California Environmental Protection Agency
AIR RESOURCES BOARD

DRAFT
TECHNOLOGY ASSESSMENT: LOW EMISSION NATURAL GAS AND OTHER ALTERNATIVE FUEL HEAVY-DUTY ENGINES

September 2015

State of California
AIR RESOURCES BOARD

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Executive Summary

This report is part of a series of technology and fuels assessment reports that evaluate the state of technology to further reduce emissions from the transportation sector including trucks, locomotives, off-road equipment, ships, commercial harborcraft, aircraft, and transportation fuels. The purpose of the assessments is to support the Air Resources Board's (ARB) planning and regulatory efforts, including the development of California's Sustainable Freight Strategies, the State Implementation Plan, funding plans, the Governor's Zero Emission Vehicle Action Plan, and the Governor's petroleum use reduction goals. The reports focus not only on zero and near-zero emission technologies that will ultimately be necessary to meet long-term air quality and climate goals, but also on improvements to conventional technologies that could provide near-term emissions reductions and help facilitate the transition to zero and near-zero emission technologies.

Specifically, this technology assessment report provides a comprehensive assessment of low emission natural gas and other alternative fuel engines for heavy-duty vehicles. The report discusses the current state and projected development of heavy-duty low emission natural gas engines over the next 5 to 10 years and includes a description of the technology, its suitability in different applications, current and anticipated costs at widespread deployment (where available), and emissions levels.

Overall, the assessment finds that emissions from stoichiometric spark ignition (SI) natural gas engines can be significantly reduced utilizing a systems approach combining advanced three-way catalysts with engine management strategies. In fact, Cummins Westport's (CWI)[1] 8.9 liter (L) SI natural gas engine was recently certified by ARB to a 0.02 gram per brake horsepower-hour (g/bhp-hr) optional NO_X standard and will be commercially available in 2016. ARB staff expects other engine sizes meeting one of the optional NOx standards (0.02, 0.05, 0.1 g/bhp-hr) to become available within the next year or two.

Presented below is an overview which briefly describes the technologies to further reduce NO_X emissions from on-road heavy-duty natural gas engines and staff's proposed next steps. For simplicity, the discussion is presented in question-and-answer format using commonly asked questions about the technology assessment. The reader should refer to subsequent chapters in the main body of the report for more detailed information.

Q. What role can heavy-duty natural gas vehicles play in meeting California's air quality goals?

A California needs significant emissions reductions from mobile sources to meet its ambient air quality, petroleum reduction, and greenhouse gas (GHG) emission

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[1] Cummins Westport is a joint venture between Cummins Inc. and Westport Innovations. Although, the engine is marketed by Cummins Westport, the engine's certification Executive Order holder on record is Cummins, Inc.

reduction goals. While the state's long term goals include widespread deployment of advanced technologies with zero tailpipe emissions, advanced technologies with near-zero emissions currently under development will also play a significant role.

Various organizations including ARB and the South Coast Air Quality Management District (SCAQMD) in partnership with the California Energy Commission (CEC) and other organizations have funded and are continuing to fund research programs to develop lower NO_X natural gas engines of various engine sizes. A result of one of these research programs is the CWI engine that was recently certified by ARB to the 0.02 g/bhp-hr optional NO_X standard. This engine is expected to be commercially available in 2016 for applications in transit buses, refuse trucks, and tractors. Research is still progressing to develop lower NO_X engines on other engines sizes (8.8L, 12L, and 15L engines) and staff expects these engines to become available within the next several years. These advanced natural gas vehicles, once developed and commercialized, are expected to deliver near term opportunities to reduce NO_X emissions, and with the use of renewable natural gas, could also deliver deep GHG emission reductions.

However, because NO_X emissions from heavy-duty natural gas vehicles are expected to be higher than those of advanced technology alternative fuel trucks such as fuel cell and battery electric trucks, a shift to natural gas-powered heavy-duty trucks alone will not be sufficient to meet California's air quality challenges in the long term.

Q. What emission standards do heavy-duty on-road natural gas engines currently meet?

A. Like heavy-duty diesel engines, heavy-duty natural gas engines are required to meet the 2010 emission limits of 0.20 g/bhp-hr NO_X emissions and 0.01 g/bhp-hr particulate matter (PM) emissions on the heavy-duty transient federal test procedure (FTP) and on the ramped mode supplemental emission test. To further reduce NO_X emissions, ARB has also adopted optional NO_X standards that are 50 percent, 75 percent, and 90 percent lower than the current 0.20 g/bhp-hr NO_X standard. The optional NO_X standards were developed to encourage engine manufacturers to develop new technologies and also to provide them with a mechanism to optionally certify engines to lower NO_X levels. Truck purchasers who buy trucks equipped with certified lower NO_X engines will become eligible for incentive funding. For example, the updates to the Proposition 1B Goods Movement Emission Reduction Program[2] guidelines include funding eligibility for trucks with engines certified to the optional NO_X standard of 0.02 g/bhp-hr. Other funding opportunities for lower NO_X engines are

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[2] ARB, *Proposition 1B: Goods Movement Emission Reduction Program. Update to Program Guidelines*. <http://www.arb.ca.gov/bonds/gmbond/gmbond.htm>.

also being considered through the Low Carbon Transportation Investments and Air Quality Improvement Program funding plan.[3]

Depending on engine weight class, heavy-duty natural gas engines are also required by the Phase 1 GHG standards to reduce carbon dioxide (CO_2) emissions by 5 to 9 percent relative to the 2010 model year by 2017. In addition to CO_2 emissions, heavy-duty natural gas engines are required to limit both methane and nitrous oxide emissions to 0.1 g/bhp-hr.

Q. What market share do heavy-duty natural gas vehicles currently have, and who makes them?

A. Approximately 187,600 and 224,030 Class 8 trucks and buses were sold nationwide in 2013 and 2014, respectively. The penetration rates of natural gas powered Class 8 trucks and transit buses were 3 percent in 2013 and 4 percent in 2014, about 9,000 units in 2014. ACT Research, a leading heavy-duty market analysis company, forecasts that the penetration rate of natural gas powered Class 8 trucks and buses will be lower at about 3 percent in 2015, but will increase to 4 percent in 2016 and 5 percent in 2017. However, adoption rates in certain vocations are much higher than for the total Class 8 truck and bus market as a whole. In particular, in 2014, natural gas fueled refuse trucks accounted for 43 percent of new refuse truck sales, while approximately 30 percent of new transit buses sold nationwide were natural gas powered.[4] In 2013, the latest year for which data are available through the Federal Transit Administration's National Transit Database, 52 percent of transit buses purchased by agencies in California were powered with natural gas.[5] The higher adoption rate in California is significantly influenced by SCAQMD rules that require many fleets (transit, solid waste collection, etc.) operating in the South Coast Air Basin to choose alternative-fuel replacement vehicles when purchasing new vehicles[6].

Heavy-duty natural gas engine offerings are still limited today, though there are efforts right now to increase product offerings. Most on-road heavy-duty natural gas engines in use today are 8.9 L and 11.9 L stoichiometric natural gas engines produced by a single manufacturer, CWI, though there are other several smaller manufacturers as well.

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[3] ARB, *Proposed Fiscal Year 2015-16 Funding Plan for Low Carbon Transportation Investments and Air Quality Improvement Program*. <http://www.arb.ca.gov/msprog/aqip/fundplan/fundplan.htm>.

[4] Natural Gas Quarterly, ACT Research, LLC. Q2, 2015 <www.actresearch.net>.

[5] National Transit Database, Federal Transit Administration, <http://www.ntdprogram.gov/ntdprogram/datbase/2013_database/NTDdatabase.htm>.

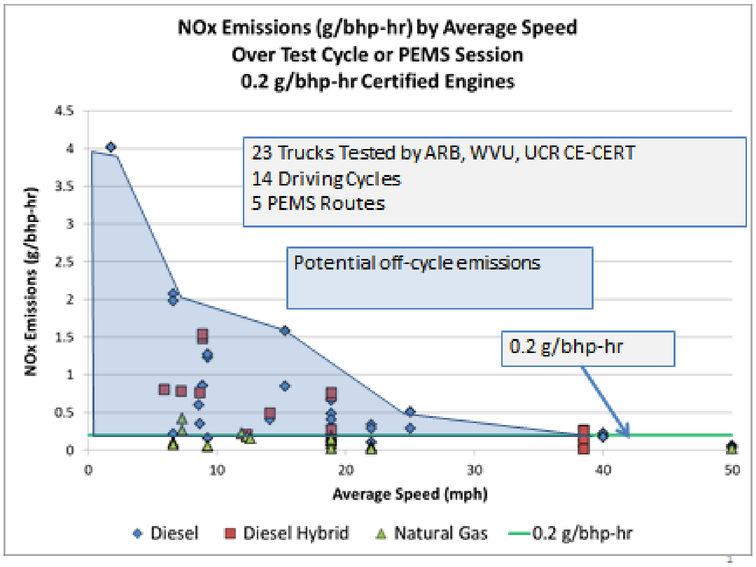
[6] SCAQMD, *Fleet Rules* <http://www.aqmd.gov/home/regulations/fleet-rules>.

Q. How do NO_X emission levels from the latest technology heavy-duty natural gas trucks compare to NO_X levels from heavy-duty diesel trucks?

A. Although natural gas truck engines are currently certified to the same emission standards as diesel truck engines, certification data indicate natural gas engines have somewhat lower emissions when measured over the heavy-duty engine certification cycle. Manufacturers normally certify their engines with a compliance margin at levels below the numerical standard to protect themselves against non-compliance due to minor increases in emissions in use. The certification levels also include deterioration factors to account for any increase in emissions over the useful life of an engine. An analysis of NO_X certification levels indicates that the compliance margins for the latest natural gas engines are larger than for their diesel counterparts. Specifically, NO_X certification levels for the latest natural gas engines are 25 percent to 75 percent below the 2010 NO_X certification standard, depending on engine size, while NO_X certification levels for the latest diesel engines are 10 percent to 60 percent below the standard.

Furthermore, as shown in Figure ES-1, recent in-use emissions test data from natural gas, diesel, and diesel hybrid engines certified to the 2010 NO_X emission standard show that natural gas engines do not appear to suffer the control challenge experienced by diesel engines in low temperature, low speed, and low load operations. However, at higher vehicle speeds and engine operating temperatures, as are seen during cruise and high-load operations, there is no significant difference between diesel and natural gas engines. Hence, based on the current certification levels and the lower in-use emissions at low temperature operations, and the success achieved for similar light-duty SI engines, staff believes natural gas engines are likely to be certified to today's optional low-NO_X emission standards sooner than will diesel engines.

Figure ES-1: In-Use Running Exhaust NOx Emissions Diesel, Diesel Hybrid, and Natural Gas Trucks



Q. How do well-to-wheel GHG emissions for natural gas powered trucks compare to those powered in other ways?

A. Natural gas is primarily composed of methane (around 90 percent), with small amounts of ethane, propane, and other gases. Because of this chemical composition, natural gas contains less carbon per unit energy than diesel, and as a result produces less carbon dioxide when it burns. Thus, for the same fuel efficiency, a stoichiometric SI natural gas engine would emit approximately 20 percent less carbon dioxide than a diesel engine. However, due to the higher pumping losses and lower compression ratios, stoichiometric SI natural gas engines are 10 to 15 percent less efficient than compression ignition (CI) diesel engines. This inefficiency partially offsets the climate benefit advantages from the lower carbon content of natural gas.

In addition to carbon dioxide emissions, methane emissions related to natural gas heavy-duty vehicle fueling and use are also important. Methane is a potent GHG with approximately 25 times the global warming potential of carbon dioxide. Thus, unless controlled, methane leakage from the production, distribution, and storage of natural gas as well as emissions and leakage from the vehicle could completely offset any potential climate benefit advantages of natural gas. Recognizing the impacts of upstream methane emissions, California is taking steps to reduce methane emissions. As part of the Short-Lived Climate Pollutants (SLCP) Reduction Strategy[7], ARB is developing a regulation to reduce methane emissions from oil and gas production, processing, and storage

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[7] ARB, Short-Lived Climate Pollution Reduction Strategy, Concept Paper, May 2015 <http://www.arb.ca.gov/cc/shortlived/shortlived.htm>.

operations. The California Public Utilities Commission is also developing rules, per SB 1371 (Leno, Chapter 525, Statutes of 2014), to reduce emissions from gas transmission and distribution pipeline leaks throughout the State. Together, these rules should create a comprehensive approach to limit methane leaks from oil and gas operations. However, about 90 percent of California's natural gas comes from out-of-state suppliers, so the State will continue to advocate for strong national methane standards to ensure potential climate benefits from using natural gas in the State.

ARB is developing a separate fuels technology assessment that will evaluate overall well-to-wheel GHG missions from various transportation fuels. Preliminary results from that assessment indicate that natural gas powered trucks using conventional natural gas are expected to have higher well-to-wheel GHG emissions than electric and fuel cell vehicles, which are intrinsically more efficient than traditionally powered vehicles and which have no tailpipe emissions. However, in the future, the increased use of renewable natural gas derived from sources such as landfills, dairies, and wastewater treatment plants could allow natural gas vehicles to provide significant well-to-wheel GHG emission benefit.

Q. What advanced natural gas engine technologies were assessed?

A. A natural gas engine can either be an SI engine or CI dual fuel high pressure direct injection (HPDI) engine. SI natural gas engines are similar to gasoline engines since they both have stoichiometric combustion operation and use a similar aftertreatment system (three-way catalyst) to control emissions. On the other hand, the HPDI engine is based on the conventional CI diesel engine, but uses a small amount of diesel fuel injected at the end of the compression stroke to initiate ignition. As with diesel engines, the HPDI natural gas engine requires selective catalytic reduction (SCR) to control NO_X and particulate filters to control particulate matter emissions. For this reason, the technology improvements for diesel engines discussed in the companion report "Technology Assessment: Lower NO_X Heavy-Duty Diesel Engines" would also be applicable to HPDI heavy-duty natural gas engines.

Currently, SI natural gas engines are the only original equipment manufacturer natural gas heavy-duty engines produced for on-road applications. Therefore, this technology assessment reviews only technologies that reduce NO_X emissions in SI heavy-duty natural gas and alternative fuel engines to levels significantly lower than those emitted by today's engines meeting the 0.20 g/bhp-hr NO_X standard. Technologies assessed include advanced stoichiometric engine and advanced catalyst control technologies, many of which potentially reduce NO_X emissions without negatively impacting GHG emissions. Advanced catalyst control technologies include advanced three-way catalyst (TWC) formulations, close-coupled light-off strategies, and ammonia slip catalysts. Advanced engine control technologies include port fuel injection, cooled exhaust gas recirculation (EGR), dedicated EGR, advanced air-to-fuel ratio control, and faster light-off engine strategies.

Q. What are the main challenges or roadblocks to wider use of heavy-duty natural gas trucks?

A. Limited fueling infrastructure, higher capital cost than comparable diesel trucks, and lack of availability of high-power/high-torque natural gas engines are the main challenges currently limiting a wider use of heavy-duty natural gas engines.

Natural gas engines are ideal candidates for centrally fueled vehicles. They are typically used in vehicles such as transit buses, local delivery trucks, short-haul tractors, school buses, refuse trucks and other general purpose trucks with operations mostly in urban areas where they could be refueled after a shift or a typical day of operation. Out of the nearly two million total heavy-duty trucks and buses (over 8,500 pounds gross vehicle weight rating) that operate in California, about 18,000 (or 1 percent)[8] are natural gas powered vehicles, including about 6,500 transit buses.[9] However, usage in line-haul vehicles has been limited due to limited refueling infrastructure. The lower energy density of natural gas also requires natural gas vehicles to have larger, heavier fuel tanks which reduce the payload capacity and thus lower productivity of natural gas vehicles.

Furthermore, broader usage generally has been slowed by the incremental cost; a natural gas truck is typically $30,000 to $80,000 more expensive than a comparable diesel truck. In addition, relative to diesel engines, commercially available natural gas engines do not deliver the same high power and high torque performance in line-haul and construction operations. Current natural gas powered buses and trucks employ 8.9 L and 11.9 L natural gas engines, while line-haul trucks typically use 13 L to 15 L engines.

Q. What is the current state of natural gas fueling infrastructure in the United States?

A. Nationwide, as shown in Table ES-1, there are currently 1,039 compressed natural gas (CNG) stations accessible to heavy-duty vehicles, of which 591 are publicly-accessible and 110 liquefied natural gas (LNG) stations accessible to heavy-duty vehicles, of which 73 are publicly accessible. Figure ES-2 shows the location of these stations.[10] California accounts for a significant fraction of these stations, with 207 CNG stations (102 of them publicly accessible) and 44 LNG stations (15 publicly accessible). Most of the CNG stations are clustered, so that

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[8] Based on the U.S. Department of Energy (DOE), Energy Information Administration database, there were approximately 18,000 natural gas fueled trucks and buses operating in California, in 2011. <http://www.eia.gov/renewable/afv/index.cfm>.

[9] The number of transit buses is from ARB's Transit Fleet Reporting database as of 3/11/15.

[10] The U.S. DOE, Alternative Fuels Data Center, provides a list of alternative fueling stations and their location in the U.S. The database is updated monthly, and the numbers shown here are as of April 21, 2015. <http://www.afdc.energy.gov/data_download/>.

there is a reasonable density of fueling stations in certain regions, with large gaps in coverage in between. There are fewer LNG stations, though a few regional corridors capable of supporting dedicated long-haul routes do exist. For comparison, there are approximately 36,000 diesel fueling stations in the nation, with 5,000 of them publicly accessible. Looking to the future, there are 213 (144 CNG and 69 LNG) heavy-duty accessible natural gas stations planned around the country, including 17 (15 CNG and 2 LNG) in California.

The CEC is also funding natural gas fueling infrastructure projects in California through its competitive grant program, the Alternative and Renewable Fuel and Vehicle Technology Program (ARFVTP). For fiscal year 2015-2016, CEC staff is recommending to award funds of about $5.5 million for natural gas fueling infrastructure projects.[11]

The SCAQMD also provides funds for development of natural gas fueling infrastructure. To date, SCAQMD has provided over $25 million in funding of cost-shared projects for installing CNG and LNG fueling stations and production facilities within the SCAQMD's 4-county jurisdiction. The projects are funded primarily through the Clean Fuels Fund, or through funds distributed by the Mobile Source Air Pollution Reduction Committee.[12]

Table ES-1: Natural Gas Refueling Stations

Heavy-Duty Accessible (Class 6 to 8)		Open stations		Planned Stations	
		Nationwide	California	Nationwide	California
CNG	Total	1039	207	144	15
	Publicly Accessible	591	102	101	6
	Private	448	105	43	9
LNG	Total	110	44	69	2
	Publicly Accessible	73	15	68	1
	Private	37	29	1	1

Medium-Duty Accessible (Class 3 to 5)		Open stations		Planned Stations	
		Nationwide	California	Nationwide	California
CNG	Total	394	64	20	4
	Publicly Accessible	207	42	17	3
	Private	187	22	3	1

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[11] California Energy Commission. *Investments in California's Alternative and Renewable Fuel and Vehicle Technology Markets.* <http://www.energy.ca.gov/contracts/transportation.html#PON-14-608>.
[12] SCAQMD, *Infrastructure and Fuel Production*. <http://www.aqmd.gov/home/library/technology-research/projects#&MainContent_C002_Col00=2>.

Figure ES-2: Map of Heavy-Duty Vehicle, Publicly Accessible, Fueling Stations

Red dots represent LNG stations, and blue dots represent CNG stations

Q. How do current heavy-duty natural gas truck purchase and operational costs compare to those for diesel trucks?

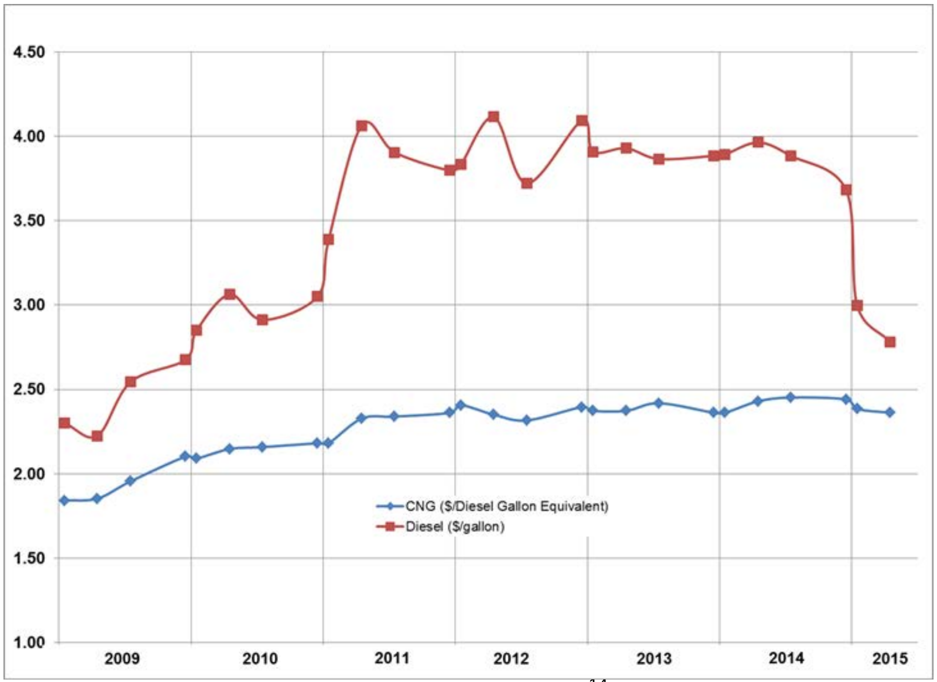
A. Current heavy-duty natural gas vehicle costs are approximately $30,000 to $80,000 higher than costs of comparable heavy-duty diesel vehicles, depending on vehicle application, weight, power, etc. (see Table ES-2). The primary reason for the wide range in the incremental cost is due to the tank package which is dependent on the various range requirements. This includes higher incremental costs mainly due to the low volume tank production, costly specialized fuel tanks, and safety requirements such as a methane detection system, pressure relief devices, and shut-off valves Maintenance costs for natural gas vehicles are also higher than for diesel vehicles due to more frequent oil changes and inspections, and high replacement costs for spark plugs, injectors, and other spare parts.

However, natural gas vehicles tend to have overall operational costs that are lower than for diesel vehicles primarily due to the lower natural gas fuel cost, as shown in Figure ES-3. Thus, the lower fuel costs allow the vehicle owner to recover the added vehicle and maintenance costs associated with heavy-duty natural gas vehicles within several years, depending on the purchase price of the vehicle, the mileage driven per year, and the price differential between diesel and natural gas. Note that the recent decline in diesel fuel prices is closing the gap between diesel and natural gas and this may have a negative impact on the payback period for natural gas vehicles. However, diesel fuel prices fluctuate more than natural gas prices and it is not known how diesel fuel prices will behave in the future. The payback period for LNG fueled vehicle would be higher since LNG fuel is more expensive than CNG fuel due to the cost to convert and transport the natural gas in a liquid form.

Table ES-2: Incremental Cost of Heavy-Duty Natural Gas Vehicles by Application[13]

Application	Incremental Cost
School Bus	$30,000 - $40,000
Transit Bus	$40,000 - $50,000
HD Vocational Truck	$50,000 - $60,000
Regional Haul Tractor	$65,000 - $80,000
Short Haul Tractor	$45,000 - $60,000
Refuse Truck	$30,000 - $40,000

Figure ES-3: Average U.S. Retail Fuel Prices per Diesel Gallon Equivalent (January 2009 – April 2015)



Sources: CNG price data from Clean Cities, U.S. DOE[14]; Diesel Prices; EIA, U.S. DOE[15]

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[13] U.S. and Canadian Natural Gas Vehicle Market Analysis: Heavy-Duty Vehicle Ownership and Production Final Report. TIAX, 2012.

[14] Clean Cities Alternative Fuel Price Reports, U.S. Department of Energy (DOE), April 2015 <http://www.afdc.energy.gov/fuels/prices.html>.

[15] Energy Information Administration (EIA), U.S. DOE <http://www.eia.gov/petroleum/data.cfm>.

Q. What package of technologies seems most promising for advanced natural gas engines?

A. This technology assessment describes individual control strategies that when packaged together could potentially provide significant NO_X reductions. The technology package of choice will be determined by its potential to provide maximum NO_X reductions while facilitating continued reductions in GHG emissions. This will require manufacturers to utilize a systems approach to integrate a multitude of technology solutions including advanced catalyst technologies and engine management strategies that improve efficiency and reduce exhaust emissions. ARB is currently contracting with Southwest Research Institute (SwRI) to demonstrate packages of technology solutions that would provide maximum NO_X reductions without increasing GHG emissions.[16]

Q. What research and development work is underway to develop a lower NO_X engine with no GHG disbenefit?

A. Both ARB and the SCAQMD in partnership with other organizations are currently independently funding research projects to demonstrate lower NO_X natural gas engines with a target NO_X emission rate of 0.02 g/bhp-hr.

In 2013, ARB contracted with SwRI to demonstrate maximum NO_X reductions possible from an 11.9 L Cummins heavy-duty natural gas engine through a combination of advanced TWCs, advanced air-to-fuel ratio control, cold engine start-up strategies, and exhaust thermal management strategies. SwRI will screen a combination of these technologies to determine technology packages that provide maximum NO_X and GHG benefits. It is required that, in addition to meeting a NO_X target of 0.02 g/bhp-hr, the technology solution must also continue to meet all applicable standards for criteria pollutants and not incur a GHG penalty. The project is expected to be completed by mid-2016.

In 2014, SCAQMD, in partnership with CEC and the Southern California Gas Company (SoCalGas) initiated projects for developing 8.9 L and 15 L natural gas engines with CWI and Cummins Inc., respectively. In addition to meeting the NO_X target of 0.02 g/bhp-hr, the project will also demonstrate system durability through on-road testing by integrating the engines onto vehicle chassis. CWI recently announced that it achieved a 0.02 g/bhp-hr NO_X emission level on the 8.9 L ISL G SI natural gas engine and will begin field testing the engine this year in California on transit buses[17]. According to CWI, in addition to lowering NO_X emissions by 90 percent from current engines, the engine also meets the 2017 heavy-duty GHG standards. The new engine has similar emission control systems (throttle body injection, TWC, EGR, etc.) as the 0.20 g/bhp-hr NO_X

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[16] *Evaluating Technologies and Methods to Lower Nitrogen Oxide Emissions from Heavy-Duty Vehicles.* <http://www.arb.ca.gov/research/veh-emissions/low-nox/low-nox.htm>.

[17] Cummins Westport, Inc. News Release: *Near Zero NOx Emissions ISL G Natural Gas Engine.* May 6, 2015. <http://www.westport.com/news/2015/near-zero-nox-emissions-isl-g-natural-gas-engine>.

engine. However, CWI did not disclose the technologies used to reduce NO_X emissions nor the cost of the low NO_X technology. These projects are expected to be completed by the end of 2017.

Additionally, in 2015, SCAQMD, in partnership with Power Systems International, Ricardo, and SoCalGas executed a contract with the Gas Technology Institute to develop an 8.8 L natural gas engine suitable for on-road applications in the Class 4 to 7 vehicle weight ratings. The target emission rate for this project is 0.02 g/bhp-hr NO_X.

Q. How much will these technology packages cost?

A. It is expected that further NO_X emission reductions from heavy-duty natural gas engines will be achieved through a combination of engine controls, combustion optimization, and the continued development and enhancements of new and existing TWCs. According to Cummins Inc. a 0.02 g/bhp-hr NO_X natural gas engine is feasible with improved current technology with minimal or no GHG penalty.[18] Staff expects that the incremental cost for such a technology (i.e., a 0.02 g/bhp-hr NO_X natural gas engine that meets current GHG standards) will be relatively modest compared to today's natural gas engines. However, new natural gas engine technologies such as improved combustion efficiency, advanced air handling, and advanced catalysts would be needed to simultaneously attain a 0.02 g/bhp-hr NO_X level and a significant reduction in GHG emissions to meet future GHG standards. It is expected that there will be costs associated with development of these technologies. Conversations with representatives from the Manufacturers of Emission Controls Association indicate that the estimated average incremental cost for a heavy-duty stoichiometric natural gas engine that achieves these objectives to be in the range of $250 to $300 per engine compared to today's natural gas engines. As previously indicated, these engine costs do not include total incremental costs of natural gas vehicles relative to diesel vehicles.

Q. What other alternative fuel engines are being developed?

A. In addition to natural gas engines, some manufacturers are also developing engines that run on other alternative fuels. For example, Volvo is developing an engine that runs on dimethyl ether (DME). DME has a cetane number similar to that of diesel which allows it to be used in a compression ignition engine, which is more efficient than SI engines. Also, unlike natural gas, DME can be stored as a liquid at pressures of 75 pounds per square inch (psi) or less in a steel tank, and does not require special handling associated with high pressures or cryogenic temperatures.

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[18] Eckerle, Wayne. *Engine Technologies for GHG and Low NOx.* Presentation at ARB Symposium on Phase 2 GHG. April 22, 2015 <http://www.arb.ca.gov/msprog/onroad/caphase2ghg/presentations/caphase2ghg_symposium_presentations.htm>.

Cummins, Inc., in partnership with the CEC, is developing an SI engine that runs on E85 (a blend of 85 percent ethanol and 15 percent gasoline by volume). The use of E85 allows for greater use of renewable energy, with the potential of up to 80 percent reduction in CO_2 emissions compared to a baseline gasoline vehicle, depending on the drive cycle and source of the ethanol in E85.

Q. What is the expected timeframe of lower-NOx natural gas engines coming to market?

A. As indicated above, CWI has certified an 8.9 L natural gas engine as a 2016 model year engine that meets a 0.02 g/bhp-hr NO_X and will begin field testing the engine this year in California on transit buses. Although CWI did not announce the commercial availability date of this engine, it has indicated that it plans to make the new engine available on new transit and refuse trucks and as an engine replacement for existing ISL G equipped vehicles.

Also, as discussed above, ARB and SCAQMD are independently funding research projects to demonstrate the feasibility of a 0.02 g/bhp-hr NO_X emission level on larger capacity, 11.9 L and 15 L heavy-duty natural gas engines. These projects are expected to be finalized between mid-2016 to end of 2017. Thus, staff expects some lower-NO_X natural gas engines to become commercially available by 2016, with additional engine sizes becoming available as time goes on.

Q. What next steps does staff recommend?

A.

- ARB should continue to support incentive funding for low-NOx heavy-duty engines to encourage engine manufacturers to develop and certify engines that meet the optional NO_X standards. Natural gas engines certified to 0.02 g/bhp-hr, capable of Class 7-8 long-haul use (12 to 15 L), and powered with renewable natural gas should be a particular focus.

- Given California's criteria pollutant, GHG, and petroleum reduction needs, staff recommends that ARB implement statewide strategies that employ lower NO_X combustion engines coupled with the use of renewable fuels in order to attain near-term air quality and climate goals.

- In order to achieve air quality goals, ARB intends to begin the development of lower mandatory NO_X standards applicable to all California-certified heavy-duty vehicles. Since out-of-state registered heavy-duty vehicles that operate in California contribute significantly to the emissions inventory, it is also critical that ARB petition the United States Environmental Protection Agency to require lower NO_X standards applicable to all heavy-duty vehicles nationally.

I. Introduction and Purpose of Assessment

This report is part of a series of technology and fuels assessment reports that evaluate the state of technology to further reduce emissions from the transportation sector including trucks, locomotives, off-road equipment, ships, commercial harborcraft, aircraft, and transportation fuels. The purpose of this technology assessment is to provide a comprehensive assessment of the current state and projected development over the next 5 to 10 years for low emission natural gas and other alternative fuel engines for heavy-duty vehicles. Such technologies support the Air Resources Board's (ARB) long-term objective of transforming the on- and off-road mobile source fleet into one utilizing zero and near-zero emission technologies to meet air quality and climate change goals. For each technology, the assessment includes a description of the technology, its suitability in different applications, current and anticipated costs at widespread deployment (where available), and emissions levels.

This technology assessment will support ARB planning and regulatory efforts, including:

- California's Sustainable Freight Strategy development
- State Implementation Plan development
- Funding plans
- Governor's Zero Emission Vehicle Action Plan
- Governor's petroleum reduction goals

Historically, natural gas has been used in conventional lean-burn engines as a clean air alternative to conventional diesel fuel to reduce regulated gaseous and particulate matter emissions. However, this lean-burn engine technology faced a challenge to meet the 2010 model heavy-duty engine oxides of nitrogen (NO_X) emission standard of 0.20 gram per brake horsepower-hour (g/bhp-hr), and was replaced by stoichiometric engine technology with a three-way catalyst (TWC) exhaust treatment system and cooled exhaust gas recirculation (EGR) (Kamel, 2006). Studies reported that this stoichiometric engine with TWC and cooled EGR reduces NO_X emissions by more than 95 percent compared to the lean-burn natural gas engine (Crawford, 2010; Yoon, 2013). However, this significant NO_X reduction requires additional fuel consumption since brake-specific fuel consumption from stoichiometric combustion tends to be 10 percent to 15 percent higher compared to lean combustion mainly due to higher pumping losses and higher thermal losses (Walkowicz, 2001). Although the current stoichiometric engine has a disadvantage of higher fuel consumption, the technology has the potential for further development to improve fuel efficiency and reduce greenhouse gas (GHG) emissions, and to further reduce NO_X emissions with advanced engine and TWC technologies that are currently under development.

The majority of light-duty vehicles in the United States are powered with stoichiometric spark-ignition (SI) combustion engines with engine combustion and aftertreatment architecture similar to those of heavy-duty natural gas engines, which provides opportunities for technology transfer. Light-duty vehicles are currently meeting the stringent Low Emission Vehicle (LEVII and LEVIII) emission standards. Compliance with these emission standards has driven and is still driving advances in emission control for stoichiometric SI combustion engines. Key technologies used to meet existing standards are advanced high cell density TWCs (close-coupled and underfloor catalysts), precise air-to-fuel (A/F) ratio control, cold start strategies such as retarded ignition timing and high idle speed, EGR to control in-cylinder NO_X, and other engine controls that improve efficiency and reduce emissions. To maximize emissions and efficiency performance, manufacturers have been utilizing a systems approach combining advanced aftertreatment technologies with engine management strategies. Because of the similarity in engine combustion and aftertreatment architectures, the advanced emission control technologies and strategies developed to control emissions from light-duty gasoline vehicles can be further developed and transferred to reduce emissions from heavy-duty natural gas engines. The fact that engineers have successfully designed systems to reduce NO_X while improving fuel economy for light-duty engines suggests the same success is achievable for the very similar heavy-duty natural gas engines.

Like heavy-duty diesel engines, heavy-duty natural gas engines are required to meet the 2010 emission limits of 0.20 g/bhp-hr NO_X emissions and 0.01 g/bhp-hr particulate matter (PM) emissions on the heavy-duty transient federal test procedure (FTP) and on the ramped mode supplemental emission test. Natural gas engines meeting these standards are currently available in engine displacements from 4 liters (L) to 12 L. To further reduce NO_X emissions, ARB has also adopted optional NO_X standards that are 50 percent, 75 percent, and 90 percent lower than the current 0.20 g/bhp-hr NO_X standard. Cummins Westport's (CWI) 8.9 L SI natural gas engine was recently certified by ARB to the 0.02 g/bhp-hr optional NO_X standard and will be commercially available in 2016.

This report consists of eight chapters and one appendix. Chapter II covers ongoing technology demonstration programs. Chapter III discusses advanced catalyst systems, natural gas engine technologies, and exhaust gas thermal management strategies that have the potential to further reduce NO_X emissions and improve efficiency. Chapter IV covers system suitability and infrastructure needs. Chapter V discusses associated costs and Chapter VI discusses associated emission levels. Chapter VII discusses engine developments on other alternative fuels. Chapter VIII discusses staff recommended next steps and conclusions. Finally, the appendix discusses natural gas fueling infrastructure.

II. Demonstration Status

ARB and other agencies such as the South Coast Air Quality Management District (SCAQMD) in Southern California and the California Energy Commission (CEC) are currently independently funding projects to develop or demonstrate lower-NO_X natural gas engines for various engine sizes. Some of these projects are briefly discussed below.

In 2013, ARB initiated a project with Southwest Research Institute (SwRI) for demonstrating maximum NO_X reductions possible from a 12 L CWI heavy-duty natural gas engine for use in Classes 6 to 8 vehicle applications such as refuse trucks, transit buses, general purpose trucks, and short haul and long haul trucks (ARB, 2014a). SwRI will demonstrate feasibility of lower NO_X emissions through a combination of engine tuning practices, thermal management strategies, and aftertreatment strategies. The engine technology must also continue to meet all applicable standards for hydrocarbons, non-methane hydrocarbons, carbon monoxide, and PM; not incur a GHG penalty; and be consistent with a technological path to meeting the upcoming U.S. Environmental Protection Agency (U.S. EPA) GHG standards for heavy-duty vehicles. The target NO_X emission rate from this project is 0.02 g/bhp-hr, a 90 percent reduction from the current standard. SwRI will conduct on-engine dynamometer screening of advanced TWCs, electrically heated catalysts, close-coupled light-off catalysts, and exhaust thermal management strategies, and determine the technology package(s) that provides maximum NO_X and GHG emission benefits. The project is expected to be completed by mid-2016.

In 2014, SCAQMD, in partnership with CEC and the Southern California Gas Company (SoCalGas), initiated projects for developing 8.9 L and 15 L natural gas engines with CWI and Cummins Inc., respectively (SCAQMD, 2013). The 8.9 L engine is designed for use in the Class 6 to 8 vehicle weight rating in on-road applications such as shuttle buses, transit buses, refuse trucks, Class 7 tractors, and the lighter end of Class 8 tractors, while the 15 L engine is designed for use in the Class 7 to 8 vehicle weight rating in on-road applications where there is a demand for high power/high torque natural gas engines. The target emission level for the new engines is 0.02 g/bhp-hr NOx or lower, a 90 percent reduction from the current standard, through stoichiometric combustion with high rates of cooled EGR and a TWC. In addition to achieving the NO_X emission reduction target, the projects' objectives also include system durability demonstration through on-road tests after the engines are integrated onto vehicle chasses. The road tests will be performed for a year, and their performance will be fully evaluated. CWI recently announced that it demonstrated a 0.02 g/bhp-hr NO_X emission level on the 8.9 L ISL G SI natural gas engine and will begin field testing the engine this year in California on transit buses (CWI, 2015). According to CWI, in addition to lowering NO_X emissions by 90 percent from current engines, the engine also meets the 2017 heavy-duty GHG standards. However, CWI did not disclose the technologies used to reduce NO_X emissions nor the cost of the low NO_X technology. The completion of these projects is expected by the end of 2017.

Additionally, in 2015, SCAQMD in partnership with Power Systems International, Ricardo, and SoCalGas executed a contract with the Gas Technology Institute to develop an 8.8 L natural gas engine suitable for on-road applications in the Class 4 to 7 vehicle weight ratings (SCAQMD, 2014). The test engine is a Power Systems International 8.8 L engine currently certified as a naturally aspirated natural gas engine with a TWC for on-road and off-road applications at 0.20 g/bhp-hr NO_X. The goal is to demonstrate a 0.02 g/bhp-hr NO_X standard with a turbocharged on-road engine by adding cooled EGR and enhancing the aftertreatment system. A kickoff meeting was held in September 2015.

III. Technology Description

As discussed in Chapter I, natural gas engine manufacturers are currently meeting the 2010 heavy-duty engine standards using stoichiometric combustion engine and TWC technologies. These technologies can be further developed and improved to achieve further reductions in NO_X emissions. This technical assessment, therefore, reviews advanced stoichiometric engine and TWC technologies that can potentially reduce NO_X emissions to levels lower than the 2010 emission standard of 0.20 g/bhp-hr, improve fuel economy, and reduce GHG emissions. It should be noted that while each individual technology alone would not necessarily achieve significant emission reductions and fuel economy improvements, an integrated engine and TWC designed using a systems approach could achieve significant NO_X emission reductions of approximately 90 percent below current standards.

Section A discusses advanced aftertreatment control technologies, which can reduce NO_X without increasing fuel consumption. Section B discuses advanced engine control technologies; those technologies without a potential fuel economy penalty are discussed first, followed by those that may have such a penalty.

A. Advanced aftertreatment control technologies

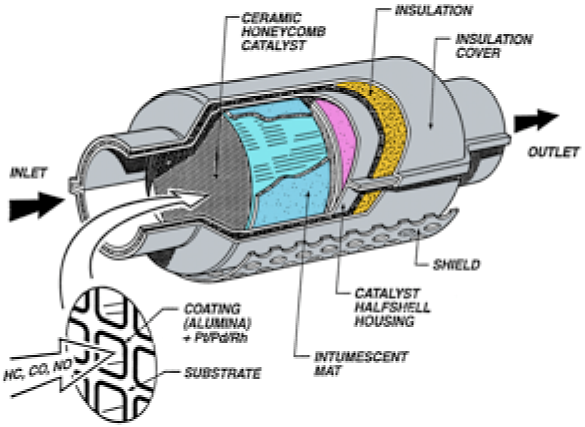
1. Advanced TWC

To meet the high catalytic conversion efficiency and extended durability requirements of LEV II standards for light-duty gasoline vehicles, TWCs have been significantly improved in the aspects of catalyst formulation, substrate design, high oxygen storage material, substrate coating process, and exhaust system thermal management (Figure III-1), all without negatively impacting fuel economy. These improvements for gasoline vehicles, discussed further in the subsections below, could be applied to TWC for heavy-duty natural gas engines because of their similar engine combustion and aftertreatment architectures. Advanced TWC technology for heavy-duty natural gas engines is in the demonstration phase.

a. Catalyst formulation

A TWC uses precious metals such as platinum, palladium, and rhodium for hydrocarbon and carbon monoxide oxidation and for NO_X reduction. Catalytic conversion efficiency depends highly on the precious metal formulation of the catalyst. Although a typical TWC uses a 5 to 1 oxidation to reduction metals formulation to maintain high performance (MECA, 2013), the formulation varies depending on engine manufacturer and vehicle size. A typical underfloor TWC uses the platinum, palladium, and rhodium formulation while a close-coupled TWC uses a palladium-only or a palladium and rhodium formulation for higher hydrocarbon removal efficiency and faster catalyst light-off.

Figure III-1: Light-duty vehicle TWC with Ceramic Substrates



(MECA, 2013)

b. Substrate design

Higher cell density and thinner wall design can provide increased geometric surface area per unit TWC volume for effective catalyst distribution, small flow channels for fast heat transfer, and reduced substrate thermal mass for faster heat up during cold starts. Marsh et al. reported approximately 50 percent and 25 percent reductions of hydrocarbon and NO_X tailpipe emissions, respectively, over the heavy-duty transient federal test procedure (FTP) cycle when cell density was doubled and wall thickness was reduced to 2/3 of the original thickness (Marsh et al., 2001).

c. High oxygen storage material

High oxygen storage capacity is critical to maintaining high catalytic conversion. Ceria-Zirconia added to the washcoat of TWCs provides high oxygen storage capacity and allows a broader window of catalytic operation, improves catalyst light-off, and enables significant reduction of NO_X emissions (Williamson, 2001).

d. Substrate coating process

Compared to a single layer coating of a conventional TWC, multi-layer and zone catalyst coatings separate the functionality of precious metals from the functionality of oxygen storage, optimize TWC performance, while minimizing unwanted precious metal degradation at high temperatures. Lindner et al. show that double layering palladium onto TWC doubles NO_X conversion efficiency (Lindner et al., 1996).

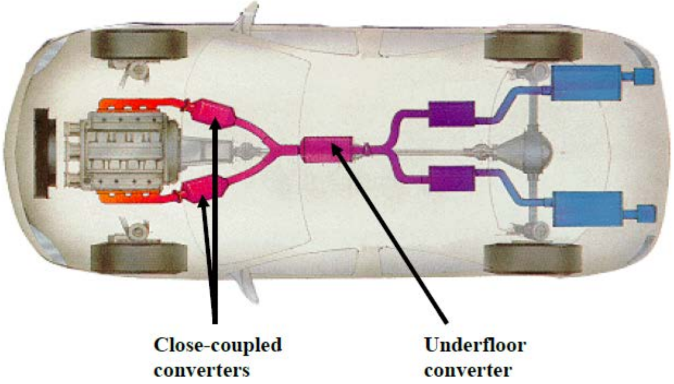
e. Exhaust system thermal management

Insulation materials with low thermal transfer characteristics could be applied between the thin inner wall and the thick outer wall of the exhaust system to minimize heat loss between the engine and the TWC (Webb, 1999). Insulating the exhaust manifold, exhaust pipeline, and TWC increases the efficiency of transferring heat generated from the engine to the catalyst with minimum heat loss, so that the transferred heat accelerates catalyst light-off at cold start and maintains high catalytic conversion efficiency.

2. Close-coupled light-off

A TWC located near the engine exhaust valves is referred to as a close-coupled converter (Figure III-2). A close-coupled converter minimizes exhaust system heat losses and accelerates catalyst light-off, without negatively impacting fuel economy. This close-coupled converter could be a critical component for natural gas engines for reducing methane emissions due to the longer oxidation duration required for reduction of methane compared to gasoline (Zhang, 1998).

Figure III-2: Close-Coupled TWC Applied to a Gasoline Passenger Car



(MECA, 2013)

3. Ammonia slip catalyst

Ammonia emissions can be formed in a situation where there is an excess supply of reducing species (e.g., hydrogen and carbon monoxide) and an insufficient supply of oxygen to the TWC (Wark, 1998). An ammonia slip catalyst could be applied downstream of the TWC to control ammonia emissions in the exhaust to the European standard of 10 parts per million (ppm) or lower. Ammonia slip catalysts are commercially available for current technology diesel engines with selective catalytic reduction (SCR), but are still in the demonstration phase for heavy-duty natural gas engines. Adding an ammonia slip catalyst to the aftertreatment system does not negatively impact fuel consumption.

B. Advanced engine control technologies

In this section, advanced engine control technologies that provide improvements or are neutral with respect to fuel consumption, such as port fuel injection, dedicated EGR, advanced A/F ratio control, are discussed first below, followed by technologies with a potential fuel economy penalty.

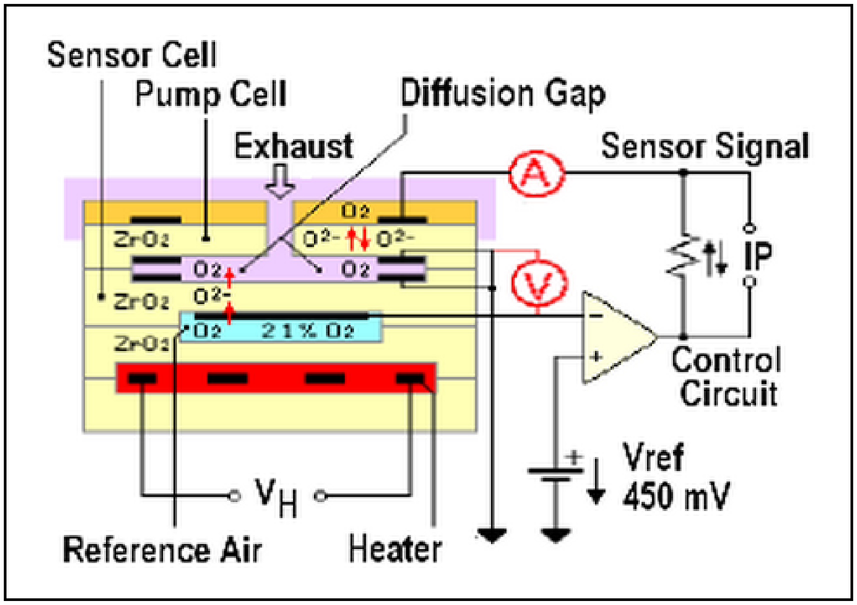
1. Port fuel injection

With port fuel injection, fuel is injected into the intake manifold where it mixes with intake air. The air/fuel mixture is then drawn into the combustion chamber during the induction stroke. Because port fuel injection provides quicker throttle response and enables accurate spark timing, the cylinder receives the exact amount of fuel needed for combustion and achieves high combustion efficiency. Port fuel injection enables higher accuracy of A/F ratio control for stoichiometric engine combustion, provides better fuel efficiency, and enables a significant performance improvement of the TWC compared to the current throttle body injection with TWC. Port fuel injection technology is the dominant fuel injection technology in light-duty vehicles certified to the LEV II emission standards. However, it is currently in the demonstration phase for heavy-duty natural gas engines.

2. Advanced A/F ratio control

Because a TWC operates within a very narrow window of A/F ratio, maintaining accurate A/F ratio in cylinders is critical to achieving maximum catalytic conversion efficiency. Maintaining accurate A/F ratio control allows for better fuel economy, lower NO_X emissions, and better engine performance. A zirconia-based wideband oxygen sensor widely used in gasoline passenger cars could be used for heavy-duty natural gas engines for accurate A/F ratio control (Figure III-3). This wideband sensor incorporates an electrochemical gas pump that directly measures the oxygen content of the exhaust gas and allows the engine control unit to adjust the fuel delivery and ignition timing of the engine quickly. This sensor technology is currently being researched for heavy-duty natural gas engine applications.

Figure III-3: Wideband Oxygen Sensor Control Diagram



(AA1Car, 2014)

3. EGR

EGR is a NO_X reduction strategy in which some portion of the exhaust gas is routed back into the cylinder. In addition to reducing NO_X, EGR is also used in SI gasoline engines to provide knock resistance, to reduce throttling losses, and to improve efficiency. There are various methods of recirculating exhaust gases to the cylinder, including external EGR, which routes a portion of the exhaust gas through an EGR valve to the intake manifold; internal EGR, which uses variable valve timing to retain a portion of the exhaust gases inside the cylinder until the next combustion cycle; or dedicated EGR, which routes the entire exhaust from one or more cylinders to the intake manifold of the other cylinders. In addition, external EGR can be cooled with an EGR cooler and can be low or high pressure depending on where in the exhaust system the EGR is drawn relative to the turbocharger. Two methods of EGR applicable to stoichiometric natural gas engines to reduce NO_X emissions and improve efficiency are discussed below.

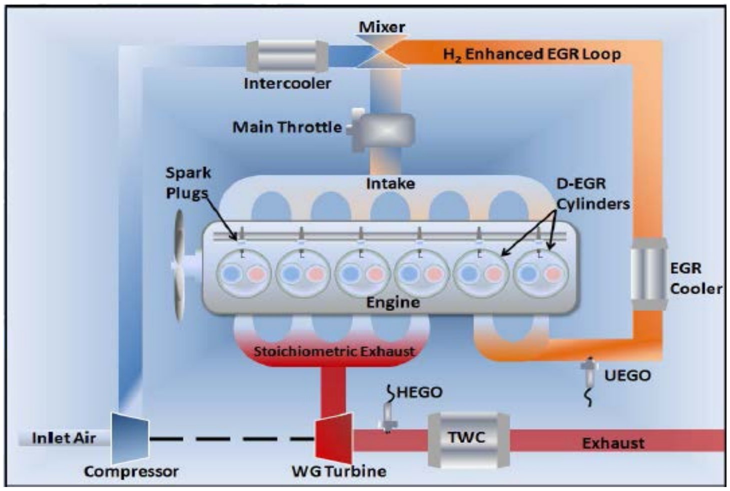
a. Dedicated EGR

Dedicated EGR runs one or more cylinders in fuel rich mode, and then routes the entire exhaust from these cylinders to the intake manifold (Figure III-4). This adds significant amounts of carbon monoxide and hydrogen to the intake mixture. The presence of carbon monoxide and hydrogen boosts the methane combustion rate and improves engine thermal efficiency. Dedicated EGR increases the EGR rate by up to 40 percent and reduces engine-out NO_X emissions significantly while improving efficiency. This technology was initially developed and demonstrated by SwRI in an engine test cell. SwRI later demonstrated the technology on a 2012 model light-duty gasoline vehicle that was converted to use dedicated EGR and achieved a 10 percent fuel efficiency improvement while simultaneously lowering exhaust emissions (Chadwell et al., 2014). It is possible that this technology could be adapted for heavy-duty natural gas engines.

b. Cooled EGR

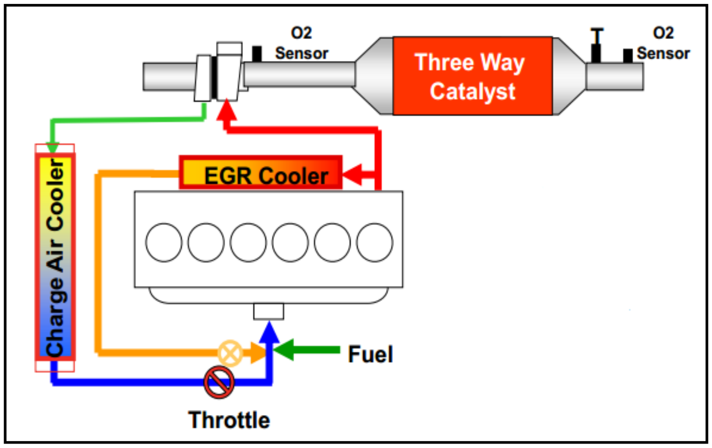
The cooled EGR system recirculates part of the exhaust flow through a cooler to the engine intake manifold, thereby decreasing the temperature of the intake mixture (air and recirculated exhaust) (Figure III-5). Cooled EGR is an essential part of reducing engine-out NO_x emissions since it reduces the NO_x removal burden from the TWC, enabling a significant reduction of NO_x and non-methane hydrocarbon emissions (Pirouzpanah, 2003). Because cooled EGR reduces the available oxygen in the cylinder, it could increase PM emissions, reduce peak power available from the engine, and potentially increasing fuel consumption. This technology is widely available commercially in current stoichiometric natural gas engines.

Figure III-4: Dedicated EGR Technology and Exhaust Flow



(Walls, 2013)

Figure III-5: Cooled EGR Articulated with Stoichiometric Engine and TWC



(Exel, 2011)

4. Faster light-off strategies

A significant portion of NO_X emissions is generated at cold engine start because the TWC is not hot enough to reduce NO_X in the exhaust. Several fast light-off strategies under development include turbocharger bypass, high engine idle speed, retarded ignition timing, and rich and lean cylinders. Because these fast light-off strategies provide extra heat to the TWC for faster catalytic activation, there are potential adverse effects of increased fuel consumption and GHG emissions. However, since these strategies would be implemented only during brief operating periods lasting several seconds and only in limited instances, such as cold engine start, the additional fuel consumption would be limited and could even be completely offset from improved combustion efficiency achieved with advanced A/F ratio controls. Thus, depending on the driving conditions and engine load, engine management systems should continuously control and adjust engine operating parameters for maximum emission reduction and better fuel efficiency performance.

a. Turbocharger bypass

As engine-out hot exhaust bypasses the turbocharger, engine inlet boost pressure decreases, and a fuel rich condition will be created in the cylinders. A fuel rich condition reduces engine-out NO_X emission and provides additional heat to the catalyst. This technology is in the demonstration phase.

b. High engine idle speed

Current natural gas engines are factory-set to idle at a curb-idle speed of around 600 revolutions per minute (rpm) after starting. Increasing engine idle speed requires more fuel to be injected into the cylinders. More fuel increases exhaust temperature and provides additional heat to the catalyst. This high engine idle speed strategy is currently in use in the latest technology diesel engines with SCR, and is in the demonstration phase for heavy-duty natural gas engines.

c. Retarded ignition timing

Retarded ignition timing delays spark ignition until after top dead center, initiates combustion later in the expansion stroke, and produces a high hydrocarbon concentration in the exhaust. The high hydrocarbon concentration enables post-flame oxidization in the catalyst, increases catalyst temperature, and accelerates catalytic activity. Furthermore, retarded ignition timing decreases the amount of useful work extracted from the combustion process and also reduces peak flame temperature in the cylinders which results in reduced engine-out NO_X emissions. The retarded ignition timing strategy is in the demonstration phase for heavy-duty natural gas engines.

d. Rich and lean cylinders

Alternating fuel rich and fuel lean conditions in a cylinder produces high hydrogen and oxygen concentrations during engine cold starts. High hydrogen and oxygen concentrations in the cylinder boost the methane combustion rate and increase the exhaust temperature for faster catalyst activation. This technology is in the research and development phase.

IV. System/Network Suitability and Operational/Infrastructure Needs

Natural gas engines are ideal candidates for centrally fueled vehicles. They are typically used in vehicles which operate mostly in urban areas, such as transit buses, local delivery trucks, short-haul tractors, school buses, and refuse trucks, which are generally refueled after a shift or a typical day of operation. Use of natural gas engines in line-haul type operations is, however, much less common, due to limited refueling infrastructure (U.S. DOE, 2013; TIAX, 2012; Walls, 2013). More information about the state of natural gas vehicle infrastructure is provided in the Appendix.

In addition to the limited infrastructure, commercially available natural gas engines do not currently meet the high power and high torque requirements for line-haul and construction operations. Current natural gas powered buses and trucks employ 8.9 L and 11.9 L natural gas engines (Exel, 2011; Zigler, 2014; Davis, 2013), while line-haul trucks typically use 13 L to 15 L engines. There is a gap in the size range of natural gas engines available to meet the full range of vocational demands, especially high power and high torque vocations. ARB and SCAQMD are currently independently sponsoring several research projects for developing lower NO_X 8.8 L, 8.9 L, 11.9 L, and 15 L natural gas engines. Once these engines are developed successfully, natural gas engines with significantly lower NO_X emissions may become available for high power and torque demands.

V. Cost

A. Current Technology

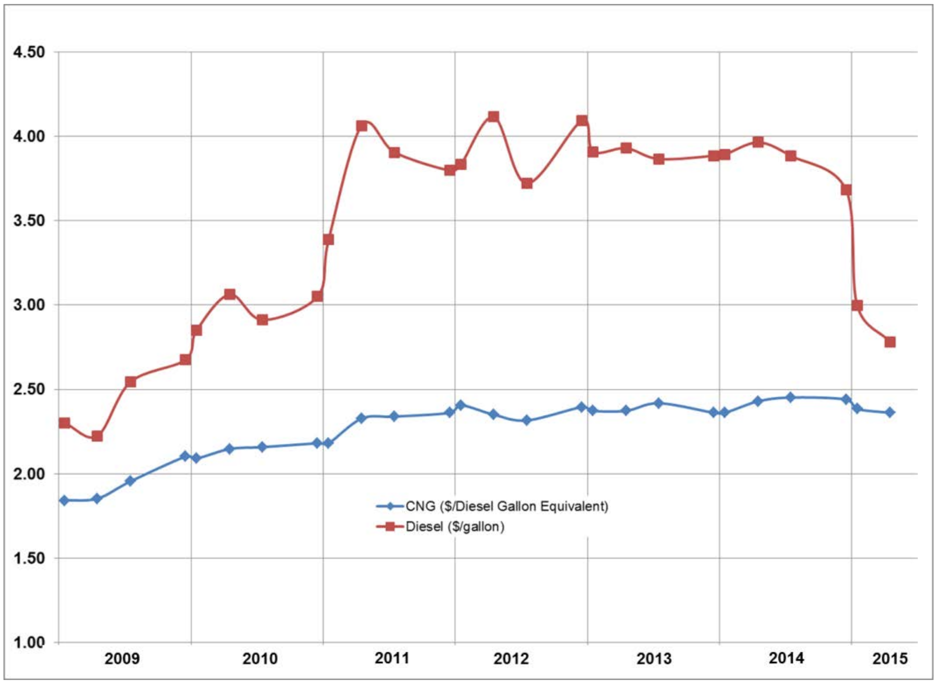
Current costs of heavy-duty natural gas vehicles are higher than those of heavy-duty diesel vehicles. The incremental cost of a heavy-duty natural gas vehicle over that of a comparable heavy-duty diesel vehicle ranges between $30,000 to $80,000, depending on vehicle weight, power, etc. (see Table V-1), with the cost of the fuel tank system accounting for the majority of the added cost (TIAX, 2012, JB Hunt, 2014). In addition, maintenance costs of natural gas vehicles are about one to two cents per mile greater than for diesel vehicles due to more frequent oil changes and inspections, high replacement costs for spark plugs, and injectors (Malloy, 2013). Natural gas vehicles, however, have a lower overall operating cost primarily due to the lower fuel cost of natural gas compared to diesel (see Figure V-1). Thus, the lower fuel costs would allow the vehicle owner to recover the added vehicle and maintenance costs associated with heavy-duty natural gas vehicles within several years, depending on the purchase price of the vehicle, the mileage driven per year, and the price differential between diesel fuel and natural gas fuel (see Figure V-1). Note that the recent decline in diesel fuel prices is closing the gap between diesel and natural gas fuel prices, and this may have a negative impact on the payback period for natural gas vehicles. However, diesel fuel prices fluctuate more than natural gas prices and it is not known how diesel fuel prices will behave in the future. The payback period for liquefied natural gas (LNG) fueled vehicle would be higher since LNG fuel is normally more expensive than compressed natural gas (CNG) fuel due to the cost to convert and transport the natural gas in a liquid form. Figure V-2, which shows the payback period for a short haul CNG truck as a function of diesel fuel cost and mileage driven in a year, illustrates how payback can range from less than 3 years to more than 15 years, depending on the differential in diesel versus CNG cost and the annual mileage.

Table V-1: Current Incremental Cost of Heavy-Duty Natural Gas Vehicles by Application

Application	Incremental Cost
School Bus	$30,000 - $40,000
Transit Bus	$40,000 - $50,000
HD Vocational Truck	$50,000 - $60,000
Regional Haul Tractor	$65,000 - $80,000
Short Haul Tractor	$45,000 - $60,000
Refuse Truck	$30,000 - $40,000

(TIAX, 2012)

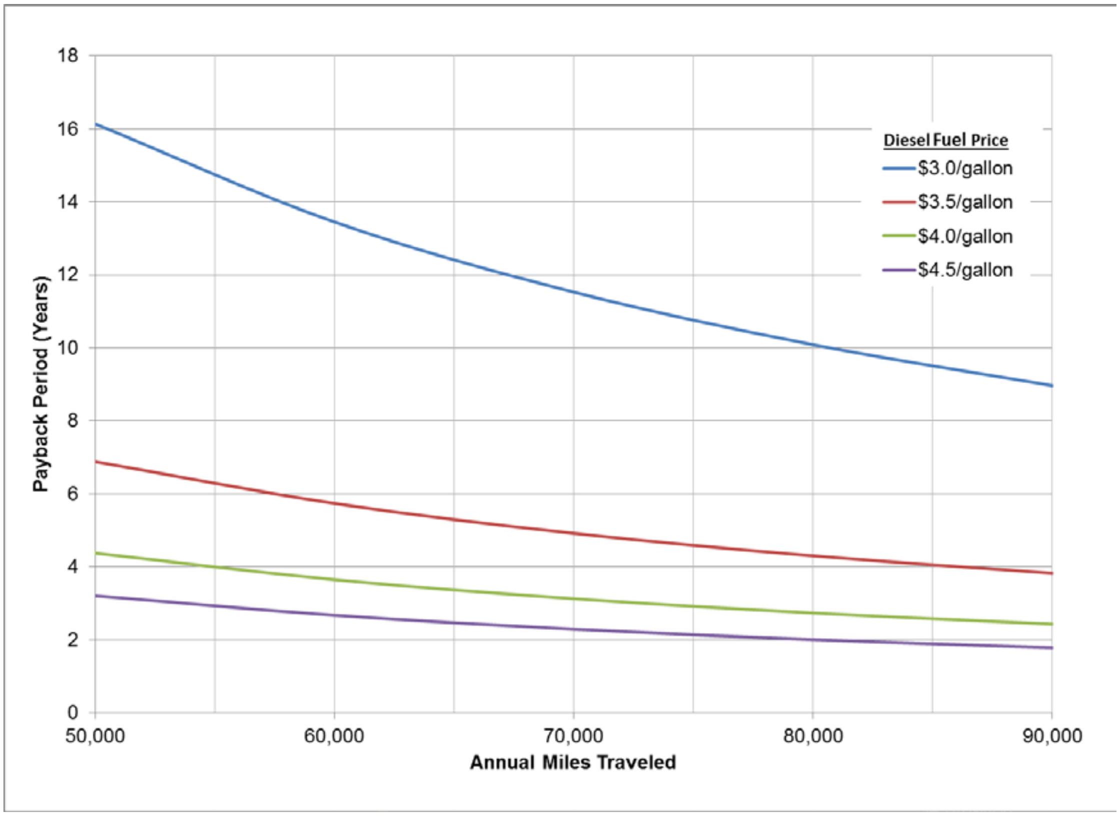
Figure V-1: Average U.S. Retail Fuel Prices per Diesel Gallon Equivalent (January 2009 – April 2015)



Sources: CNG price data from Clean Cities (U.S. DOE, 2015a); Diesel Prices from EIA (U.S. DOE, 2015b)

As the demand for natural gas vehicles grows, the production volume of natural gas engines is expected to increase, leading to possible decreases in the capital cost of the truck from economy of scale. A growing demand could also introduce additional manufacturers of natural gas engines into the market, potentially further reducing prices and shortening payback periods. The cost of natural gas is expected to stay low due to domestic production from hydraulic fracturing. Natural gas fuel retail prices are also expected to be relatively protected from fluctuations in energy prices in relation to diesel fuel since as much as 75 percent of the retail price is for compression or liquefaction of the fuel, rather than for the fuel itself.

Figure V-2: Sensitivity of Payback Period to Diesel Fuel Cost for Short Haul CNG Truck



Assumptions used to develop Figure V-2	CNG Truck (short haul)	Diesel Truck
Truck incremental cost	$50,000	---
Fuel cost ($/diesel gallon equivalent)	$2.36(a)	$3.00/$3.50/$4.00/$4.50
Fuel economy (miles per gallon)	5.45(b)	6.0
Diesel Emission Fluid (DEF) cost ($/gallon)	---	$2.79(c)
DEF consumption (miles per gallon)	---	300(d)
Incremental maintenance cost ($0.01 to $0.02/mile – (Malloy, 2013)	$0.015	---

(a) http://www.afdc.energy.gov/fuels/prices.html
(b) Assumes CNG truck is about 90% as efficient as a comparable diesel truck.
(c) Web site quoted DEF price at the pump: nationwide average of three major truck stops (9/24/2015)
(d) 1 gallon of DEF lasts 300 miles on a truck averaging 6 MPG. (https://www.cumminsfiltration.com/pdfs/product_lit/americas_brochures/MB10033.pdf)

B. Future Technology

It is expected that further NO_X and GHG emission reductions from heavy-duty natural gas engines will be achieved through a combination of engine controls, combustion optimization, and the continued development and enhancement of new and existing TWCs. According to Cummins Inc., a natural gas engine that meets a 0.02 g/bhp-hr

NO_X emission level with minimal GHG penalty is achievable with modest improvements to current technology. Staff expects that the additional incremental cost for such a technology will be relatively minimal, especially when seen against the current incremental cost of natural gas vehicles when compared to diesel vehicles. However, new natural gas engine technologies such as improved combustion efficiency, advanced air handling, and advanced catalysts would be needed in order to simultaneously attain both the 0.02 g/bhp-hr NO_X level and significant reductions in GHG emissions to meet future GHG standards. It is expected that there will be costs associated with development of these technologies. Based on conversations with representatives from the Manufacturers of Emission Control Association, the estimated average incremental cost for an advanced heavy-duty stoichiometric natural gas engine that meets significant NO_X and GHG emission reductions would be approximately $250 to $300 per engine (Kubsh, 2015). As previously indicated, these incremental engine costs do not include the incremental cost of natural gas vehicles relative to diesel vehicles.

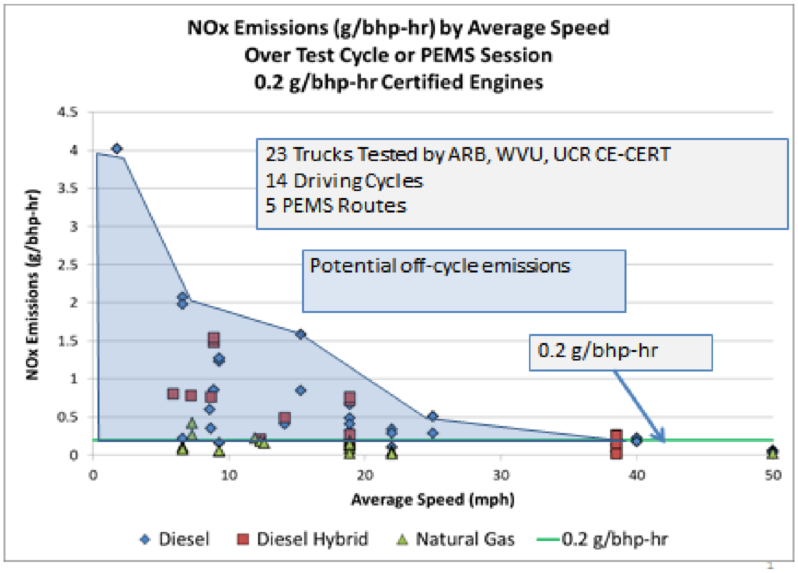
VI. Emission levels

A. NO_X Emissions

Although natural gas truck engines are currently certified to the same emission standards as diesel truck engines, certification data indicate natural gas engines have somewhat lower emissions when measured over the heavy-duty engine certification cycle. Manufacturers normally certify their engines with a compliance margin at levels below the numerical standard to protect themselves against non-compliance due to minor increases in emissions in use. Furthermore, the certification levels also include deterioration factors to account for any increase in emissions over the useful life of an engine. An analysis of NO_X certification levels indicates that the compliance margins for the latest natural gas engines are larger than for their diesel counterparts. Specifically, NO_X certification levels for the latest natural gas engines are 25 percent to 75 percent below the 2010 certification standard, depending on engine size, while NO_X certification levels for the latest diesel engines are 10 percent to 60 percent below the standard (ARB, 2014b).

Furthermore, as shown in Figure VI-1, recent in-use emissions test data from natural gas, diesel, and diesel hybrid engines certified to the 2010 NO_X emission standard show that natural gas engines do not appear to suffer the control challenge experienced by diesel engines in low temperature, low speed, and low load operations (ARB, 2014c). The excess NO_X emissions from the diesel and diesel hybrid trucks are believed to be due to reduced effectiveness of the SCR system at low temperatures; at high speed engine operating temperature, as are seen during cruise and high-load operations, there is no significant difference between diesel and natural gas engines. Hence, based on the current certification levels and the lower in-use emissions at low temperature operations, and the success achieved for similar light-duty SI engines, staff believes natural gas engines are likely to be certified to today’s optional low-NO_X emission standards sooner than will diesel engines.

Figure VI-1: In-Use Running Exhaust NOx Emissions Diesel, Diesel Hybrid, and Natural Gas Trucks



Based on the technologies described in Chapter III, certification and emissions data for current heavy-duty natural gas engines, and the success achieved for similar light-duty SI engines, staff expects that natural gas engines with significantly reduced NO_X, improved fuel economy, and reduced GHG will become available in the next 1-4 year timeframe (Youssef, 2014). As mentioned above, CWI has already certified an 8.9 L natural gas engine that meets the 0.02 g/bhp-hr optional NO_X standard and the 2017 U.S. EPA Phase1 GHG standards. Staff expects this engine to be commercially available by 2016. The current efforts of SCAQMD and ARB are also expected to successfully demonstrate the feasibility of lower NO_X emissions on other engine sizes, and staff expects these engines to be commercially available thereafter.

B. GHG Emissions

Natural gas is primarily composed of methane (around 90 percent), with small amounts of ethane, propane, and other gases. Because of this chemical composition, natural gas contains less carbon per unit energy than diesel, and as a result produces less carbon dioxide when it burns. Thus, for the same fuel efficiency, a stoichiometric SI natural gas engine would emit approximately 20 percent less carbon dioxide than a diesel engine. However, due to the higher pumping losses and lower compression ratios, stoichiometric SI natural gas engines are 10 to 15 percent less efficient than compression ignition (CI) diesel engines. This inefficiency partially offsets the climate benefit advantages from the lower carbon content of natural gas.

In addition to carbon dioxide emissions, methane emissions related to natural gas heavy-duty vehicle fueling and use are also important. Methane is a potent GHG with approximately 25 times the global warming potential of carbon dioxide. Thus, unless controlled, methane leakage from the production, distribution, and storage of natural gas as well as emissions and leakage from the vehicle could completely offset any potential climate benefit advantages of natural gas. Recognizing the impacts of upstream methane emissions, California is taking steps to reduce methane emissions from agricultural, waste treatment, and oil and gas sectors. In particular, as part of the Short-Lived Climate Pollutants (SLCP) Reduction Strategy, ARB is developing a regulation to reduce methane emissions from oil and gas production, processing, and storage operations. The California Public Utilities Commission is also developing rules, per SB 1371 (Leno, Chapter 525, Statutes of 2014), to reduce emissions from gas transmission and distribution pipeline leaks throughout the State. Together, these rules should create a comprehensive approach to limit methane leaks from oil and gas operations. However, about 90 percent of California's natural gas comes from out-of-state suppliers, so the State will continue to advocate for strong national methane standards to ensure potential climate benefits from using natural gas in the State (ARB, 2015).

Preliminary ARB staff estimates indicate natural gas heavy-duty vehicles provide little to no GHG improvement over conventional diesel vehicles. Natural gas powered trucks are expected to have higher well-to-wheel GHG emissions than electric and fuel cell vehicles, which are intrinsically more efficient than traditionally powered vehicles and which have no tailpipe emissions. However, in the future, the increased use of renewable natural gas derived from sources such as landfills, dairies, and wastewater treatment plants could allow natural gas vehicles to provide significant well-to-wheel GHG emission benefits.

VII. Other Alternative Fuels

Besides natural gas, other cleaner-burning fuels are also being considered for use in medium- and heavy-duty vehicles. Currently, an engine powered using dimethyl ether (DME) and an engine powered on an 85 percent ethanol, 15 percent gasoline (E85) blend are in the demonstration phase of their development process.

A. DME

DME is a synthetic fuel manufactured from synthesis gas generated from natural gas or from biomass, helping reduce dependency on imported fuel. DME has an energy content of 53 percent that of diesel per unit volume, but unlike natural gas, DME is stored as a liquid under 75 pounds per square inch (psi) of pressure in a steel tank, so it does not require special handling associated with a high-pressure or cryogenic fuel. In addition, DME has a cetane number similar to that of diesel, allowing it to be used in a compression ignition engine, which is more efficient than an SI engine. DME engines produce very low levels of PM emissions, eliminating the need for a particulate filter. However, meeting the 2010 model year NO_X standard may require the use of both EGR and NO_X aftertreatment (Greszler, 2013).

For several years now, Volvo has been conducting customer field tests of the new D13-DME engine both in the United States and in Europe. The D13-DME engine can deliver up to 435 horsepower (hp) with a peak torque of 1650 pound-foot (lb-ft). However, it is not known yet when Volvo will introduce DME-fueled vehicles to the market.

B. Gasoline-Ethanol Blend (E85)

Cummins Inc. has partnered with the CEC to develop their new Ethos 2.8 L downsized, SI, 4-cylinder engine that would run on E85 fuel. E85 is a blend of 85 percent ethanol and 15 percent gasoline by volume. The engine is designed to operate at cylinder pressures similar to those of a diesel engine, and can deliver up to 250 hp with a peak torque of 450 lb-ft, for use in Class 4 - 6 medium-duty vehicles. The use of E85 fuel allows for greater incorporation of renewable energy, with the potential of up to 80 percent reduction in carbon dioxide (CO_2) emissions compared to the baseline gasoline vehicle, depending on the drive cycle, if lignocellulosic-derived ethanol is used. The project is currently in the demonstration phase, with the engine installed in a Class 5 step-van vehicle that also incorporates stop-start technology and higher efficiency engine oils. The prototype vehicle has accumulated over 1000 miles and 1500 hours of operation over the past 2.5 years (Cummins, 2014).

VIII. Next steps

- ARB will continue to support incentive funding for low-NO_X heavy-duty engines to encourage engine manufacturers to develop and certify engines that meet the optional NO_X standards. Natural gas engines certified to 0.02 g/bhp-hr, suitable for use in Class 7-8 over-the-road applications (12 to 15 L), and powered with renewable natural gas should be a particular focus.

- Given California's criteria pollutant, GHG, and petroleum reduction needs, staff recommends that ARB implement statewide strategies that employ lower NO_X combustion engines coupled with the use of renewable fuels in order to attain near-term air quality and climate goals.

- In order to achieve air quality goals, ARB intends to begin development of lower mandatory NO_X standards applicable to all California certified heavy-duty vehicles. Since out-of-state registered heavy-duty vehicles that operate in California contribute significantly to the emissions inventory, it is also critical that ARB petition U.S. EPA to require lower NO_X standards applicable to all heavy-duty vehicles nationally.

IX. References

(AA1Car, 2014) AA1Car. “*Wideband O2 Sensors and Air/Fuel (A/F) Sensors*.” AA1Car. <http://www.aa1car.com/library/wraf.htm> (accessed on October 3, 2014).

(ARB, 2014a). California Air Resources Board. “*Evaluating Technologies and Methods to Lower Nitrogen Oxide Emissions from Heavy-Duty Vehicles*.” December 16, 2014 <http://www.arb.ca.gov/research/veh-emissions/low-nox/low-nox.htm> (accessed on April, 8, 2015).

(ARB, 2014b). On-Road New Vehicle & Engine Certification Program. Executive Orders Listing. <http://www.arb.ca.gov/msprog/onroad/cert/cert.php#6>.

(ARB, 2014c). California Air Resources Board “*Technology and Fuels Assessment Workshop. Truck Sector In-Use Emissions*.” September 2, 2014. Sacramento, California. <http://www.arb.ca.gov/msprog/tech/presentation/truckinuse.pdf> (accessed on April 11, 2015).

(ARB, 2015). California Air Resources Board, *Short-Lived Climate Pollution Reduction Strategy*, *Concept Paper*, May 2015. <http://www.arb.ca.gov/cc/shortlived/shortlived.htm> (accessed on September 9, 2015).

(Bean, 2013) Bean, Patrick, and Gregory C. Staple. “*Driving on Natural Gas: Fuel Price and Demand Scenarios for Natural Gas Vehicles to 2025*.” Rep. Washington, DC: American Clean Skies Foundation, 2013. Print.

(CEC, 2015) California Energy Commission. *Program Opportunity Notice (PON-14-608) - Natural Gas Fueling Infrastructure* (*Notice of Proposed Awards).* August 12, 2015. <http://www.energy.ca.gov/contracts/transportation.html#PON-14-608> (accessed on September 11, 2015).

(Chadwell et al., 2014). Chadwell, C., Alger, T., Zuehl, J., and Gukelberger, R., "*A Demonstration of Dedicated EGR on a 2.0 L GDI Engine*," SAE Int. J. Engines 7(1):434-447, 2014, doi:10.4271/2014-01-1190.

(Crawford, 2010) Crawford, R., Lyons, J., & Heiken, J. “*Effects of gas composition on emissions of heavy-duty natural gas engines*.” Sierra Research, Inc. 2010.

(Cummins, 2014) Cummins Inc. “*Cummins Ethos 2.8L Engine Demonstrates 50 to 80 Percent Reduction in Carbon Dioxide Emissions.”*” Cummins Inc. 2014. <http://cumminsengines.com/cummins-ethos-28l-engine-demonstrates-50> (accessed on April 11, 2015).

(CWI, 2015) Cummins Westport, Inc. News Release: *Near Zero NOx Emissions ISL G Natural Gas Engine.* May 6, 2015. <http://www.westport.com/news/2015/near-zero-nox-emissions-isl-g-natural-gas-engine> (accessed on May 6, 2015).

(Davis, 2013) Davis, P. "*Next Generation Technologies for Commercial Trucks*." Department of Energy. 2013. <http://www.emi-global.com/ntea_presentations/27.pdf> (accessed on August 7, 2014).

(Exel, 2011) Exel, G. *"Compelling case for natural gas*." Cummins Westport. 2011. <http://www.cleanvehicle.org/workshop/portland/ExelCumminsWestportPortland.pdf> (accessed on May 7, 2014).

(Greszler, 2013). Greszler, D. Anthony. "*DME from Natural Gas or Biomass: A Better Fuel Alternative*." Presentation. SAE 2013 Government/Industry Meeting. January 30, 2013. <http://www.sae.org/events/gim/presentations/2013/greszler_anthony.pdf> (accessed on April 20, 2015).

(JB Hunt, 2014). "*Natural Gas In Transportation - J.B. HUNT Perspective. White Paper REV 02/14*." https://www.jbhunt.com/company/newsroom/white_papers/. (accessed on April 11, 2015).

(Kamel, 2006) Kamel, M. "*Development of a Cummins Westport SI-EGR Natural Gas Engine at 0.2 G/bhp-H,"* Cummins Westport. 2006. <http://www.nrel.gov/docs/fy07osti/40757.pdf> (accessed on May 7, 2014).

(Kubsh, 2015) Email communication with Joe Kubsh, Executive Director, Manufacturers of Emissions Control Association, June 21, 2015.

(Lindner, 1996) Lindner, D., Lox, E., van Yperen, R., Ostgathe, K. "*Reduction of Exhaust Gas Emissions by Using Pd-based Three-way Catalysts*," SAE Technical Paper 960802. 1996.

(Marsh, 2001) Marsh, P., Acke, F., Konieczny, R., Brück, R. "*Application Guideline to Define Catalyst Layout for Maximum Catalytic Efficiency*," SAE Technical Paper 2001-01-0929. 2001.

(MECA, 2013) Manufacturers of Emission Controls Association (MECA). "*LEV III and Tier 3 Exhaust Emission Control Technologies for Light-Duty Gasoline Vehicles,"* MECA 2013. <http://www.meca.org/galleries/files/LEV_III_Tier_3_white_paper_final.pdf> (accessed on May 7, 2014).

(Pirouzpanah, 2003) Pirouzpanah, V., and Sarai, R. K. *"Reduction of emissions in an automotive direct injection diesel engine dual-fuelled with natural gas by using variable exhaust gas recirculation,"* Journal of Automotive Engineering, 217, pp. 719-725. 2003.

(SCAQMD, 2012) SCAQMD. “*UPS Ontario - Las Vegas LNG Corridor Extension Project: Bridging the Gap,”* <http://energy.gov/sites/prod/files/2014/03/f10/arravt047_ti_watkins_2012_o.pdf> (accessed on September 1, 2014).

(SCAQMD, 2013) SCAQMD. “*Recognize Revenue and Execute Contracts for Development, Integration, and Demonstration of Ultra-Low Emission Natural Gas Engines for On-Road Heavy-Duty Vehicles,”* Board Meeting Date: October 4, 2013 Agenda No. 9. <http://www.aqmd.gov/docs/default-source/Agendas/Governing-Board/2013/2013-oct4-009.pdf?sfvrsn=2> (accessed on November 10, 2014).

(SCAQMD, 2014) SCAQMD. “*Execute Contract to Develop Ultra-Low Emission Natural Gas Engine for On-Road Class 4 to 7 Vehicles*,” Board Meeting Date: October 3, 2014. Agenda No. 2. <http://www.aqmd.gov/docs/default-source/Agendas/Governing-Board/2014/2014-oct3-002.pdf?sfvrsn=2> (accessed on April 8, 2015).

(TIAX, 2005) TIAX, LLC. “*Comparative Costs of 2010 Heavy-Duty Diesel and Natural Gas Technologies, Final Report*,” TIAX LLC. 2005. <http://publicsolutionsgroup.com/Websites/publicsolutionsgroup/Images/documents/FINAL percent20HDDV_NGVCostComparisonFinalr2 percent207.15.05.pdf> (accessed on August 7, 2014).

(TIAX, 2012) TIAX, LLC. U.S. and Canadian Natural Gas Vehicle Market Analysis: Heavy-Duty Vehicle Ownership and Production. TIAX LLC. 2012. <http://anga.us/issues-and-policy/transportation/tiax-natural-gas-vehicle-market-analysis> (accessed on May 7, 2014).

(U.S. DOE, 2013a) U.S. DOE. "*Natural Gas Vehicles*." Alternative Fuels Data Center. U.S. DOE, 2013. <http://www.afdc.energy.gov/vehicles/natural_gas.html> (accessed on September 1, 2014).

(U.S. DOE, 2014a) DOE. "*Fuel Properties Comparison*." Alternative Fuels Data Center. U.S. DOE, 2014. <http://www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf> (accessed on September 1, 2014).

(U.S. DOE, 2014b) U.S. DOE. "*Data Downloads*." Alternative Fuels Data Center. U.S. DOE, 2014. <http://www.afdc.energy.gov/data_download/> (accessed on September 1, 2014).

(U.S. DOE, 2015a). *Clean Cities Alternative Fuel Price Reports.* Clean Cities, U.S. Department of Energy, April 2015. <http://www.afdc.energy.gov/fuels/prices.html> (accessed on September 3, 2015).

(U.S. DOE, 2015b). *Weekly Retail Gasoline and Diesel Prices*. Energy Information Administration, U.S. DOE. August 31, 2015 <http://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm> (accessed on September 3, 2015).

(TIAX, 2012) TIAX, LLC. "*Natural Gas Vehicle Market Analysis - America's Natural Gas Alliance*." TIAX LLC. 2012. <http://anga.us/issues-and-policy/transportation/tiax-natural-gas-vehicle-market-analysis> (accessed on May 7, 2014).

(Walkowicz, 2001) Walkowicz, K., Stephens, D., and Stork, K. "*The DOE/NREL next Generation Natural Gas Vehicle Program - an Overview*." SAE 2001-01-2068. 2001.

(Walls, 2013) Walls, M. "*Natural Gas Engine and Vehicle Research, Development and Demonstration*." Cummins Inc. 2013. <http://www1.eere.energy.gov/cleancities/pdfs/ngvtf14_walls.pdf> (accessed on May 7, 2014).

(Wark, 1998) Wark, K., Warner, C. F., and Davis, W. T. "*Air Pollution Its Origin and Control, 3rd ed*.' Menlo Park, California: Addison-Wesley. 1998.

(Webb, 1999) Webb, C., Bykowski, B., Weber, P., and McKinnon, D. "*Using Advanced Emission Control Systems to Demonstrate LEV II ULEV on Light-Duty Gasoline Vehicles*," SAE Technical Paper 1999-01-0774. 1999.

(Williamson, 2001) Williamson, W., Richmond, R., Nunan, J., Bortun, "*A. Palladium and Platinum/Rhodium Dual-Catalyst NLEV and Tier II Close-Coupled Emission Solutions*," SAE Technical Paper 2001-01-0923. 2001.

(Yoon, 2013) Yoon, S., Collins, J., Thiruvengadam, A., Gautam, M., Herner, J., Ayala, A. "*Criteria pollutant and greenhouse gas emissions from CNG transit buses equipped with three-way catalysts compared to lean-burn engines and oxidation catalyst technologies,*" Journal of the Air and Waste Management Association,63, 923-933. 2013.

(Youssef, 2014) Youssef, Cherif. "*Natural Gas Transportation Technology Pathways to Achieve Air Quality Goals,"* Presentation Natural Gas Vehicle Technology Forum & ARPA-E MOVE, Los Angeles. October 16, 2014. <http://www1.eere.energy.gov/cleancities/natural_gas_forum_meeting_oct2014.html> (accessed on April 11, 2015).

(Zhang, 1998) Zhang, F.R., K. Okamoto, S. Morimoto, and F. Shoji. "*Methods of increasing the BMEP (power output) for natural gas spark ignition engines*." SAE Technical Paper 981385. 1998.

(Zigler, 2014) Zigler, B. “*Natural Gas Engine Development Gaps*,” Department of Energy. 2014. <http://www1.eere.energy.gov/cleancities/pdfs/ngvtf14_zigler.pdf> (accessed on August 7, 2014).

Appendix: Natural Gas Vehicle Infrastructure

1. Overview

There are currently about 112,000 natural gas vehicles in the United States (U.S. DOE, 2013a), including about 20,000 heavy-duty (Class 7-8) vehicles and about 40,000 medium-duty (Class 3-6) vehicles. Together, these vehicles consume 0.1 billion cubic feet of natural gas per day, which is 0.14 percent of total demand for natural gas (Bean, 2013).

2. Natural gas fuel

Natural gas is a hydrocarbon gas mixture composed primarily of methane. While most of the natural gas available today is fossil fuel extracted from natural gas reserves in the ground, renewable natural gas can also be produced by anaerobic digestion of organic matter such as biogas or landfill gas. Because biogas or landfill gas would escape into the atmosphere if not captured, the use of such sources of renewable natural gas could provide immediate greenhouse gas (GHG) reductions.

Natural gas fuel for vehicle use is available in two forms: compressed natural gas (CNG) and liquefied natural gas (LNG). CNG is stored onboard vehicles in pressurized fuel tanks under 3600 psi of pressure and contains about 25 percent of the energy content of diesel per unit volume. To increase the amount of energy per unit volume of fuel, natural gas can instead be condensed into LNG, which is available as a fuel at -200 degrees Fahrenheit and 100 psi, bringing the energy content to 60 percent of that of diesel per unit volume (U.S. DOE, 2014a). LNG is stored in insulated cryogenic tanks, and is kept cool by the evaporation of some of the LNG, a process known as auto-refrigeration. The evaporated gas is normally used as fuel, but if the vehicle is unused for extended periods, the gas is vented into the atmosphere to prevent pressure build-up within the fuel tank.

3. Fueling stations

Natural gas fueling stations differ greatly depending on whether they supply LNG, CNG, or both. Stations that dispense both are known as liquefied-compressed natural gas (LCNG) stations.

3.1 LNG stations

LNG stations generally do not have on-site liquefaction units, so natural gas is liquefied to LNG at a liquefaction plant and brought to the fueling station by tanker truck. Natural gas condenses into a liquid at -260^{o}F, so upon arrival at the fueling station, the fuel is typically “conditioned” by passing the LNG through a heat exchanger to raise the temperature to -200^{o}F and a saturation pressure of 100 psi, the required fueling condition for most LNG vehicles (TIAX, 2012), and then stored in a cryogenic storage vessel. There is currently no standardized fueling nozzle and fuel tank receptacle, so vehicles needing to refuel at a publicly accessible station would need to ensure that the nozzle configuration of the station is compatible with the vehicle's fuel receptacle. The construction cost of an LNG station varies with the design capacity of the station, with the greatest component of the cost coming from the cryogenic storage vessel.

3.2 CNG stations

Unlike LNG stations, CNG stations are usually supplied with natural gas from pipelines. CNG stations can be divided into fast-fill or time-fill configurations. Fast-fill stations are intended for quick refueling of vehicles, requiring about the same amount of time to refuel vehicles as gasoline and diesel refueling stations, whereas time-fill stations typically are designed to refuel large number of vehicles simultaneously over a period of several hours. Most fleets with private stations serving vehicles that return to the base at the end of the day would use a time-fill configuration.

3.2.1 Time-fill stations

Typical equipment that comprise a time-fill station include a dryer for removing water or water vapor from the natural gas supply, a compressor to increase the pressure of the natural gas from pipeline pressure to 3600 psi for vehicle use, a back-up compressor in case the main compressor fails, and dispensers that refuel vehicles with natural gas directly from the compressors. A time-fill station may take several hours to refuel a vehicle; so typically, multiple vehicles are refueled at the same time through multiple dispensers.

3.2.2 Fast-fill stations

Fast-fill stations are designed to refuel vehicles with CNG rapidly and are suitable for publicly accessible CNG stations which require fast filling for multiple vehicles at the same time, both during peak fueling periods and randomly throughout the day. In addition to the equipment found in a time-fill station, fast-fill stations also require high-pressure storage vessels so that natural gas may be compressed and stored, allowing for fueling to occur more quickly than the compressor can compress in order to meet peak demands. For both time-fill and fast-fill stations, the greatest component of the cost would be from the compressors, though the additional requirement of storage vessels makes fast-fill stations more costly to construct than time-fill stations.

3.3 LCNG stations

Certain stations dispense both LNG and CNG fuel, with the natural gas delivered by tanker truck as LNG. Some of the LNG is then regassified and compressed on-site. The use of regassified CNG is more typical in locations that lack access to a natural gas pipeline, requiring natural gas to be delivered by truck.

3.4 Availability of fueling stations

The U.S. Department of Energy's (DOE) Alternative Fuels Data Center (AFDC) tracks and lists on its website existing and planned natural gas fueling stations across the United States. Among other things, the listing provides information on whether the station is private or open to the public and the vehicle class sizes that the station can accommodate.[19] As of the last update to the database[20], nationwide, there are approximately 1039 open, heavy-duty accessible CNG fueling stations and approximately 110 open, heavy-duty accessible LNG fueling stations. There are also approximately 394 open medium-duty accessible CNG stations nationwide. Detailed numbers are provided in Table A-1 (U.S. DOE, 2014b).

Most states have at least one CNG station but 4 states (California, New York, Utah, and Oklahoma) account for over one-third of the stations; California alone has 207 CNG stations, of which 102 are publicly accessible. There are LNG stations in 22 states, but nearly half, 44 of the stations, are located in California (U.S. DOE, 2014b). Figure A-1 shows a map of the geographic distribution of publicly accessible heavy-duty vehicle natural gas fueling facilities in the country.

Because of the limited number of stations, and the uneven distribution of stations, there are concerns about access to refueling sites. For comparison, there are 36,000 diesel fueling stations in the country, with 5000 of them being publicly accessible (TIAX, 2012), so a greater density of CNG and LNG stations may be needed for greater adoption of CNG and LNG for use in heavy-duty vehicles. Due to the difference in energy content of CNG, LNG, and diesel, natural gas vehicles typically have shorter ranges than diesel vehicles and require more frequent refueling, so access to fueling stations is particularly important for natural gas vehicles. This plays a role in limiting natural gas vehicles to return-to-base type of applications, such as transit buses, refuse trucks, and vocational or delivery trucks.

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[19] Heavy-duty accessible stations can accommodate vehicles class sizes 1 through 8. Medium-duty accessible stations can accommodate vehicle class sizes 1 through 5.

[20] The numbers of natural gas fueling stations reported here are based on the AFDC database last updated on April 21, 2015.

Table A-1: Natural Gas Refueling Stations

Heavy-Duty Accessible (Class 6 to 8)		Open stations		Planned Stations	
		Nationwide	California	Nationwide	California
CNG	Total	1039	207	144	15
	Publicly Accessible	591	102	101	6
	Private	448	105	43	9
LNG	Total	110	44	69	2
	Publicly Accessible	73	15	68	1
	Private	37	29	1	1

Medium-Duty Accessible (Class 3 to 5)		Open stations		Planned Stations	
		Nationwide	California	Nationwide	California
CNG	Total	394	64	20	4
	Publicly Accessible	207	42	17	3
	Private	187	22	3	1

(U.S. DOE 2014b)

Figure A-1: Map of Heavy-Duty Vehicle, Publicly Accessible, Fueling Stations

Red dots represent LNG stations, and blue dots represent CNG stations (U.S. DOE, 2014b)

3.4.1 Further development of natural gas fueling infrastructure

While access to fueling stations is still inadequate for widespread adoption of natural gas vehicles due to the low number of stations available, limited geographic distribution of stations, and the fact that nearly half of all stations are not publicly accessible, new stations are being planned and constructed. According to the AFDC database, there are 144 CNG stations and 69 LNG stations planned around the country, including 15 CNG stations and 2 LNG stations planned in California. Furthermore, public-private partnerships are also helping to increase the number of stations available in key corridors. A recent partnership between United Parcel Service (UPS), the South Coast Air Quality Management District, and others, has constructed a publicly accessible LNG fueling station located in Las Vegas, Nevada, making it possible for LNG trucks to now travel from the Greater Los Angeles area to Salt Lake City (SCAQMD, 2012).

The California Energy Commission (CEC) is also funding natural gas fueling infrastructure projects in California through its competitive grant program, the Alternative and Renewable Fuel and Vehicle Technology Program (ARFVTP). For fiscal year 2015-2016, the CEC staff is recommending to award funds of about $5.5 million for natural gas fueling infrastructure projects (CEC, 2015).

4. Maintenance Facility Considerations

In addition to fueling stations, another infrastructure requirement for the deployment of natural gas vehicles is the maintenance facilities needed for servicing natural gas vehicles. A key difference between natural gas and liquid fuels such as gasoline and diesel is that natural gas is lighter than air, so natural gas rises towards the ceiling, whereas gasoline and diesel are heavier and would pool on the ground. This difference means that indoor service facilities designed for working with gasoline or diesel powered vehicles may not be suitable for servicing natural gas vehicles due to inadequate ventilation near the ceiling or the presence of equipment near the ceiling that may cause sparks, such as space heaters (TIAX, 2012).