investment Needed: ***$1 million*** Priority/Impact: ***Medium***	• Identify current emission profiles for natural gas vehicles	• Fund the development of aftertreatment and emission controls, including methane, that will provided for enhanced emission profiles and more efficient operations	
Address LNG Storage Tank Venting on Vehicles			
Investment Needed: ***$1 million*** Priority/Impact: ***Low***		• Fund research to reduce LNG venting during operations, which may include recirculation, greater insulation, or cooling	

Figure 20: Natural Gas Vehicle Research Roadmap Recommendations and Timing – Analysis and Information Sharing

Analysis and Information Sharing — R&D Objective: *Enhanced Baseline Understanding of NGV Market, Impacts, and Technology Potential*

	Short (0–1 year)	Medium (1-5 years)	Long (5-10 years)
Update Emission Data on Natural Gas Vehicles			
Investment Needed: ***$1 million*** Priority/Impact: ***High***		• Conduct vehicle chassis dynamometer testing to compare emission levels between various gasoline, diesel, and natural gas vehicles and engines utilizing drive cycles that represent NGV market opportunities	
Continue and Enhance Coordinated NGV Research and Support the NGVTF			
Investment Needed: ***<$1 million*** Priority/Impact: ***High***	• Continue to leverage the NGVTF as a means to gather stakeholder input and discuss and refine research priorities • Identify opportunities for collaboration with DOE and ARPA-E via funding opportunity announcements and regular program activities	• Explore the inclusion of additional technologies such as marine and rail into the NGVTF • Determine the need to revise and rescope the NGVRR	
Determine the Best Use of Natural Gas in Transportation			
Investment Needed: ***<$1 million*** Priority/Impact: ***Medium***		• Fund a study to look at competing uses for natural gas in the transportation sector in light of policy objectives and elsewhere to determine the best opportunities, applications, or niches for future R&D	

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Analysis and Information Sharing — R&D Objective: *Enhanced Baseline Understanding of NGV Market, Impacts, and Technology Potential*			
	Short (0–1 year)	Medium (1-5 years)	Long (5-10 years)
Continue to Enhance Publically Available Information on Natural Gas Vehicles			
Investment Needed: ***<$1 million*** Priority/Impact: ***Medium***	• Develop better data and mechanisms for collecting data on the resale and repurposing of vehicles to run on natural gas		
Identify Market Impact of Technology Developments			
Investment Needed: ***<$1 million*** Priority/Impact: ***Low***		• Fund a study to quantify the economic and deployment potential of the various technology investments outlined in the NGVRR	

CHAPTER 5: Conclusions

Natural gas vehicles continue to present an opportunity to realize California ratepayer benefits. The long-term economic, operational, and environmental benefits of natural gas vehicles can help California achieve its energy, environmental and economic policy goals. The *2015 Natural Gas Vehicle Research Roadmap* is intended to help maximize the impact of investments made by the California Energy Commission and has been updated to reflect changes in the market, regulatory environment, and natural gas vehicle technology.

Both the regulatory environment, driven by California and federal requirements, and energy market dynamics and increased domestic natural gas supplies, have changed substantively since 2009. These changes present an opportunity and a challenge for natural gas vehicles. Despite relatively favorable fuel economics over the past five years, vehicle incremental costs for natural gas vehicles remain high over their gasoline and diesel counterparts. While this gap is closing, performance increases and efficiency investments in traditionally fueled vehicles and engines present new challenges that must be addressed for natural gas vehicles to maintain beneficial progress. Specifically:

- The cost of on-board natural gas storage must decrease while capacity and vehicle integration must increase.
- Greater natural gas engine and vehicle availability is required. Natural gas vehicles must improve efficiency and maintain similar performance characteristics to their gasoline and diesel counterparts.
- Emission and environmental performance will be a continued area of focus as NO_x requirements become more stringent and greenhouse gas emissions, including methane, become more critical in meeting state and federal regulatory requirements.
- Additional information on natural gas vehicle markets and performance is necessary to continue to provide decision makers with current, accurate, and timely information.
- Continued coordination and collaboration between and among California and federal agencies with natural gas vehicle stakeholders will be necessary to adapt to changing markets, customer needs, and technology developments.

From the perspective of vehicle market adoption, medium and heavy-duty markets continue to present significant opportunities for petroleum displacement and high use provides more favorable economics than light-duty vehicle markets for natural gas. Additionally, high-horsepower applications such as marine and rail operation merit further exploration for research and development. Ultimately, the level of success and role of natural gas vehicles will largely depend on investments and innovations that further leverage this natural resource into a transportation option that can continue to provide substantive and growing benefits to Californians.

GLOSSARY

Term	Definition
ARB	• California Air Resources Board
ARPA-E	• Advanced Research Projects Agency - Energy
CAFE	• Corporate Average Fuel Economy
CEC	• California Energy Commission
CNG	• Compressed natural gas
DI	• Direct injection
DME	• Dimethyl ether
g/bhp-hr	• Grams per brake-horsepower hour
GDI	• Gasoline direct injection
GGE	• Gasoline gallon equivalent
GPS	• Global positioning system
HCCI	• Homogenous charge compression ignition
HDV	• Heavy-duty vehicle
HPDI	• High-pressure direct injection
L	• Liter
L/CNG	• Liquefied and compressed natural gas
LDV	• Light-duty vehicle
LNG	• Liquefied natural gas
MCF	• Thousand cubic feet
MOVE	• Methane Opportunities for Vehicular Energy
MPG	• Miles per gallon
NGVRR	• Natural Gas Vehicle Research Roadmap
NGVTF	• Natural Gas Vehicle Technology Forum
NOx	• Nitrogen oxide
NREL	• National Renewable Energy Laboratory
OEM	• Original equipment manufacturer
PIER	• Public Interest Energy Research
ppb	• Parts per billion
psi	• Pounds per square inch
R&D	• Research and development
RD&D	• Research, development and demonstration
RDD&D	• Research, development, demonstration, and deployment
RNG	• Renewable natural gas
SCAQMD	• South Coast Air Quality Management District
U.S. DOE	• United States Department of Energy
U.S. EPA	• United States Environmental Protection Agency

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Appendix A:
Organizations that Provided Input to the NGVRR

The Natural Gas Vehicle Research Roadmap development benefited tremendously from the input of a number of stakeholders in the natural gas vehicle industry. In addition to being presented and reviewed at the 2014 Natural Gas Vehicle Technology Forum, which consisted of more than 130 participants, the following organizations provided valuable input to the development of this roadmap.

Agility

American Honda Motor Co.

Atlanta Gas and Light

California Air Resources Board

California Energy Commission Alternative and Renewable Fuel and Vehicle Technology Program

Clean Vehicle Education Foundation

Cummins Westport

Fiat Chrysler Automobiles

Gas Technology Institute

General Motors

Gladstein, Neandross, and Associates

NGVAmerica

Pacific Gas and Electric Company

Port of Los Angeles

South Coast Air Quality Management District

Southern California Gas Company

U.S. Department of Energy – Advanced Research Projects Agency - Energy

U.S. Department of Energy – Vehicle Technologies Office

Waste Management

Westport