Pathways to Near-Zero-Emission Natural Gas Heavy-Duty Vehicles

A white paper from Gladstein, Neandross & Associates

GLADSTEIN, NEANDROSS & ASSOCIATES

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List of Terms

ACRONYM	DEFINITION
AQMP	Air Quality Management Plan
ARB	California Air Resources Board (Also "CARB")
AB	Assembly Bill
BEV	Battery Electric Vehicle
CalHEAT	California Hybrid, Efficient and Advanced Truck Research Center
CO_2	Carbon Dioxide
CI	Carbon Intensity
CEC	California Energy Commission
CAA	Clean Air Act
CNG	Compressed Natural Gas
CWI	Cummins Westport Inc.
DGE	Diesel Gallon Equivalent
DOE	U.S. Department of Energy
EGR	Exhaust Gas Recirculation
EPA	U.S. Environmental Protection Agency
FCV	Fuel Cell Vehicle
g/bhp-hr	Grams per Brake Horsepower-Hour
GHG	Greenhouse Gas
GVWR	Gross Vehicle Weight Rating
HCCI	Homogeneous Charge Compression Ignition
HDE	Heavy-Duty Engine
HDV	Heavy-Duty Vehicle
HEV	Hybrid Electric Vehicle
HPDI	High Pressure Direct Injection
ICCT	International Council for Clean Transportation
LFG	Landfill Gas
LCFS	Low Carbon Fuel Standard
LEV	Low-Emission Vehicle
LNG	Liquefied Natural Gas
LTC	Low-Temperature Combustion
MECA	Manufacturers of Emissions Control Equipment
NAPCA	National Air Pollution Control Administration
NAS	National Academy of Sciences
NAAQS	National Ambient Air Quality Standards
NG	Natural Gas
NMOG	Non-Methane Organic Gases
NSCR	Non-Selective Catalytic Reduction
NOx	Oxides of Nitrogen
OEM	Original Equipment Manufacturer
PPB	Parts Per Billion
PPM	Parts Per Million
PCCI	Premix Charge Compression Ignition
PZEV	Partial Zero-Emission Vehicle
PM	Particulate Matter
PON	Program Opportunity Notice

ACRONYM	DEFINITION
RNG	Renewable Natural Gas
SCAQMD	South Coast Air Quality Management District
SJVAPCD	San Joaquin Valley Air Pollution Control District
SCR	Selective Catalytic Reduction
SoCAB	South Coast Air Basin
NAPCA	National Air Pollution Control Administration
TWC	Three-Way Catalyst
ULSD	Ultra Low Sulfur Diesel
ZEV	Zero-Emission Vehicle

Executive Summary

California has the most stringent air quality and climate protection policies in the nation. Nonetheless, the state is not on track to meet smog reduction requirements and will have to generate greenhouse gas (GHG) emission reductions earlier than currently projected to maximize the benefit of GHG reductions on global climate change. Although California is working to harmonize its air quality and climate protection planning, policy makers face significant challenges in their efforts to devise a "pathway" that can simultaneously help the state achieve NOx and GHG reduction targets. Compared to the 2010 "Business as Usual" scenario -- which includes all adopted emission control measures for the South Coast -- NOx levels must be reduced by 65 percent and by 75 percent to meet the 2023 and 2032 ozone standards, respectively. An 80 percent reduction of GHG emissions is targeted for 2050, relative to 1990 levels.

Heavy-duty diesel trucks are the largest contributors to the nitrogen oxide (NOx) inventories of the South Coast and San Joaquin Valley ozone non-attainment areas. They are also major producers of toxic air contaminants and GHGs. To meet federal deadlines for attainment of ozone and fine particulate matter ($PM_{2.5}$) standards, these regions must expeditiously phase in heavy-duty vehicles (HDVs) that emit at, or below, the equivalent of "zero-emission" battery-electric vehicles when accounting for pollution from base load electricity generation. This constitutes a NOx reduction of approximately 90 percent below the current federal heavy-duty engine standard of 0.2 grams per brake horsepower-hour (g/bhp-hr).

Since the advent of the first Low-Emission Vehicle (LEV) regulations in 1990 and the passage of California Assembly Bill 32 (AB 32) in 2006, the California Air Resources Board (ARB) has attempted to address the state's air quality and climate goals by requiring development of motor vehicles that do not directly emit NOx or other criteria pollutants. Policy makers have emphasized policies that compel the manufacture and/or purchase of vehicles that emit zero-emissions at the tailpipe. These "technology forcing" requirements, which direct manufacturers to phase-in sales of battery-electric vehicles or large transit fleets to buy zero-emission buses, have not resulted in the commercialization of zero-tailpipe emission vehicles as quickly as air quality regulators hoped or planned for. Zero emission vehicle mandates have, however, spurred tremendous innovation by the manufacturers of internal combustion engines, emission control equipment, and advanced vehicle drive trains. The resulting technological transformations have dramatically increased the menu of options available to policy makers to meet the state's air quality and GHG reduction goals.

The use of heavy-duty engines powered by natural gas offers a unique and viable strategy to meet California's aggressive reduction goals for NOx and GHG emissions.

Given the sector's dominant contribution to California's ozone pollution and toxic air contaminant problems, the ARB and other air quality regulators are keenly focused on dramatically reducing emissions from the state's heavy-duty vehicle fleet. With ozone reduction deadlines looming, strategies that quickly reduce NOx emissions from this sector are essential. Fortunately, an alternative to diesel in heavy-duty vehicles has already found a substantial foothold in the market and is poised to achieve the NOx and GHG emission reductions necessary to push California toward attainment of its air quality and climate protection objectives. The use of heavy-duty engines powered by natural gas (NG) offers a unique, viable and complementary pathway to help meet California's aggressive reduction goals for NOx and GHG emissions. It also supports a variety of other state and national goals, such as reducing the public's exposure to toxic diesel exhaust and reducing the nation's dependence on foreign energy sources. Natural gas-fueled trucks, buses, and off-road equipment can serve as a key element of California's smog reduction and climate mending programs, while dramatically decreasing the mass of cancer-causing chemicals in our air.

Today's commercially available natural gas engines already emit NOx at levels well below the current (2010) federal heavy-duty engine standard. Heavy-duty vehicles fueled by natural gas are also recognized by the ARB as a method of reducing GHG emissions. This provides a low-emission, low-carbon baseline upon which engineers have begun to apply a suite of well understood technologies that have been utilized to improve the emissions performance and fuel efficiency of conventionally-fueled engines. In the near term, utilization of technologies such as optimized compression ratios, enhanced three-way catalysts (TWC), integration of electric and hydraulic hybridization, improved aerodynamics, and low pressure storage are expected to help reduce NOx emissions from natural gas heavy-duty vehicles by 75 percent. Engine manufacturers have already begun to integrate these technologies into natural gas heavy-duty engines, and are thus expected to bring product to market in the next few years with NOx emissions less than 0.05 g/bhp-hr. At the same time, advancements in engine and vehicle design will dramatically increase fuel efficiency, thereby reducing GHG emissions.

Furthermore, research indicates that heavy-duty natural gas engines are on a trajectory to be certified at a NOx level of 0.02 g/bhp-hr, an emissions level so low that it equates to the power plant emissions that would result from charging an electric vehicle of a comparable size. These technologies, which are currently being developed, include advanced aftertreatment and waste heat recovery, lean burn plus lean NOx emissions traps, integration of zero-emission miles technologies, further refinements in reducing friction and parasitic energy losses, and widespread utilization of renewable and hydrogenized natural gas. Integration of these technologies will increase the likelihood that California can meet smog reduction requirements, and also help heavy-duty natural gas engines meet the 2050 goal to reduce GHG emissions by 80 percent.

Furthermore, research indicates that heavy-duty NG engines are on a trajectory to be certified at a NOx level of 0.02 g/bhp-hr, an emissions level so low that it equates to the power plant emissions that would result from charging an electric vehicle.

Heavy-duty natural gas engines are well along the path to achieve a 90 percent NOx reduction from the existing heavy-duty engine NOx standard, while also becoming increasingly fuel efficient to reduce GHG emissions. Widespread deployment of these near-zero and power plant emission-equivalent heavy-duty natural gas vehicles (NGVs) are needed to meet tough air quality and climate protection goals. To realize these benefits, supportive public policies and public-private partnerships are needed that continue to encourage the development, demonstration, and deployment of critical natural gas-fueled heavy-duty vehicle technologies.

California's policy makers can encourage this development with three actions: 1) Implement policies that fund the research, development, and demonstration of these crucial pathway technologies; 2) Support modifications to the state's already robust air quality incentive programs that promote the commercialization of near-zero and power plant emissions-equivalent heavy-duty vehicles; and 3) Develop new and innovative requirements for the use of pathway technologies throughout the state. Coupled with continued promotion of zero-emission technology, particularly in those sectors of the vehicle population in which the most progress is being made, an air quality plan that encourages the rapid development and massive deployment of near-zero and power plant emissions-equivalent NGVs can propel California down the path to a cleaner, more climate-friendly future.

Introduction: California's Air Quality Challenges and Possible Solutions

California has always been at the forefront of policies to protect and improve the environment. Nowhere is this more evident than the state's efforts to reduce smog, toxic air contaminants, and emissions of anthropogenic GHGs, which are the heat-trapping pollutants that lead to long-term disruptions in the Earth's climate. For nearly 50 years, California has led the nation in the development of tough policies and stringent regulations to decrease public exposure to air contaminants that cause asthma, heart disease, cancer, and many other health problems. More recently, the state passed far-reaching measures to reduce GHG emissions, including those that originate from the transportation sector. Coupled with its efforts to increase energy efficiency, conservation, and the use of renewable resources, California continues to push the envelope of progressive environmental and energy policy.

Now more than ever, California's visionary public policy goals require innovative new programs and policies to encourage the creation and commercialization of ultra-clean motor vehicle technologies. To increase the likelihood of success, these policies must be results-oriented, cost-effective, and allow flexibility in compliance pathways for both public and private-sector stakeholders. The following discussion describes such an initiative that can greatly advance and expedite California's progress to meet its aggressive air quality and GHG objectives.

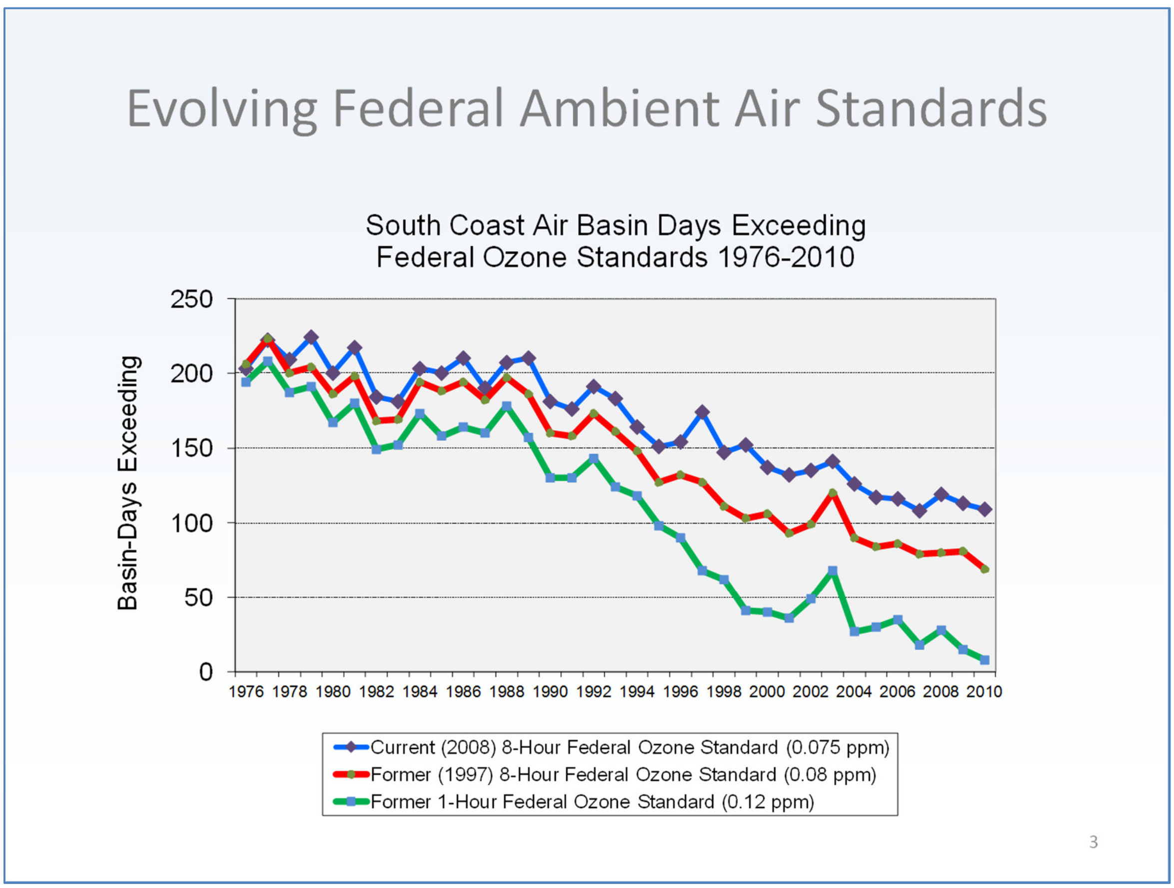

Figure 1 – Although significant progress has been made, the SoCAB still does not meet ozone standards (Source: SCAQMD)

Meeting California's Air Quality Goals: Tough Challenges Ahead

Since the mid-1970s, when motor vehicle emission controls first began to proliferate, California has done remarkably well in improving air quality. Through synergistic combinations of improved fuel quality and vehicle emissions standards, the state has steadily reduced criteria pollutant emissions. In tandem with strong controls on "stationary" sources of air pollution, the result has been gradually improving air quality throughout California, especially in its largest urban areas. As shown in Figure 1, the number of days exceeding the National Ambient Air Quality Standards (NAAQS) for ozone (photochemical "smog") has steadily decreased over the last 35 years in the South Coast Air Basin (SoCAB), which is America's most impacted air shed. Clearly, major strides have been made—air quality in the Los Angeles basin and throughout California is significantly more healthful today than in 1975.

Pushing Back the Goal Posts

Notwithstanding this tremendous progress, the SoCAB still does not meet health-based NAAQS for ozone and fine particulate matter. Though the lines in Figure 1 are headed lower, they have not reached zero exceedance days. California has yet to meet the original ozone NAAQS created in 1979.[1] Moreover, air quality standards have not remained static over the decades; they have become more stringent. Medical researchers have broadened and deepened their knowledge of how key air pollutants harm human health, finding that adverse impacts occur at much lower concentrations than previously believed. Given this growing understanding of air pollution's health effects, scientists have recommended—and the United States Environmental Protection Agency (U.S. EPA) has approved—several changes to the NAAQS for ozone. These changes have lowered the ozone concentration in ambient air that is considered to be healthful, while also revising the way that we measure exposure time to such levels. Thus, the ozone NAAQS has changed from a one-hour exposure limit at 120 parts per billion (ppb), or 0.12 parts per million (ppm), to an eight-hour exposure limit at 75 ppb (0.075 ppm). As Figure 1 demonstrates, tightening standards have moved the goal posts, making it harder for California's most impacted air basins to meet clean air requirements.

Tightening standards have moved the goal posts, making it harder for California's most impacted air basins to meet clean air requirements.

Short Time to Meet Air Quality Goals

The practical outcome of these changes in the ozone NAAQS is that we must reduce ozone-precursor emissions to levels so low that they are approaching background levels. This is especially true with NOx, a key pollutant in the formation of ground-level ozone[2]. Figure 2 shows this problem in stark terms. The colored bars on the left signify the projected 2023 SoCAB inventory of the top 15 NOx sources after all currently adopted emission control measures have been implemented. These 15 largest sources of NOx make up 93 percent of the total projected inventory of NOx in 2023. Based on the figures in the 2012 Air Quality Management Plan (AQMP) for the South Coast Air Quality Management District (SCAQMD), the NOx inventory in 2023 will be 319 tons per day; this is 204 tons per day more than air quality planners believe is necessary to meet the 1997 ozone NAAQS. The gold arrows on the right show the additional NOx emission reductions that will be needed over the next 10 years to meet the standard. NOx emissions in the SoCAB must be reduced well beyond the levels that are expected through all existing or currently defined control measures. In the San Joaquin Valley Air Basin, the challenge for the

[1] See http://www.epa.gov/ttn/naaqs/standards/ozone/s_o3_history.html.

[2] In addition to forming smog, NOx is also linked to the secondary formation of fine particulate matter.

San Joaquin Valley Air Pollution Control District (SJVAPCD) to meet the ozone NAAQS is also quite daunting.

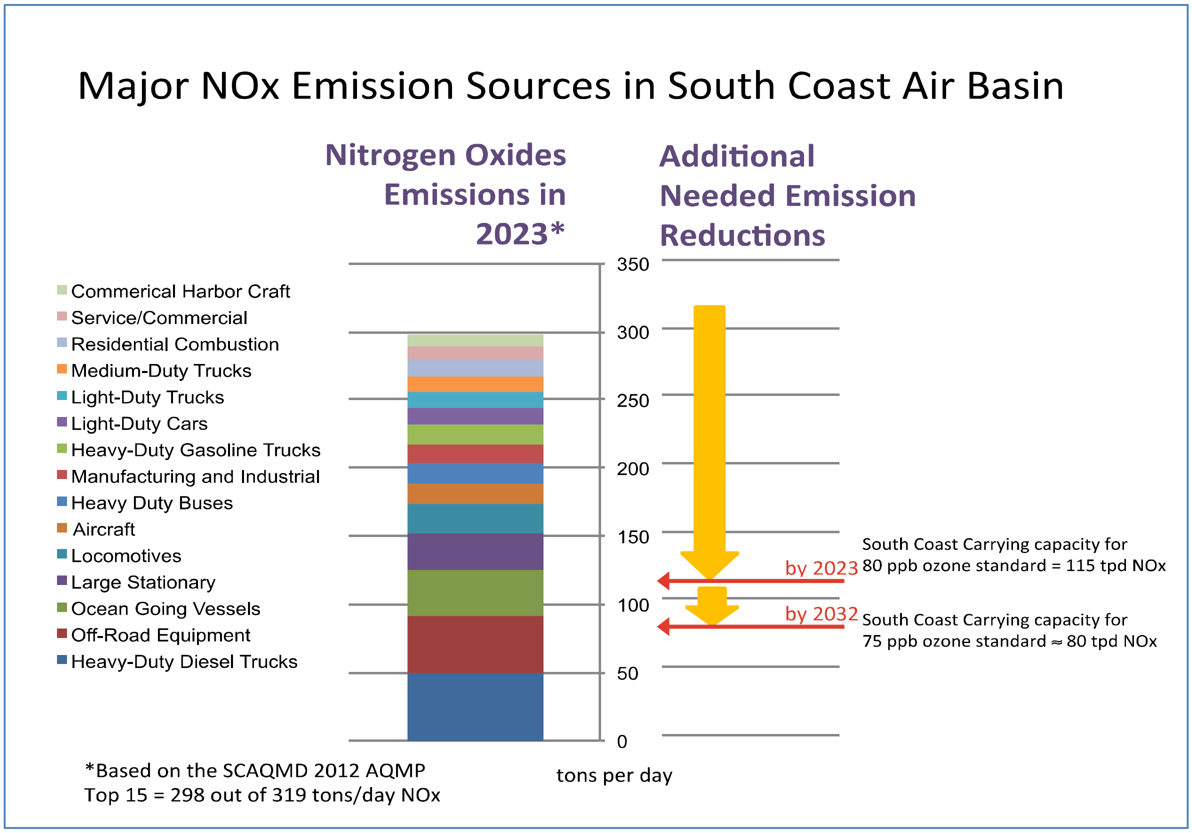

Figure 2 – Current AQMPs do not provide for sufficient NOx reductions to meet NAAQS (Source: SCAQMD)

For air quality planners, 10 years is a short period of time to develop, implement, and achieve emission reductions. This task is made even more overwhelming by two additional factors: 1) current ozone-reduction targets are interim requirements, and 2) criteria pollutant reduction targets must be harmonized with California's goals to reduce GHGs and toxic air contaminants.[3] The extent of the formidable challenge faced by the state is illuminated in the June 2012 *Vision for Clean Air: A Framework for Air Quality and Climate Planning*[4] document, published by a consortium of key air quality agencies. In the *Vision* draft, air quality planners attempted to better understand the interplay between strategies to meet air quality and climate protection goals. As defined under AB 32, California has a 2020 goal to reduce GHG emissions by 20 percent from 1990 levels. Executive Order S-3-05 established the state's long term GHG reduction goal of an 80 percent reduction from 1990 levels by 2050.[5]

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[3] The use of natural gas as a substitute for diesel is widely recognized by air quality regulators as reducing exposure to the carcinogenic and mutagenic chemicals found in diesel exhaust. Some, however, have raised concerns that alternative fuel vehicles, such as NGVs that are not equipped with particulate filters, may result in increased emissions of ultrafine particles (UFPs). The health impacts of which are still poorly understood. More research is needed.

[4] Vision for Clean Air: A Framework for Air Quality and Climate Planning, http://www.arb.ca.gov/planning/vision/docs/vision_for_clean_air_public_review_draft.pdf.

[5] See http://gov38.ca.gov/index.php?/print-version/executive-order/1861/. Executive Order S-3-05 was signed by Governor Arnold Schwarzenegger on June 1, 2005.

Goal	Year	Percent Reductions from 2010	
O3 Standard (ppb)	Target	NOx	CO_2
84	2023	80%	
75	2032	90%	
65*	2050	95%	
GHG	2050		85%

Table 1 – Vision for Clean Air Targets
* Anticipated standard. Not yet adopted.
Source: ARB

The draft *Vision for Clean Air* document also summarizes evolving targets for ozone NAAQS levels and associated compliance dates. California has until 2023 to meet the 1997 revision to the ozone NAAQS of 84 ppb (the red line in Figure 1). Since that time, the ozone standard has been revised once, and it was nearly adjusted again. In 2007, the EPA revised the ozone NAAQS to 75 ppb (the blue line in Figure 1). As Table 1 and Figure 2 show, SoCAB NOx emissions will need to be reduced down to (or below) 80 tons per day (90 percent below 2010 levels) to achieve an ambient ozone concentration of 75 ppb. The SoCAB has until 2032 to meet the 75 ppb ozone NAAQS. Making the situation more vexing is that air quality planners are aware that the EPA is likely again to change the ozone NAAQS.[6] It is widely anticipated that the EPA will soon lower the ozone standard to a level of 60 ppb to 70 ppb.[7] As noted in the *Vision for Clean Air*, this will necessitate a 95 percent reduction from 2010 NOx emissions levels.

Current Plans Won't Provide the Needed NOx Reductions

California's current plans are inadequate to meet the ozone NAAQS, as indicated in Figure 2, despite being the nation's most stringent. These aggressive air quality measures will not reduce NOx emissions to the

- Fugitive Methane Emissions -

There has been some controversy in recent years regarding the impact that fugitive methane emissions from unconventional gas production may have on the GHG reduction value of replacing diesel with natural gas in heady-duty vehicles. The issue arose in April 2011, when the U.S. EPA dramatically increased its estimate of the methane leakage rate from U.S. natural gas production (to 2.4 percent of total production) when it submitted the U.S. GHG inventory to the International Panel on Climate Change (IPCC). The change, which was based on a limited set of data collected from the agency's Gas Star program, was hotly contested by industry. After working with industry and examining a much larger, diverse, and more comprehensive collection of measurements, U.S. EPA amended its IPCC filing, reducing its estimate of fugitive methane emissions from natural gas production to 1.5 percent, a 39 percent reduction from the 2011 filing.

ARB's Low Carbon Fuel Standard (LCFS) documents estimate that CNG produced from North American natural gas has 31 percent lower carbon intensity (gCO2e/MJ) than Ultra Low Sulfur Diesel (ULSD). LNG is 15 percent lower in carbon intensity than diesel; however, the LCFS models use lower leakage rates than the most current figures from U.S. EPA. The LCFS assumes leakage rates from CNG and LNG pathways that are roughly one-third of the U.S. EPA's estimated leakage rate of 1.5 percent for the U.S. natural gas sector. If the U.S. EPA figure for leakage is used, CNG and LNG lose five percentage points of CO_2 reductions, becoming 26 percent and 10 percent lower in carbon intensity than diesel. It should be noted, however, that a number of studies are currently being conducted on the leakage rates of methane throughout the natural gas production, transportation, distribution, and end-use value chain. Preliminary indications are that, although there are some outliers, the majority of gas producers follow practices that dramatically reduce the release of methane. This may lead U.S. EPA to reduce its estimates even lower.

Note that this report assumes a 20 percent GHG reduction from switching to natural gas. This also accounts for an estimated 15 percent fuel economy penalty for using natural gas in traditionally diesel applications. Applying the EPA leakage rate of 1.5 percent would reduce CNG benefits to 16 percent.

[6] The Clean Air Scientific Advisory Committee (CASAC) was tentatively scheduled to meet in July 2013 to review the Health Risk and Exposure Assessment and the Policy Assessment. This meeting was delayed until March 25 – 27, 2014 in order for EPA to have sufficient time to prepare second drafts of the Health and Welfare Risk and Exposure Assessment and the Policy Assessment for CASAC and public review. See memo from Lydia N, Wegman, Director, Health and Environmental Impacts Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, "Schedule for CASAC Review of the 2nd External Drafts of EPA's Health and Welfare Risk and Exposure Assessment and the Policy Assessment Review of the Ozone National Ambient Air Quality Standards," June 19, 2013.
[7] See Jason Plautz, "Science review prompts concerns about another delay for ozone standard," Greenwire, June 21, 2013.

extent required to meet federal, state, and local environmental obligations in the legally mandated time frames.

The enormity of the task to meet the ozone NAAQS is further illustrated in Figure 3. The blue line and the light green line project the "Current Path" for the level and pace of NOx emission reductions that are currently anticipated under the respective SoCAB and San Joaquin Valley AQMPs. It is important to focus on these two particular air sheds because they are the only two "extreme" ozone non-attainment areas in the nation. The large dots represent the maximum daily NOx emissions in tons per day that air quality planners project the two air sheds can "carry" to reach attainment of targeted health-based air quality standards. The red dot is the carrying capacity for the San Joaquin Valley in 2023, while the two dark dots are the projected carrying capacities for the SoCAB in both 2023 and 2032. The solid red line entitled "Path to Attainment" represents the rate of NOx reductions needed to meet the carry capacity goals and achieve the various NAAQS targets in 2023 and 2032. The light blue-shaded area represents the deficit that currently exists between what is planned and what is needed for attainment. It is worth noting that the "Current Path" includes substantial assumptions for ZEV deployment.

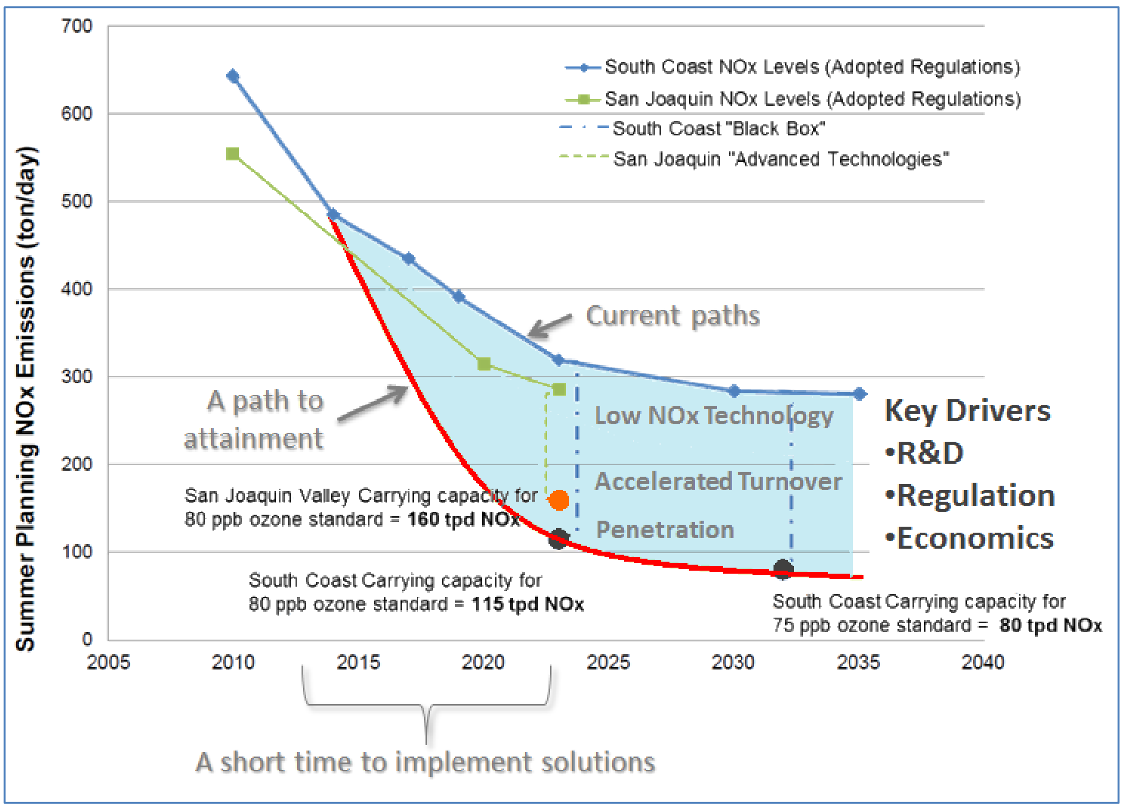

Figure 3 – California's two worst non-attainment areas need rapid, dramatic NOx reductions sooner

Figure 3 illustrates the dilemma facing California, as well as the tenets of the strategy that could greatly help meet its ambitious air quality goals. Much greater NOx emission reductions are needed than are currently planned, and these reductions must take place in the near term to maximize chances of meeting 2023 and 2032 NAAQS attainment deadlines for ozone. Both the San Joaquin Valley and the SoCAB will require rapid development and implementation of major new NOx reduction measures to achieve ozone attainment goals. To complement rapid technological development, a successful strategy must include rapid development of ultra-low-NOx technology (particularly in the mobile sector), continued fleet modernization to accelerate older vehicle turnover, and the provision of incentives to support commercialization and market penetration of the cleanest technologies.

GHG Reduction Policies Also Benefit Air Quality, but Too Slowly

As noted, the tremendous challenge to achieving ozone attainment in the SoCAB and San Joaquin Valley addresses only part of California's air pollution story. The state is also in the process of updating and implementing a far-reaching climate protection plan that seeks to greatly reduce GHG emissions. As elements of a broad strategy to reduce emissions, numerous measures are being adopted to improve energy efficiency, reduce the use of carbon-intense fuels, de-carbonize electricity production and increase vehicle fuel economy. While focused on reducing GHG emissions, these efforts should yield significant NOx emission reductions that have beneficial results for air quality.

Unfortunately, such reductions from the state's climate protection policies will accrue too gradually to ensure compliance with legally required deadlines for attaining the ozone NAAQS. Figure 4, based on the 2012 Vision for Clean Air document, illustrates that NOx reductions from implementation of AB 32 will be realized at least a decade too late to meet the state's legal requirements. Moreover, air quality officials are obligated to provide the state's residents with healthful air quality *as rapidly as possible*. Figure 4 helps to clarify how California's current Vision to reduce GHG emissions do not significantly accelerate achievement of its air quality goals. As currently crafted, the state's climate protection program will not provide timely support for California's smog reduction efforts.

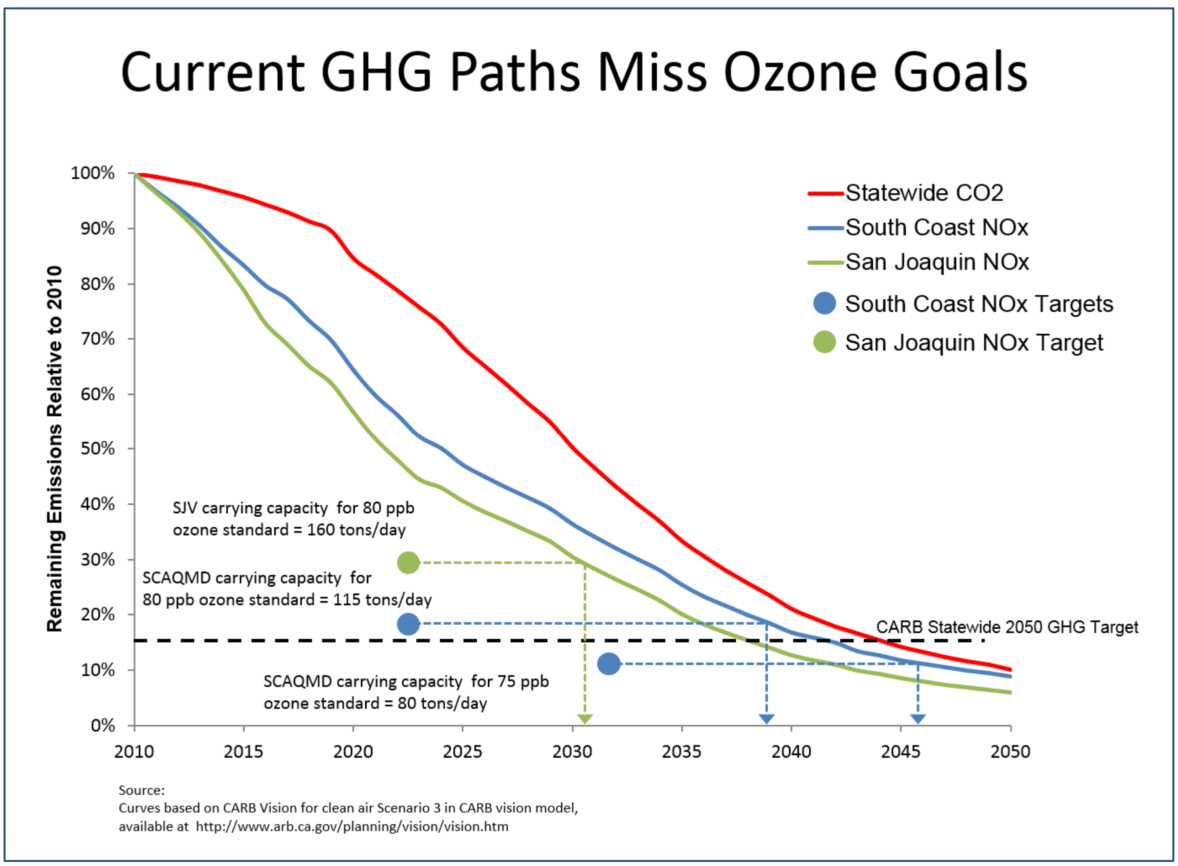

Figure 4 – The State's Climate Protection Strategies do not help meet NAAQS Standards

Climate Protection Necessitates Accelerated CO_2, Black Carbon Reduction Strategies

Carbon dioxide (CO_2) is the primary anthropogenic GHG, and the transportation sector is California's largest source of such emissions. CO_2 remains in the atmosphere for a very long time, and adds to the heat-trapping characteristics of the atmosphere for more than 100 years after it is first emitted. Because of this long atmospheric life, near term reductions in CO_2 will yield important long-term dividends. The sooner we can reduce the carbon footprint of the state, the better California can contribute to the mitigation of global climate change. This will also help accelerate achievement of the ozone NAAQS. Thus, for the state's 2050 goals to be achieved, greater emission reductions are needed for both criteria pollutants and GHGs, and these need to occur more expeditiously than current plans call for. We must rapidly reduce emissions of CO_2 and other climate-altering gases; this will allow the climate to stabilize and normalize, as already-emitted GHGs gradually dissipate in the atmosphere. We must also greatly accelerate emission reductions of NOx to meet ozone NAAQS and restore healthful air quality. And, as described below, NOx and GHG emission reductions in California's two worst non-attainment areas (the SoCAB and the San Joaquin Valley) will need to come from mobile sources, with a major focus on reducing emissions from the heavy-duty vehicle sector.

Equally as important is the impact that reducing emissions of black carbon can have on providing immediate cooling effects. Black carbon, essentially the soot that is produced by burning diesel, coal and wood, is now believed to be the second largest man-made contributor to climate change. This ubiquitous pollutant accelerates warming in multiple ways, primarily by settling into snow and ice packs where the black soot absorbs heat, reduces the reflectivity of the frozen surfaces, and accelerates melting. The authors of a landmark study released in early 2013 suggest that "black carbon emission reductions targeting diesel engines… would have an immediate cooling impact."[8] According to EPA, utilizing natural gas as a fuel in heavy duty engines can provide substantial black carbon reductions.[9]

Mobile Sources are the Problem, Especially in the Diesel-Fueled Heavy-Duty Sector

Air quality regulators have known since the early 1950s that the primary source of smog in California's non-attainment areas is mobile sources. More than 90 percent of the NOx inventory in Southern California comes from internal combustion engines that power motor vehicles, ocean-going vessels, and aircraft. As noted in the draft *Vision for Clean Air* document, 90 percent of the NOx reductions needed by 2032 to meet the 75 ppb ozone NAAQS will need to come from mobile sources. Motor vehicles are also the major source of ozone-precursor emissions in the San Joaquin Valley, although not to the levels seen in the SoCAB.

Although LDVs represent two-thirds of the region's on-road fuel consumption they produce only 20 percent of the region's NOx, while diesel fueled heavy duty on and off road technologies produce 71 percent of the region's NOx. This is because policy makers and auto manufacturers have been very successful over the decades in decreasing emissions from gasoline-fueled engines, while simultaneously improving the average LDV's fuel economy. This has been done in tandem with efforts by the petroleum industry to improve the quality and characteristics of gasoline to reduce emissions of volatile organic compounds, and enable the use of advanced emissions control equipment. The result is that today's modern LDVs emit very low levels of NOx and other criteria pollutants. However, LDVs continue to be a significant part of the GHG challenge for California.

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[8] See T.C. Bond, S.J. Doherty, D.W. Fahey, et al, "Bounding the role of carbon in the climate system: A scientific assessment, Journal of Geophysical Research: Atmospheres, Vol 118, Issue 11, pp 5380-5552, Article first published online on June 6, 2013.
[9] U.S. EPA, "Report to Congress on Black Carbon," Chapter 8: Mitigation Approaches for Mobile Sources, page 89, http://www.epa.gov/blackcarbon/2012report/Chapter8.pdf.

Still, as Figure 5 illustrates, on- and off-road[10] vehicles together comprise 92 percent of the NOx inventory in Southern California; 54 percent of the total comes from on-road vehicles.[11] By contrast, point and area sources contribute only nine percent of the region's NOx emissions, because California has been so successful at reducing stationary source emissions. Without dramatic new reductions in NOx emissions from the transportation sector, Southern California has little chance of achieving health-based NAAQS in the prescribed timeframes.

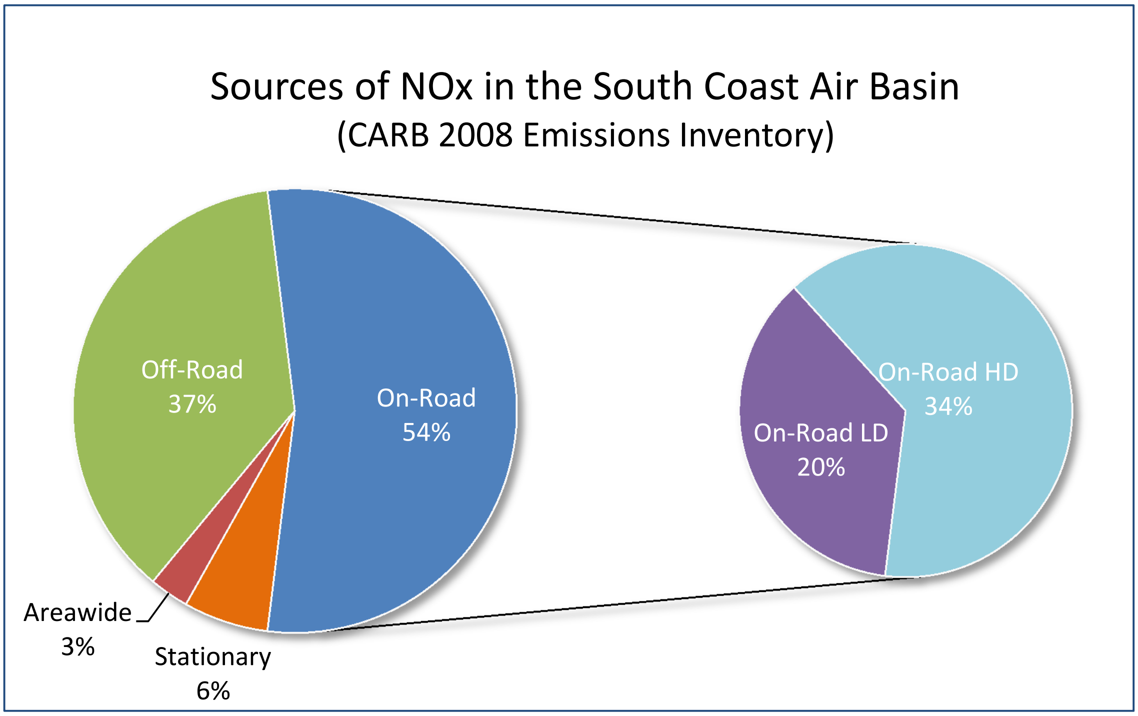

Figure 5 – Mobile sources are the largest NOx source in SoCAB, and heavy-duty vehicles are two-thirds of the on-road mobile

While it is true that air quality regulators at the state and federal level have made extraordinary progress controlling auto emissions, they have made less progress in controlling emissions from heavy-duty internal combustion engines fueled by diesel. The heavy-duty engines that power trucks and buses have not been subjected to the same level of regulation, over as long of a duration, as LDVs. Whereas regulations to limit emissions from automobiles were first introduced in the 1965 Motor Vehicle Air Pollution Control Act,[12] and later strengthened substantially in the Clean Air Act Amendments of 1970

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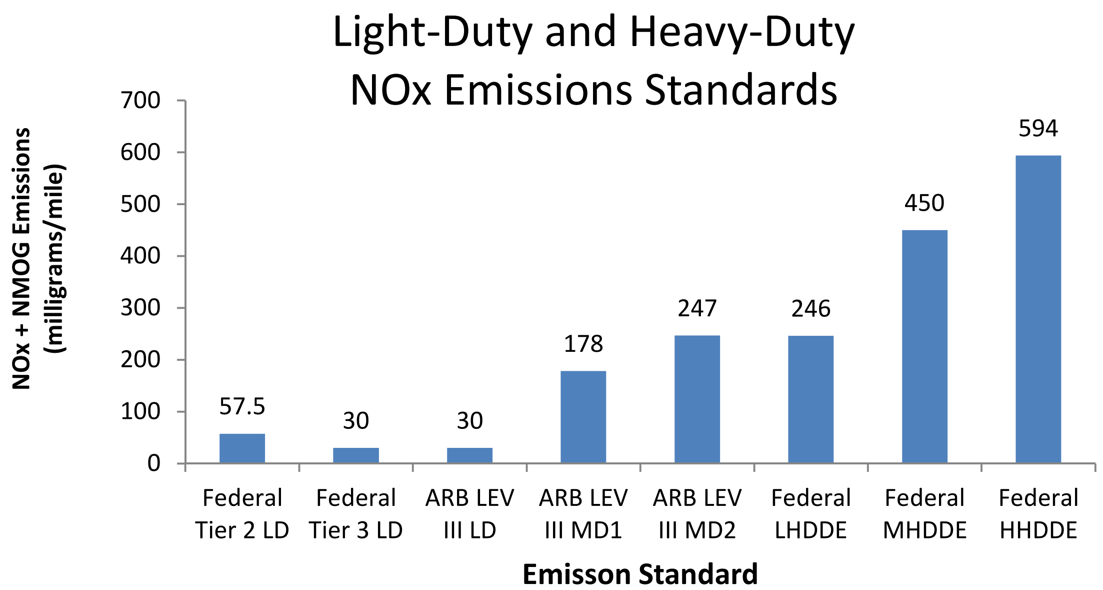
[10] Off-road sources include a wide range of equipment types including ships, locomotives, cargo handling equipment, construction equipment, and agricultural equipment. Examples of how on-road pathway technologies can be applied to off-road sources are provided in Appendix B.

[11] See ARB's 2008 NOx inventory data for the SoCAB.

[12] The United States Congress passed the Motor Vehicle Air Pollution Control Act in 1965, allowing the Secretary of Health, Education, and Welfare to establish the first federally mandated emission standards on light-duty vehicles. These new standards came into effect with all 1968 models, and called for reductions of several 1963-base emissions. The Act called for a 72 percent reduction of hydrocarbons, 56 percent reduction of carbon monoxide, and a 100 percent reduction of crankcase hydrocarbons. It established the National Air Pollution Control Administration (NAPCA), which became responsible for future pollution control efforts. The Secretaries modeled the new national standards after Californian standards, which came into effect in 1966. In addition to establishing national standards, the Act also initiated the coordination of pollution control between the United States, Canada, and Mexico in an effort to decrease overall emissions. Research into vehicle emissions of sulfur dioxide was carried out in an effort to achieve emission reductions while keeping automobile prices low. The Motor Vehicle Air Pollution Control Act of 1965 would later be amended with the Clean Air Act of 1970.

and 1990, significant regulation of heavy-duty engines did not really begin in earnest until the mid-1990s. Among the most significant moves to clean up diesel engines occurred in 1997, when new rules and a settlement agreement with heavy-duty engine manufacturers led to current emission standards. Hence, with nearly a 30-year head start, emissions from LDVs have been reduced much more significantly than emissions from heavy-duty engines, including high-horsepower technologies used in large off-road vehicles. This discrepancy is highlighted in Figure 6, which shows the contrast in current emissions standards for non-methane organic gases (NMOG) and NOx among light-, medium-, and heavy-duty vehicles. Today's LDVs emit one twentieth of the pollution per mile than today's HDVs.



Heavy-duty engine emissions rates estimated based on conversion factors provided by the U.S. EPA to estimate average energy per mile (bhp-hr/mile).

Figure 6 – Heavy-duty vehicles are nearly 1900 percent dirtier on a pollution per mile basis than LDVs.

The slower pace of clean up in HDVs is reflected in their growing contribution to the smog problem in California. While recent progress has been significant, diesel-fueled on-road HDVs remain the largest sources of NOx in California's key ozone non-attainment areas. Figure 7 helps to illustrate the disproportionally large contributions of HDVs to the ozone problem in both the San Joaquin Valley and the SoCAB; NOx inventories from both non-attainment regions are dominated by diesel-fueled heavy-duty trucks. Off-road diesel-fueled vehicles and equipment that use very similar engines, such as cargo-handling equipment, locomotives, and ocean-going vessels, are also major sources of NOx for both the SoCAB and the San Joaquin Valley. Notably, LDVs are only the 10th largest source of NOx for the SoCAB, and they are not even among the top 15 NOx sources for the San Joaquin Valley.

Moreover, what Figure 7 conveys is that most of NOx emission reductions beyond those already identified as necessary to meet the 2023 and 2032 ozone NAAQS will need to come from heavy-duty engines, the vast majority of which are fueled by diesel.

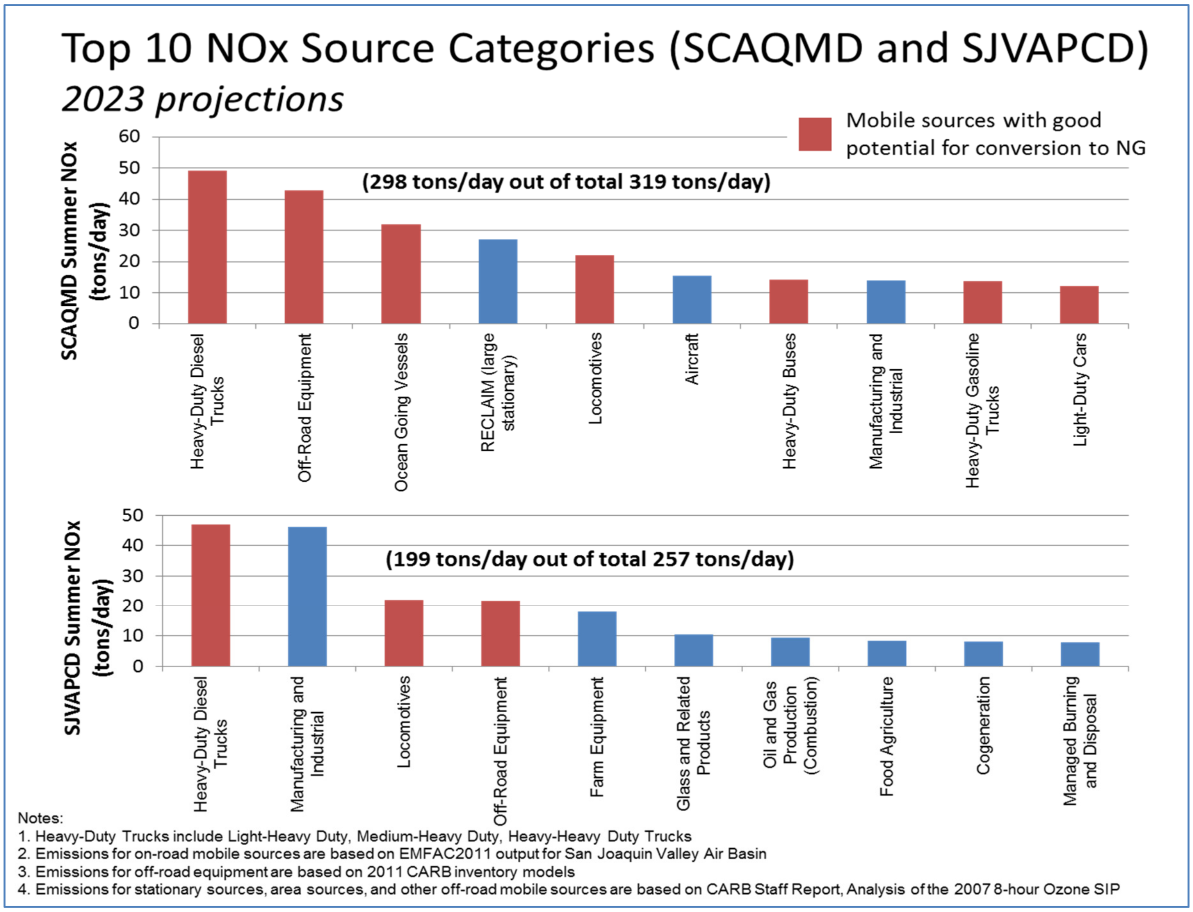


Figure 7 – Diesel-fueled technologies are the largest source of NOx

To summarize, existing NOx-control measures fall short of the mark to meet health-based air quality standards for ground-level ozone. By the two deadlines for achievement of the ozone NAAQS—the first of which is fewer than 10 years away—existing regulations are clearly inadequate for the task, leaving the state 62 percent short in 2023 and 75 percent short in 2032. The state's GHG reduction plans will not reduce NOx emissions in time to help. To achieve NAAQS attainment for ozone, California has to dramatically expand and accelerate its efforts to achieve greater NOx emission reductions; without such progress, at least another generation of Californians will continue to breathe unhealthful air. The necessary reductions needed to achieve the 2023 and 2032 NOx NAAQS requirements must be derived from the state's vast mobile sector, primarily from diesel-fueled heavy-duty on- and off-road vehicles and high-horsepower equipment.

Battery Electric and Fuel Cell Vehicles: Crucial Technology, Insufficient Progress

Since the introduction of the Low Emission Vehicle (LEV) program in 1990, California air quality officials have pursued a dual strategy to reduce emissions from the light- and medium-duty vehicle sectors (primarily passenger cars). The primary element of the program has been the establishment of vehicle emission performance standards that have tightened over time. This approach, which was soon emulated by the U.S. EPA, sets a benchmark for the maximum mass of pollution that can be emitted by a light- or medium-duty vehicle without proscribing to the manufacturer how to achieve this requirement. Performance standards have been an extremely successful tactic in the fight against air pollution, and are responsible for most of the improvements in air quality that we enjoy today.

An additional aspect of the LEV program is the Zero Emission Vehicle (ZEV) mandate, which is intended to accelerate the development and adoption of electric drive vehicles with zero emissions at the tailpipe. Stimulating the development of ZEVs has been a dominant focus of the ARB for nearly 25 years. It is based on the premise that wide-scale deployment of vehicles with zero direct (tailpipe or evaporative) emissions is the only way to reduce pollution fast and far enough to meet the ozone NAAQS.[13] A key assumption of this approach is that vehicles powered by internal combustion engines are unable to achieve emission rates near-zero, or equivalent to it.[14] This perspective has also impacted climate protection planning, as is evidenced by projections for increased penetration of ZEV technologies, particularly in the HDV sector, in the draft *Vision for Clean Air* document.

Effectively, the net result of ARB's ZEV regulation is that vehicle manufacturers doing business in California are forced to research, develop, demonstrate, and market battery electric vehicles (BEVs) and fuel cell vehicles (FCVs). This has presented formidable challenges for manufacturers, particularly in the heavy-duty sector where it can be more difficult to incorporate electric or fuel cell propulsion technology. To date, BEVs and FCVs that have been commercialized by motor vehicle manufacturers have been relegated to small specialty niches of the LDV marketplace, as customers have not been quick to adopt products developed as a response to technology-forcing mandates.

Although ZEV requirements have been a cornerstone of California's air quality policy for over two decades, regulations forcing the development of BEV and FCV technologies have been slow to deliver the needed emissions reductions. To date, the ZEV mandate has yet to provide cost-effective, affordable vehicles in numbers and at a pace needed to achieve the state's air quality and climate protection objectives. The first ZEV requirements, adopted 23 years ago and designed to make light-duty ZEVs available to consumers beginning in 1998, did not produce market-competitive BEVs until December 2011[15]. The major automakers are still reluctant to manufacture large numbers of BEVs and

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[13] One of the biggest projected benefits of BEVs, and a factor in why air quality planners rely on them as an emission reduction strategy, is that they remain "zero-emissions" for their useful lives (tail pipe and evaporative emissions). Unlike vehicles powered by internal combustion engines, BEVs can never directly emit criteria pollutants, even as they get older and mechanically deteriorate. The "tailpipe" emissions in the tenth year of operations of a BEV are the same (zero) as the day the vehicle was purchased. Internal combustion engines, no matter how clean when new, will emit higher levels of pollutants over time as parts age and emission control equipment weakens. On the other hand, batteries do deteriorate, and the amount of energy that can be stored in a battery diminishes over time, thereby impacting its performance. Still, from a regulator's point of view, it will always be better to control emissions from a few stationary sources (power plants) than from millions of motor vehicles with combustion engines.

[14] Zero-emission equivalency, for an internal combustion engine in a motor vehicle of any size, is when the emissions associated with the combined sources of electrical generation that deliver to California are the same, on a miles traveled or unit of energy consumed basis, as those being emitted from the tailpipe of a vehicle powered, at least in part (in the case of a hybrid) by an internal combustion engine.

[15] Until the introduction of the Tesla in the U.S. in June 2012, the only all-electric sedan sold in the U.S. whose sales had surpassed a couple hundred vehicles was the Nissan Leaf. In 2013, the Leaf sold 22,610 units in the entire U.S., up from only 9,819 units in 2012. The Tesla Model S sold approximately 18,800 units in the U.S. in 2013. The base price for the Tesla Model S, however, equipped with a 60kWhr battery pack (~200 mile range), starts at $69,900 after the $7,500 federal tax credit, while the base price of the Nissan Leaf (24 kWh battery pack / 75 mile range) is $35,430. See Sebastian Blanco, "Nissan Leaf ends 2013 with best sales month ever, but can't catch Chevy Volt", autobloggreen, Jan. 3, 2014 (http://green.autoblog.com/2014/01/03/nissan-leaf-ends-2013-best-sales-month-ever-chevy-volt/); David Shepardson, "2013 electric vehicle sales jump 84%", The Detroit News, Jan. 4, 2014 (http://www.detroitnews.com/article/20140103/AUTO01/301030070/1121/AUTO01/EVs-sales-jump-in-2013); EPA rating for 85 kWh Tesla Model S: 89 MPGe, 265-mile range", Green Car Congress, June 21, 2012 (http://www.greencarcongress.com/2012/06/models-20120621.html); Michelle Krebs, "Will Higher Gas Prices Boost Hybrid, EV

FCVs, preferring to focus their efforts on hybrid-electric vehicles (HEVs) or plug-in hybrids. These vehicles offer many of the benefits of electric drive while continuing to employ internal combustion engines for greater vehicle range, performance and utility. Fifteen years after major auto manufacturers were to begin to sell light-duty ZEVs, the initial ZEV penetration goals have yet to be realized.[16]

Analogous, albeit less intense, efforts have been made to compel ZEV purchases in the HDV sector. The Zero-Emission Bus purchase mandate (ZBus), passed in 2000 for transit agencies with 200 buses or more, has yet to be enforced, eight years after the original deadline. The battery and fuel cell technologies that have been developed to meet ZBus requirements have not progressed as quickly as projected. Prototype vehicles continue to cost twice as much and stay on the road one-half of the time before requiring service, relative to the natural gas buses that now dominate transit service in Southern California.[17] This has resulted in several delays in the implementation of the ZBus purchase requirement. As of this writing, the fate of the requirement is unknown, as the deadlines have been suspended and the rule is under review by the ARB.

If the difficulties that manufacturers have experienced in meeting ZEV mandates for transit buses and LDVs are any indication, to meet ozone-reduction and climate change goals air quality planners will need to expand the options for reducing the environmental footprint of the heavy-duty sector. Using the analogue of ZEV development in the light-duty sector, air quality planners should not put all their eggs in the zero tailpipe emission basket. Assuming that regulators established ZEV technology-forcing requirements on the entire heavy-duty sector in 2014 and that the past is prologue, we would not expect commercially available heavy-duty BEVs or FCVs until the mid- to late 2030s. If current patterns in the light-duty market hold, ZEV sales volumes in the heavy-duty market would likely be too low to make a significant impact. Yet, as clearly demonstrated above, HDVs need to get much cleaner much faster to meet air quality and climate-protection targets.

The benefits of ZEV mandates, however, can also be measured by the advancements these policies have compelled in conventional transportation technology. ZEV requirements have been successful in stimulating innovation, resulting in lower-emitting internal combustion engine and hybrid-electric drive technologies in the light-duty sector. Emission control devices, improved thermodynamics, electronic controls, and many other advances have resulted in vehicles that emit a fraction of the pollutants that their predecessors did 40 years ago. Wide-scale deployment of such technologies remains the key weapon in the arsenal of air quality planners to simultaneously address California's goals for air quality and climate change mitigation. Overall, the performance-based approach of the LEV program has been tremendously successful in driving the technology developments needed to reduce emissions. By contrast, the technology-proscriptive ZEV mandate has not yet resulted in significant emissions reductions.

Sales?", Edmunds.com, Feb. 28, 2012, (http://www.edmunds.com/industry-center/analysis/will-higher-gas-prices-boost-hybrid-ev-sales.html).

[16] Sales of BEVs have fallen far short of the 7.5% of California LDV sales mandated by the original ZEV requirement. The Electric Drive Transportation Association reports that U.S. BEV sales are 47,694 units, or 0.3% of the 15,531,309 vehicles sold in 2013 in the U.S. This does, however, represent a dramatic increase of 235% above U.S. BEV sales of 14,251 units for all of 2012. See http://www.electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952. It should also be noted that both Honda and Toyota announced in 2013 that they would provide fuel cell cars for sale in 2015, and that the California Energy Commission released a Request for Proposal in December 2013 to provide $20 million to fund the development of hydrogen fueling stations throughout California in 2014.

[17] Gladstein, Neandross and Associates, "Equivalent Strategies for the ARB Zero-Emission Bus Regulation," April 2012.

When faced with slower-than-expected technology development and product commercialization, ARB has provided manufacturers with flexibility in how they meet emission reduction goals. This flexibility took the form of performance-based standards, enabling auto manufacturers to introduce new technologies that advanced the state-of-the-art and dramatically reduced the environmental footprint of cars and light trucks equipped with internal combustion engines. The ARB recognized this progress, and altered the LEV program to allow for technology advancements with very low-emitting LDVs that did not meet the ZEV definition. This gave rise to LDV categories such as the Partial Zero-Emission Vehicle (PZEV) which have received much greater market acceptance than ZEVs.[18]

ARB's modifications to the ZEV requirement have been necessary because development of cost-effective, commercially viable light-duty BEVs and FCVs continue to be behind schedule. Manufacturers of heavy-duty engines and vehicles face even greater challenges to successfully integrate battery and fuel cell technologies into their products. Since major reductions in smog-forming pollutants and greenhouse gases are needed immediately, ARB should provide HDV manufacturers with flexibility to comply with emission reduction targets. Augmenting ZEV requirements in the heavy-duty sector with options based on emission performance standards will actually increase the likelihood that California will meet its air quality and climate protection objectives. As will be explored in the pages that follow, non-ZEV technologies are emerging that can provide these much needed emission reductions.

A Solution to California's Need: Near-Zero-Emission, Natural Gas-Fueled Heavy-Duty Vehicles

Manufacturers have responded to performance-based regulations with innovation and creativity. In response to tightening emissions standards, as well as consumer demand for higher vehicle fuel economy, motor vehicle and engine makers have developed key technologies that utilize advanced electric propulsion systems, highly effective emission control devices and cleaner alternative fuels like natural gas. As a cost-effective and commercially viable approach to very low emissions, manufacturers have greatly improved internal combustion engine technologies, and are now achieving emissions levels believed to be impossible just a decade ago. More importantly, technology is now in development to reduce emissions much, much further. As discussed below, heavy-duty NGVs offer a pragmatic and promising pathway to near zero-emissions. Advanced NGVs are on a trajectory to provide a viable alternative that can be implemented in the near term to meet the emission reduction levels badly needed by the state.

Heavy-duty natural gas vehicles offer a pragmatic and promising pathway to near zero-emissions.

ARB and other air quality regulators have monitored these developments in the motor vehicle industry closely. The slow pace of ZEV technology development is troublesome, given the need for the accelerated reductions in criteria pollutant and GHG emissions. However, when faced with an emission standard that must be met to sell their products, vehicle and engine manufacturers have proven to be resilient and responsive. Simply put, manufacturers appear to react best to the establishment of performance standards, rather than being told what products to make or how to make them. This enables engineering of the best solutions to meet such standards. It also allows manufacturers to account for factors that most impact a given vehicle platform's commercial viability, including cost (both

[18] The total sales of BEVs in 2013 in the U.S. was 47,694 units, or 0.3% of total U.S. LDV sales, while the sales of hybrid electric and plug-in hybrid electric vehicles that same year were 544,538 units. IBID, Electric Drive Transportation Association.

purchase and operating), maintenance, availability of fueling infrastructure, performance, and residual value. The development of a more performance-based approach is particularly valuable in the heavy-duty sector, as ZEV technologies that are only beginning to scratch the light-duty market will be much more difficult to apply to diesel-fueled trucks, tractors, and other work-horse equipment.

Based on the lessons of the LDV sector, the most technically sound and cost-effective approach for HDVs is for California to establish a new "near-zero-emission" and/or a "power plant equivalent" emission standard. Such a standard would be the functional equivalent to ARB's current ZEV standard for an HDV (no direct vehicle emissions), but would take into account the emission of criteria pollutants associated with the generation of electricity from a new generation, natural gas-fueled power plant necessary to recharge a comparable heavy-duty BEV. The proposed emission standard should also take into account full fuel-cycle GHG emissions of various HDV fuels and technologies. Such a new standard would enable manufacturers to pursue a greater menu of fuel and technology pathways, e.g., natural gas or hydrogen internal combustion engines, as long as they achieve ZEV equivalency. It would provide greater long-term market choices for fleet owners. Most importantly, it would help state and local air quality regulators to accelerate progress towards meeting air quality goals for ozone NAAQS attainment and mitigation of climate change.

Where do heavy-duty NGVs stand in this push for near-zero and/or power plant equivalent emissions? In contrast to BEVs and FCVs, heavy-duty NGVs are commercially and technologically mature vehicle platforms. Today's compressed natural gas (CNG) and liquefied natural gas (LNG) fueled trucks and buses are equipped with engines that are already the benchmarks for low-NOx and GHG emissions. The average heavy-duty natural gas engine today is 50 percent cleaner than its diesel counterpart on NOx emissions, and new generations are even cleaner. Natural gas engine developers project that, with the application and integration of available technology, natural gas engines will steadily evolve toward power plant emission-equivalency. As natural gas engines continue to get cleaner, it is imperative for California also to evolve its air quality and climate protection policies to encourage these and other promising ultra-low emission heavy-duty engine technologies.

With the complement of appropriate incentives, public policies, and investments, a clear path can be envisioned for heavy-duty NGVs to achieve power plant emissions equivalency.

Advances in ultra-low-NOx heavy-duty NGVs continue at a compelling pace. With the complement of appropriate incentives, public policies, and investments, a clear path can be envisioned for heavy-duty NGVs to achieve power plant emissions-equivalency. With steady application of known and proven engine and control technologies, it is widely believed by engine manufacturers and other researchers that heavy-duty natural gas engines can meet a NOx emission level of 0.05 g/bhp-hr, which is 75 percent below today's standard. This, industry observers believe, can be achieved in the near term, and certainly prior to the 2023 deadline to achieve the 80 ppb ozone NAAQS. In the longer term, these same observers believe that a 90 percent reduction in NOx emissions from 2010 standards is achievable, which will enable heavy-duty NGVs to emit no more NOx from the tailpipe than would be emitted by power plants providing electricity to equivalent heavy-duty BEVs.

This presents a very important point: *today's very low-emitting natural gas HDVs are more than just "bridge technologies"* to the future of California's near-zero-emission heavy-duty transportation sector. These technologies can and should be a **foundation** of that future. Thousands of heavy-duty NGVs are on California's roadways logging millions of miles with very low emissions, even as the technology steadily evolves toward power plant emissions-equivalency. If the near zero technologies outlined in this paper are developed in the time frame described herein, they will dramatically enhance the state's ability to meet air quality standards and climate protection objectives. Coupled with other strategies for light duty vehicles, area sources, and the stationary sector, increased use of natural gas in the heavy-duty sector is a fast, cost-effective, and deployable fuel and technology combination.

California cannot and need not wait for the development of as-yet-unproven all-electric technologies. The state can accelerate reductions of NOx and GHGs—as well as various other critical state objectives—through the development and promotion of HDVs powered by near-zero-emission natural gas engines. In the pages that follow, various technologies are explored that can enable ongoing development and commercialization of ultra-low heavy-duty natural gas-fueled vehicles.

Today's very low-emitting natural gas HDVs are more than just "bridge technologies" to the future of California's near-zero-emission heavy-duty transportation sector. These technologies can and should be a foundation of that future.

Technology Pathways to Near-Zero & Power Plant Emission-Equivalent Natural Gas Heavy-Duty Vehicles

Introduction

Today's commercially available natural gas engines already emit NOx levels well below the current (2010) federal standard of 0.2 g/bhp-hr. The most popular natural gas engine, the Cummins ISL G, tests at 0.1 g/bhp-hr, 50 percent below the current heavy-duty engine standard. This workhorse natural gas engine also produces half as much particulate matter as the 2010 standard. This is due to the fact that natural gas is inherently cleaner than fuels that are refined from petroleum. The explanation is in the simplicity of the methane molecule, the largest single component of natural gas. As shown in Figure 8, methane is a single carbon molecule, compared to much more complex, carbon-intense gasoline and diesel molecules. Figure 8 below helps to illustrate why natural gas is such a clean-burning fuel.

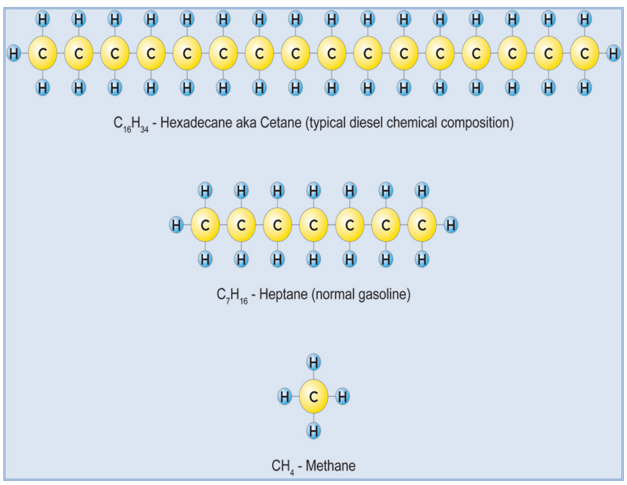

Figure 8 – The clean simplicity of the Methane molecule

A variety of near-term technological developments and engineering techniques are rapidly progressing that show strong promise for heavy-duty NGV engines to emit less than 0.05 g/bhp-hr. Over a longer horizon, heavy-duty natural gas engines will be available for certification at a "super-low" NOx level of 0.02 g/bhp-hr. Heavy-duty natural gas engines are already well underway for to achieve a 90 percent NOx reduction from the existing heavy-duty engine standard, while also becoming increasingly more efficient to reduce GHG emissions. Major public-private initiatives have been launched to drive this progress, funded by agencies such as the California Energy Commission (CEC), the U.S. Department of Energy (DOE), the South Coast Air Quality Management District, and others.

Five Technology Pathways

There are five overarching technology pathways for heavy-duty NGVs to meet progressively lower NOx and GHG emissions:

1) Advanced Engines;
2) Advanced After Treatment;
3) Hybridization;
4) Vehicle Integration; and
5) Fuels, Storage, and Infrastructure.

Each technology pathway includes various techniques and technologies that incrementally advance progress toward near-zero-emissions, which is illustrated in Figure 9. In the 2015 to 2020 time frame, it is expected that combinations of technologies that emerge from these pathways will enable original equipment manufacturers (OEMs) to build and sell heavy-duty NGVs that have emissions profiles equivalent to BEVs for full fuel-cycle criteria pollutant. In addition, increased fuel efficiency, integration

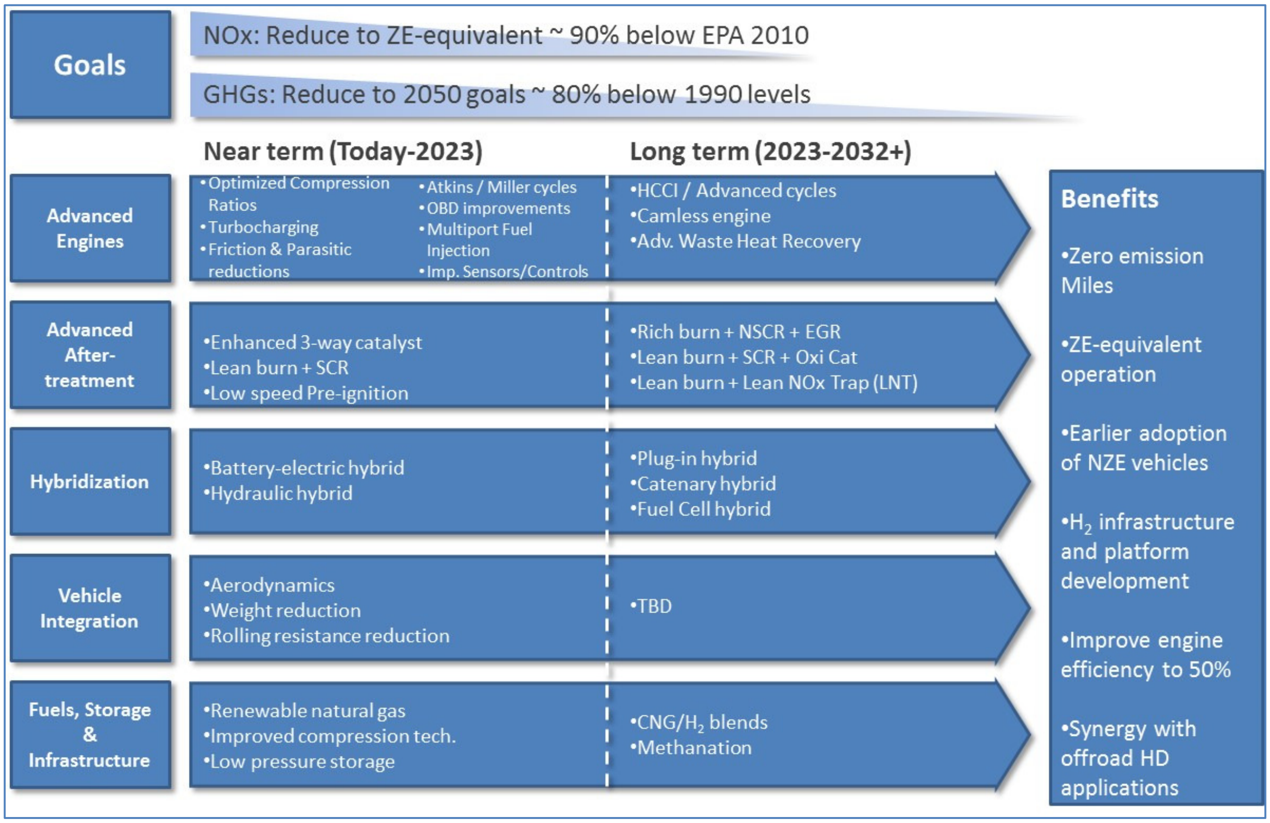

Figure 9 – Five technology paths for very-low-NOx and GHG emissions from heavy-duty natural gas engines

of biofuels and "hydrogenization"[19] strategies will yield GHG emissions on par with the 80 percent reduction below 1990 levels reductions sought by the state. These five pathways will push the next generation of natural gas heavy-duty engines to power plant emissions-equivalency for both criteria and GHG pollutants. This will be achieved through combinations of attributes; as Figure 9 summarizes, some of these combinations include barely detectible tailpipe emissions, the ability to operate in zero-emission mode for limited miles, and/or the achievement of very high systems efficiency.

As noted, various public-private partnerships are presently underway to direct and facilitate these important technological developments. These technology development programs seek to accelerate the application of existing technologies, as well as the development of new technologies, that will allow for the advancement of the five pathways described above. They combine public funding with private ingenuity to push the envelope, and to increase the likelihood that the technologies which are described in detail in this section will be commercialized in a timeframe necessary to bring needed products to market. For example, the California Hybrid, Efficient, and Advanced Truck Research Center (CalHEAT)[20] *Roadmap for Optimized Alternative Fuel Engines* defines three stages for optimizing heavy-duty natural gas engines over the next several decades. Each of these stages is described in Table 2 below.

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[19] This term refers to the process of enriching natural gas with hydrogen gas, thereby displacing a portion of the energy content that comes from methane with hydrogen. Coupled with other strategies, this reduces the carbon content of the fuel.

[20] CalHEAT refers to the California Hybrid, Efficient and Advanced Truck Research Center. Sponsored by the California Energy Commission, CalHEAT is a California-based resource for research, development, demonstration, and commercialization of advanced, efficient truck technologies and systems. See http://www.calstart.org/projects/CalHEAT.aspx.

Stage	General Focus and Approach	Specific Techniques / Technologies
1	Integrate current engine and fuel technologies to improve efficiency, torque, and NOx emissions	• Compression ignition using high pressure, direct injection (HPDI) and diesel pilot • Spark ignition using stoichiometric air fuel ratio (AFR), two-way catalyst, and cooled exhaust gas recirculation (EGR)
2	Reduce weight, improve efficiency, reduce costs	• Variable valve actuation with cylinder deactivation • More compact fuel storage tanks • Expansion of optimized engines into wider applications
3	Downsize engine, improve after treatment	• Improved turbocharging • Optimized exhaust heat recovery • Homogeneous Charge Compression Ignition (HCCI) • Cam-less engine • Improved methane catalysts

Table 2 – The staged approach in CalHEAT's roadmap for low-NOx, low-GHG alternative fuel engines

Heavy-Duty NGVs Can Achieve Power Plant NOx Equivalency and Ultra-Low GHG Emissions

In general, improving the environmental performance of today's diesel engines entails challenging tradeoffs between reducing tailpipe NOx emissions without negatively impacting fuel economy, i.e., increasing emissions of CO_2, the most important GHG. However, these two objectives need not be mutually exclusive. Heavy-duty natural gas engines require minimal emissions control after treatment; therefore, the resulting reduction in hardware additionally reduces vehicle complexity, weight, and life-cycle costs. Technologies that promote fuel efficiency such as drive-train hybridization are being coupled with natural gas engines to further reduce emissions of NOx and other criteria pollutants. Efficiency improvements, which are achieved by improved aerodynamics, lower tire rolling resistance, and weight reductions, will also translate into lower tailpipe-emissions, as well as reduced CO_2 emissions.[21]

Figure 10 displays the anticipated path for heavy-duty natural gas engines to achieve power plant NOx emissions-equivalency over the next 20 years.[22]
Figure 11 displays a similar projected path to achieve low GHG emissions over the same timeframe. The intervals showcased in these two figures focus on the results that are projected from the development and application of pathway technologies, with appropriate policy support, between today and the existing deadline for the 75 ppb ozone NAAQS (2023), as well as the projected deadline for a possible 65 ppb ozone NAAQS (2032). These two diagrams illustrate the strong technological and industrial synergy that exists for heavy-duty NGVs to reduce emissions of criteria pollutants while simultaneously achieving the dramatic improvements in fuel efficiency necessary to decrease climate impacts.

[21] National Highway Traffic Safety Administration, "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles" October 2010

[22] Powerplant equivalency refers to the smokestack emissions that would result from a contemporary natural-gas fired combined cycle baseload power plant generating electricity for a heavy-duty BEV of comparable size. It does not refer to the emissions associated with the average MW-hr consumed in California, as this includes zero emission nuclear, renewable and hydroelectric sources of power.

Applying the Five Strategies for NOx Reductions from Natural Gas

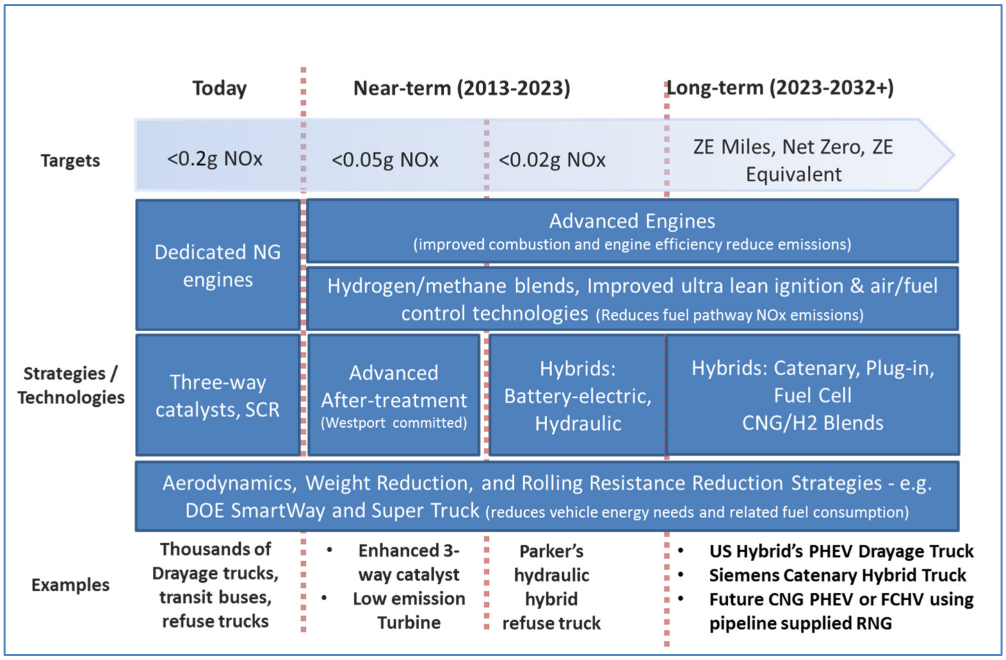

Figure 10 – Anticipated path for heavy-duty natural gas engines to achieve power plant equivalent NOx emissions

Applying the Five Strategies for GHG Reductions from Natural Gas

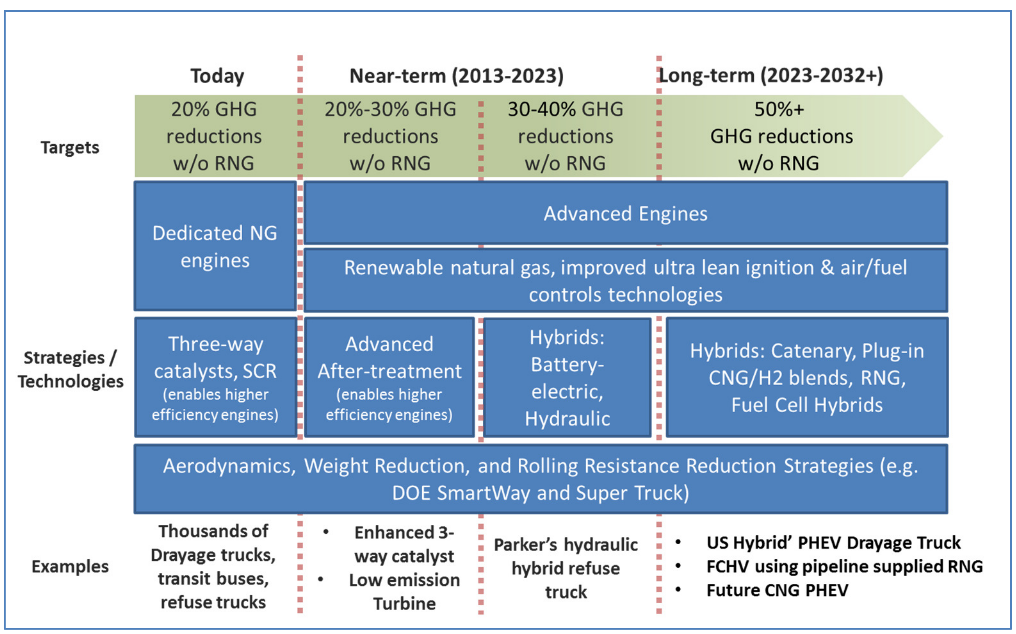

Figure 11 – Anticipated path for heavy-duty natural gas engines to achieve low GHG emissions (RNG: renewable natural gas)

Descriptions of Technology Pathways to Near-Zero-Emission and Power Plant Equivalent-Emissions Natural Gas HDVs

The following subsections provide brief overviews of how specific technologies and techniques are being applied to heavy-duty natural gas engines in order to achieve NOx emissions that are equivalent to ZEV levels on a full fuel cycle basis, while simultaneously providing low GHG emissions.

Advanced Engines

A variety of advanced technology heavy-duty natural gas engines are being developed to meet progressively lower criteria pollutant and GHG emissions. The goal of this engine development work is generally to provide enhanced combustion and/or higher systems efficiency. One focus of emerging engine technologies is to provide more finely controlled high-pressure fuel injection. According to the 2010 National Academy of Sciences (NAS) study[23] that assesses fuel economy technologies for heavy-duty vehicles, this will be "a key enabler for more fuel efficient combustion, and a cleaner, more consistent fuel burn." Current heavy-duty engine technology uses very high pressure (up to 240 bar) common rail injection systems with advanced nozzle designs. The NAS study indicates that potential future advancements will "continue to improve control, allow more accurate timing and metering of injection with combustion events, and further increase fuel injection pressure" by approximately 25 percent. In addition, next-generation systems "will also utilize increasingly sophisticated injection techniques" such as variable-spray nozzles, piezo-electric nozzles, and other technological improvements. All of these fuel injection enhancements can contribute to improved fuel efficiency and/or reduced emissions by providing better fuel atomization and more precise control of the engine's air-fuel ratio, across continually changing operational characteristics.

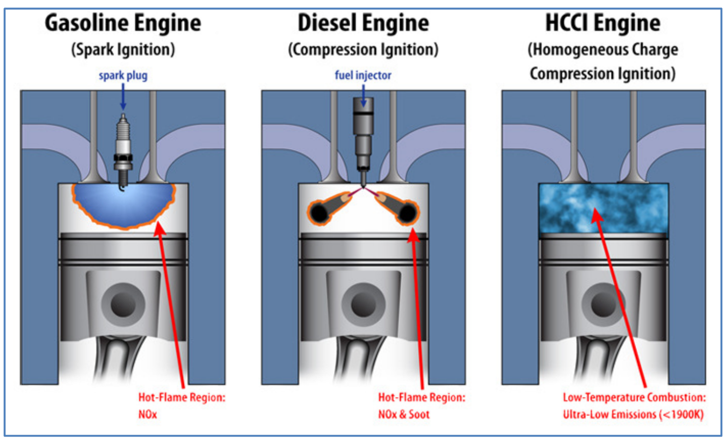

Figure 12 – Diagram of HCCI engine compared to conventional technology (Source: Lawrence Livermore National Laboratory)

New Engine Types and New or Enhanced Combustion Cycles

A variety of alternatives exist to the standard heavy-duty combustion cycles that are currently used in compression- and spark-ignition natural gas engines. The primary function of these alternative cycles is to achieve very low emissions, especially for NOx in heavy-duty diesel cycle engines. In addition, such alternative combustion cycles can simultaneously deliver higher efficiency than standard diesel combustion. Examples of these advanced combustion cycles include low-temperature combustion (LTC), homogeneous charge compression ignition (HCCI)[24], and premix charge compression ignition (PCCI).[25] According to a recent draft final report prepared for the California Energy Commission, natural

[23] National Academy of Sciences, Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles, National Academic Press, 2010.

[24] HCCI relies upon a very lean (high proportion of air to fuel) and well-mixed (homogeneous) air-fuel mixture (charge) that is compressed (compression) until it auto ignites (ignition). The resulting spontaneous burn produces a flameless energy release in a large zone almost simultaneously, very different than the spark/gasoline burn or the compression/diesel burn. See http://www.greencarcongress.com/2004/05/keep_an_eye_on_.html.

[25] NAS 2010

gas-fueled technologies that can achieve reduced NOx levels of 0.02g/bhp-hr include cam-less engines and HCCI.[26] HCCI can also produce good fuel consumption, although this presents control challenges across all engine loads and in transient operation.[27]

Improved Accessories, Sensors, and Controls

Accessories on HDVs, e.g., water pump, air compressor, power steering pump, etc., are traditionally driven by the vehicle's engine using a gear or belt mechanism. To reduce power demand, some of these accessories can be converted to electric power. Shifting these accessories to electricity reduces the amount of mechanical energy that is diverted from the engine, enabling that energy to be used for propulsion. Some accessories can also be better regulated so that their operation is restricted except when needed. Another way this can reduce power consumption is that accessories can be run at speeds independent of engine speed. Enhanced sensors and controls enable the utilization of electric-powered accessories in a way that can improve fuel economy.

As a package on a hybrid vehicle, the NAS study found that a three to five percent fuel consumption reduction is possible through the integration of improved accessories, sensors, and controls.[28] A 2009 TIAX report estimated a two to four percent fuel consumption improvement for accessory electrification, noting that the effect will be more pronounced in short-haul/urban applications, e.g. drayage, than in line-haul trucking applications.[29] Advanced sensors can also improve fuel efficiency. For example, real-time combustion control with start of combustion sensors can yield a fuel consumption reduction of one to four percent. Better use of calibration tools to improve control of EGR, injection rate shapes, multiple injection events, and increased injection pressure can yield reductions in fuel consumption of one to four percent.[30]

The 2010 National Academy of Science (NAS) study found that a three to five percent fuel consumption reduction is possible through the integration of improved accessories, sensors, and controls.

Waste Heat Recovery

Approximately 48 percent of the fuel energy consumed by typical diesel engines in Class 8 line-haul truck applications is lost and fails to perform useful work. The losses come from combinations of inefficiency in the vehicle drivetrain, rolling resistance, aerodynamic drag, and auxiliary loads. All totaled, engine heat accounts for 26 percent of the fuel consumed, and exhaust heat accounts for another 24 percent. Technologies and techniques exist or are emerging that can recapture this wasted heat and help reduce vehicle emissions as well as fuel consumption.

For example, "bottoming cycle" natural gas engines can be developed that use waste heat to produce additional work. In a bottoming cycle, the waste heat from the engine is used to power a generator that produces additional electricity or mechanical power for the vehicle. This uses "free" energy that is otherwise discarded by the primary engine. Two technologies being developed are thermoelectric converters—electronics that can convert heat directly to electricity—and Rankine cycle systems that

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[26] California Hybrid, Efficient and Advanced Truck Research Center, "CalHEAT Research and Market Transformation Roadmap for Medium- and Heavy-Duty Trucks," Draft Final Project Report for the California Energy Commission, February 2013
[27] CalHEAT 2013
[28] NAS 2010
[29] TIAX LLC, "Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and C02 Emissions, Final Report"; NESCAUF, ICCT, Southwest Research, and TIAX; October 2009
[30] NAS, 2010

operate on the same principal as steam power plants. Heat sources for a bottoming cycle include exhaust gas flow, EGR flow, charge air flow, and engine coolant. Bottoming cycles have been used for many years in stationary power plants. The challenges for vehicle applications include cost, weight, packaging, reliability, and performance.[31]

Advanced After Treatment

Technologies that remove pollutants from the exhaust "after" combustion are a key element in the strategy to reduce emissions of criteria pollutants from internal combustion engines. Since the introduction of the first catalytic converters in the mid-1970s, after treatment technologies have and continue to make great advancements. Nearly all motor vehicles today are equipped with some form of exhaust after treatment, particularly in the heavy-duty engine sector. For the most part, natural gas engines have been able to achieve lower emissions due to the cleaner characteristics of the fuel; however, as the after treatment technologies that were needed by diesel engines to meet the 2010 heavy-duty engine standards are applied to natural gas engines, even lower emissions can be achieved.

There are three primary kinds of exhaust after treatment relevant to this report. These are:

- Selective catalytic reduction (SCR)
- Lean NOx absorber catalyst
- Three-way catalyst (sometimes referred to as "non-selective catalytic reduction" or NSCR)

Natural gas engine manufacturers are now researching the benefits of adding these after treatment technologies to natural gas engines, or improving their existing applications.[32] The preliminary results are very promising, and demonstrate that, when starting from the lower emissions baseline inherent with natural gas engines, near-zero-emissions is possible. The descriptions that follow highlight the four primary after treatment technologies that researchers are beginning to integrate into heavy-duty natural gas engines.

Selective Catalytic Reduction

SCR is a technology that is widely used to reduce NOx emissions from power plants and other large pollution sources, and is now used on diesel engines to achieve contemporary heavy-duty emission standards. An agent that will catalyze NOx, typically urea, is sprayed into the exhaust stream, dramatically reducing the proportion of the smog-forming compound that is emitted into the atmosphere. Improved SCR is one approach being used by Westport Innovations, a global leader in heavy-duty natural gas engine development. Westport is developing next-generation high pressure direct injection (HPDI) LNG engines that can meet very low fuel cycle emissions of NOx by combining lower carbon-intensity natural gas, e.g., biogas, with improved SCR, and increased engine efficiency. [33]

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[31] TIAX LLC, "Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and C02 Emissions, Final Report"; NESCAUF, ICCT, Southwest Research, and TIAX; October 2009

[32] One issue that has arisen regarding aftertreatment is the formation of ammonia. Both diesel and natural gas aftertreatment systems have the potential to produce excess ammonia. Whereas there are technological solutions to address this issue, the integration of these solutions will be driven by regulatory requirements. As of this writing, ammonia is not a regulated by-product of exhaust aftertreatment and thus manufacturers are not required or compelled to control it.

[33] Kevin Oversby, Westport Innovations, "Transitioning to Zero-Emission Freight Transport Technology," presentation to the SCAQMD Transitioning to Zero-Emissions Technology Symposium, April 10, 2013, http://www.aqmd.gov/tao/ConferencesWorkshops/ZeroEmissionFreightForum/13_KOversby.pdf.

Lean NOx Adsorber Catalyst

Lean NOx absorber catalysts are devices with characteristics similar to catalytic converters used on gasoline (stoichiometric) engines, but with the addition of materials that adsorb NOx under typical lean engine operations. Adsorption technologies operate by encouraging the adhesion of pollutants to a surface, often through ionic, chemical, or magnetic bonds. They can be combined with other NOx-control technologies, e.g., SCR, to further reduce NOx emissions from HDVs. According to the Manufacturers of Emissions Control Equipment (MECA), lean NOx absorber catalysts can be coated directly on ceramic filter substrates to simultaneously reduce NOx and diesel particulate matter emissions. This appears to be a potential strategy for near-term future application to heavy-duty natural gas engines that use pilot injection of diesel fuel to maintain compression ignition, e.g., Westport's HPDI technology.[34]

Three-Way Catalyst (TWC)

Development efforts are underway by heavy-duty natural gas engine OEMs such as Cummins Westport to develop catalyst designs that can achieve NOx emissions below 0.05 g/bhp-hr when used in conjunction with new engine control strategies. For example:

- Cummins Westport (CWI) is using an advanced TWC strategy with cooled EGR to obtain very low emissions on its next-generation heavy-duty natural gas engines, including the new ISX12 G engine shown in Figure 13. This strategy also allows CWI to achieve high engine torque and efficiency. According to CWI engineers, near-zero NOx emissions have already been demonstrated over hot cycles; getting down to very low NOx levels is largely an issue of controlling cold start emissions. This emerging technology is "capable of reaching significantly lower emissions levels" with further development. Various technologies are being investigated by CWI for this strategy. One significant challenge is emissions deterioration, but CWI does not envision any "show stoppers" to achieve the targeted 0.02 g/bhp-hr level of NOx.[35]

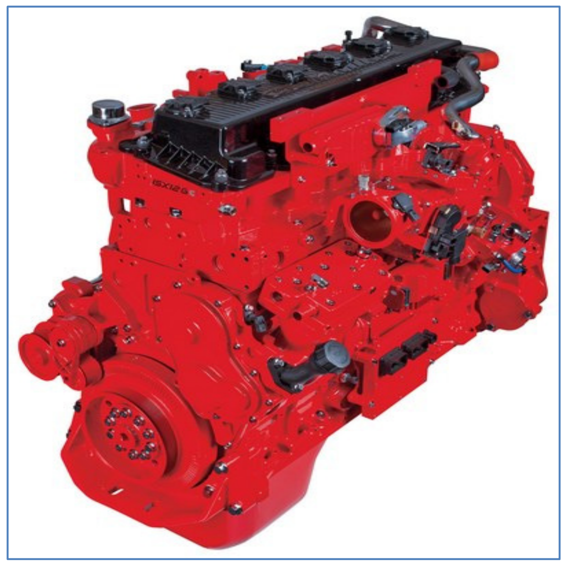

Figure 13 – CWI ISX12 G Natural Gas Engine (Source: Cummins Westport)

- Southwest Research Institute, Doosan Engine Company, and various other government-industry partners have teamed to develop an ultra-low-NOx version of Doosan's 11-liter GL11K natural gas engine. The newer engine technology is also expected to achieve a 5 percent improvement in brake specific fuel consumption. Doosan's technology pathway is to use combinations of stoichiometric combustion, EGR, high ignition energy, optimized turbocharging, and improved TWC technology. The near-term NOx emissions target is less than 0.03 g/bhp-hr NOx—a reduction of approximately 80 percent from the current NOx certification of 0.15 g/bhp-hr (already 25 percent below the 2010

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[34] Manufacturers of Emissions Controls, Mobile Source Technologies to Reduce Greenhouse Gas Emissions, April 2009, http://www.meca.org/galleries/default-file/MECA%20GHG%20Whitepaper%20April%202009.pdf.

[35] Mostafa M. Kamel, Cummins Inc., "Natural Gas Technology for Near-Zero NOx," presentation to the SCAQMD Transitioning to Zero-Emissions Technology Symposium, April 10, 2013, http://www.aqmd.gov/tao/ConferencesWorkshops/ZeroEmissionFreightForum/12_MKamel.pdf.

federal standard).[36] Specific modifications that the Doosan team is making to its current production GL11k heavy-duty natural gas engine include the following:

- Stoichiometric, instead of lean burn
- Cooled EGR
- Advanced ignition system
- High efficiency turbocharger
- Optimized after treatment
- Optimized in-cylinder turbulence
- Optimized piston design and camshaft profile

Drive Train Hybridization and Other Improvements

Hybridization involves the integration of both mechanical and electric components to propel the vehicle. The benefit of hybridization is that it enables engineers to optimize the power capabilities and energy efficiencies of both internal combustion and electrically-driven technologies for a specific application during various aspects of its duty cycle. When combined with systems to capture waste heat, kinetic energy, and other potential sources of power that are typically "lost" in the drive cycle, hybridized vehicles can realize substantial gains in energy efficiency over conventional technology.

TIAX (2009) summarized application-specific potentials to reduce fuel consumption of HDVs via application of drive train hybridization. TIAX found that fuel consumption reductions on heavy-duty hybrid vehicles of five to 50 percent can be realized, by enabling optimum engine operation, downsizing in certain cases, regenerative braking, accessory electrification, and engine shutdown at idle. A wide range of hybrid-electric and hydraulic architectures can be utilized, depending mainly on application, duty cycle, and cost-benefit trade-offs. The keys to maximizing this potential while satisfying performance and emissions requirements are optimization of component sizing, as well as effective power management.[37]

Numerous heavy-duty engine and vehicle manufacturers are now working on hybrid vehicle platforms that integrate in heavy-duty natural gas engines. These include the following:

- U.S. Hybrid is working to develop and demonstrate a Class 8 drayage truck that features a plug-in hybrid drive train with a CNG-fueled Cummins Westport ISL G engine. Objectives of the project include technical and market validation of the pre-commercial platform in preparation for a "full-scale, commercial vehicle production launch." The vehicle will feature an all-electric, zero-emission range of 30 miles, while operating at very low emissions when powered by natural gas the remainder of the time. The key challenge is not the technology, but building a vehicle with low life-cycle cost of ownership.[38]

- Capstone Turbine Corporation is working on a series of hybrid drive systems that use microturbines fueled by natural gas to achieve very low-NOx and low-GHG emissions. NOx emissions are already

[36] Timothy J. Callahan, Southwest Research Institute, "Doosan Low Emissions Natural Gas Engine, presentation at the 2012 Natural Gas Vehicle Technical Forum, accessed online on http://www1.eere.energy.gov/cleancities/pdfs/ngvtf12_callahan.pdf.
[37] National Highway Traffic Safety Administration, "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles" October 2010
[38] Abas Goodarzi, US Hybrid, Integrated Electric and Hybrid Components Powering Clean Mobility, presentation to the SCAQMD Transitioning to Zero-Emissions Technology Symposium, April 10, 2013, http://www.aqmd.gov/tao/ConferencesWorkshops/ZeroEmissionFreightForum/6_GGoodarzi.pdf.

at the 0.05 g/bhp-hr level. Demonstrations of this technology are expected to begin in late 2013.[39] Other companies such as ICR Turbine Engine Corporation are working on similar concepts.

- Transpower is working with Siemens Corporation to build and demonstrate hybrid drayage trucks that will be zero-emission when driven along a catenary electric system, and near-zero-emission off the catenary through the utilization of a very clean heavy-duty natural gas engine such as the Cummins-Westport ISL-G). The concept would enable trucks that operate from marine terminals to be powered by electricity when moving cargo from dock-side to nearby intermodal facilities, but allow them to retain the flexibility to travel anywhere off the catenary system utilizing the cleanest available internal combustion technology.

Figure 14 – Artist's rendering of the Siemens – Transpower catenary/natural gas drayage truck (Source: Siemens)

Electric Drive as an Enabler of Waste Heat Recovery

Heavy-duty natural gas HEVs can also become more fuel efficient because electric drive can enable use of waste heat recovery systems, such as electric turbo-compounding or electric bottoming cycles. According to the NAS report, electric waste heat systems in HEVs "can offer an additional one to two percent efficiency benefits at neutral cost compared to an equivalent mechanical waste heat system."

Idle Reduction through Advanced Drivetrains

Heavy-duty NGVs can become more fuel efficient and lower emitting by reducing idle time and integrating efficient electrical accessories. For example, Transpower is working on an automated manual transmission with four forward speeds, an electric reverse, no torque converter, motor synchronized shifting, and no transmission cooler or pump. Such technologies can be combined with hybrid-electric drive systems, such as efforts underway by Transpower[40], Balqon, and other manufacturers specializing in heavy-duty electric drive systems.

Vehicle Integration

Several strategies exist to reduce the amount of energy required by a vehicle to perform a given task. In the on-road heavy-duty sector, examples of these technologies include improved vehicle aerodynamics, rolling resistance reductions, and vehicle weight reductions. By reducing the energy demands of the vehicle, fuel consumption and associated emissions of air pollutants are also reduced. The 21st Century

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[39] Steve Gillette, Capstone Turbine Corporation, "Microturbine Technology Overview," presentation to the SCAQMD Transitioning to Zero-Emissions Technology Symposium, April 10, 2013, http://www.aqmd.gov/tao/ConferencesWorkshops/ZeroEmissionFreightForum/8_SGillette.pdf.

[40] James Burns, Transpower, "Transpower Zero-Emission Freight Transport," presentation to the SCAQMD Transitioning to Zero-Emissions Technology Symposium, April 10, 2013, http://www.aqmd.gov/tao/ConferencesWorkshops/ZeroEmissionFreightForum/5_JBurns.pdf.

Truck Partnership, a consortium of several U.S. agencies and industry partners[41], notes that 85 percent of the usable energy available from an engine is used to overcome aerodynamic drag and rolling resistance in a typical long haul truck travelling at highway speeds.[42] Hence, reductions in these loss mechanisms can significantly reduce the energy demands of the vehicle.

Aerodynamics

Aerodynamic drag is a significant source of energy loss for any vehicle that spends much of the time operating at highway speeds. Approximately 53 percent of the useful energy available from a truck engine is lost to aerodynamic drag at these speeds. As a result, the U.S. DOE has set a goal to demonstrate a 20 percent reduction in aerodynamic drag for a long haul truck. If achieved, this would reduce the vehicle's fuel consumption by 10 to 15 percent.[43]

Rolling Resistance

Rolling resistance represents approximately 30 percent of a vehicle's resistance to forward motion.[44] The EPA estimates that the use of "single-wide" tires to reducing rolling resistance can result in reductions in NOx emissions and fuel consumption of three percent or more[45.] Tire composition, tread design, and wear all affect rolling resistance and will be important factors in maximizing fuel economy while maintaining vehicle performance. U.S. DOE has set a goal of developing and demonstrating low rolling resistance tires for a long haul truck that reduce rolling resistance by 35 percent.

Weight Reduction

The use of lightweight materials and advanced manufacturing techniques can reduce the weight of a vehicle without compromising the safety, durability, or performance of the vehicle. In freight movement applications, reducing the vehicle weight can improve overall freight efficiency by enabling the vehicle to carry additional cargo in the same vehicle footprint. In applications with significant amounts of "stop and go" driving, reduced vehicle weight reduces the amount of energy needed to accelerate the vehicle, and improves fuel economy.

Fuels, Storage, and Infrastructure

In the long term, two of the best strategies to obtain the final increments of GHG reduction in NGVs will be increasing the use of methane that results from biological sources, such as digester or landfill gas, as well as increasing the hydrogen content of natural gas. Biogas is also known as renewable natural gas (RNG), because it is generated by feed stocks that can be continually replenished. To a great extent, biogas is produced anyway, but often escapes in to the atmosphere as methane, a much more powerful heat-trapping gas. If such fugitive methane emissions can be captured and harnessed by mixing the bio-methane into the natural gas system used to fuel natural gas HDVs, not only are the methane emissions avoided, but the use of geologically-sourced natural gas is reduced.

Another strategy includes increasing the hydrogen content of the natural gas used to fuel vehicles. Hydrogen-enriched natural gas works by displacing molecules of methane that contain carbon. Not only does this reduce the carbon intensity of the fuel, but it also has been demonstrated, in some natural gas

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[41] Agency partners include the U.S. Department of Energy, Department of Transportation, Department of Defense, and the Environmental Protection Agency.

[42] 21st Century Truck Partnership, "Roadmap and Technical Whitepapers", February 2013

[43] Ibid

[44] Ibid

[45] U.S. EPA, SmartWay Technology Program – Verified Low Rolling Resistance Tires. Accessed at http://www.epa.gov/smartway/technology/tires.htm#tires.

engine technologies, to reduce NOx formation as well. Both the RNG and hydrogen-enriched strategies are described in greater detail below.

Hydrogen Enriched Natural Gas ("Hydrogenization")

Natural gas can be blended with hydrogen to increase its energy content, further reduce its already low carbon intensity, and help mitigate NOx emissions. In this process of enriching natural gas with hydrogen, aslo known as "hydrogenization", the hydrogen can be mixed into natural gas pipelines, or it can be blended at the natural gas fueling station. Blending hydrogen into natural gas in heavy-duty NGVs was successfully demonstrated in the early 2000s by Sunline Transit in Thousand Palms.[46] Sunline partnered with various public and private entities to fuel CNG buses on an 80 percent methane/20 percent hydrogen mixture known as Hythane®. This blend resulted in a 50 percent NOx emission reduction relative to the "baseline" conventional CNG buses. Unfortunately, the introduction of EGR in later-generation natural gas engines appeared to eliminate the NOx-reduction benefit of hydrogenization; however, heavy-duty OEMs continue to see promise with, and pursue research and development into, hydrogenation as a means of reducing NOx and GHG emissions from internal combustion HDVs.

Renewable Biomethane

RNG is a very promising emerging fuel pathway to help California achieve its long-term climate and air quality goals in the transportation sector. RNG is created through commercially mature technologies involving anaerobic digestion of organic waste such as municipal garbage, sewage, manure, discarded food, leftover agricultural biomass, etc. Recovering and processing these by-products results in a mixture of methane, carbon dioxide, and small amounts of other gases. This biogas can be used directly as fuel for combined heat and power gas engines, or it can be upgraded to pipeline-quality natural gas. Once contaminants are removed, RNG is essentially the same as conventional natural gas, and can be used as a transportation fuel in the form of LNG or CNG. Two leading feedstock to make RNG are landfill gas and dairy digester gas.

RNG's displacement of petroleum fuels in the transportation sector offers major and compelling benefits as a GHG reduction strategy.[47] According to ARB, today's average California diesel fuel has a total carbon intensity value of 94.71 gCO_2e/MJ. CNG made from landfill gas (LFG) and then cleaned up to pipeline quality is estimated to have a total carbon intensity of 11.26 gCO_2e/MJ. This translates to an 88 percent GHG emission reduction (full fuel cycle) for LFG compared to today's on-road California diesel fuel. CNG from dairy digester biogas is almost as low on a fuel-cycle GHG basis. It has an estimated carbon intensity of 13.45 gCO_2e/MJ; this equates to an 86 percent reduction in fuel cycle GHG emissions compared to today's on-road California diesel fuel.[48]

Landfills are emerging as a means to produce significant volumes of RNG for use in HDVs. Approximately three to five years after being disposed in a solid waste landfill, decomposing organic waste begins to produce the mixture of methane and CO_2 that makes up LFG. Generally, a landfill will

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[46] See William L. Clapper, Jr., "Sunline Transit Agency: Hydrogen Commercialization for the 21st Century," http://www.nrel.gov/hydrogen/pdfs/41001.pdf; Roger W. Marmaro, "Hythane® – Bringing Hydrogen to Zero Emissions Reality," presentation to ARB, June 28, 2006, http://www.arb.ca.gov/msprog/bus/zbus/meetings/hythane_062806.pdf.

[47] Mostafa M. Kamel, Cummins Inc., "Natural Gas Technology for Near-Zero NOx," presentation to the SCAQMD Transitioning to Zero-Emissions Technology Symposium, April 10, 2013, http://www.aqmd.gov/tao/ConferencesWorkshops/ZeroEmissionFreightForum/12_MKamel.pdf.

[48] California Air Resources Board, "Table 7. Carbon Intensity Lookup Table for Diesel and Fuels that Substitute for Diesel," accessed online at http://www.arb.ca.gov/fuels/lcfs/121409lcfs_lutables.pdf.

continue to produce LFG for roughly 30 years after it is closed. LFG is typically about 50 percent methane, which is considered to be "low-Btu" gas. To be used as a transportation fuel, LFG must be converted to a more pure and energy dense gas by reducing the content of carbon dioxide, nitrogen, oxygen and other gases. Once this cleanup occurs, any technology or application that uses conventional natural gas can also use LFG.

In late 2009, Waste Management officially opened a high-tech fuel plant that demonstrates the viability of LFG as an alternative transportation fuel. Project partner Linde North America built the plant based on technology patented by the Gas Research Institute. Each day, the Altamont plant processes 3.0 million cubic feet of LFG, yielding 13,000 gallons of renewable LNG; according to Waste Management, this is then used to fuel 300 garbage trucks. [49] At a capacity of 4.0 million LNG gallons per year, this plant is one of the largest LFG-to-LNG plants in the world. This is enough renewable LNG annually to displace 2.8 million gallons of diesel fuel. Additional methane recovery from the landfill co-produces all power requirements for the system, e.g., gas and refrigeration compressors, controls, transfer pumps, and auxiliaries, through onsite electricity generation.[50]

Figure 15 – Altamont LFG-to-LNG Facility

It is important to emphasize that RNG types such as LFG and digester gas provide a "here and now" low-GHG transportation fuel strategy; these fuels are already being used in commercial applications. Demonstration programs in California are proving the viability of RNG for rigorous HDV applications. For example, the LFG being used to fuel garbage trucks at the Altamont Landfill and Resource Recovery Facility is believed to be the world's lowest GHG fuel being used in commercialized HDVs.[51]

The potential expansion of LFG production in California is substantial; EPA lists 278 municipal solid waste landfills in California alone.[52] The Altamont project serves as a model for similar facilities. Many California landfills are already producing RNG to generate electricity rather than make vehicle fuel. Waste Management operates 131 LFG-to-energy plants that currently generate enough renewable

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[49] Waste Management website, "Altamont Landfill," http://altamontlandfill.wm.com/green-energy/index.jsp.
[50] California Energy Commission, "Capturing, Purifying, and Liquefying Landfill Gas for Transportation Fuel," May 2012, accessed online at http://www.energy.ca.gov/2012publications/CEC-500-2012-FS/CEC-500-2012-FS-021.pdf.
[51] Based on a review of California Air Resources Board's Low Carbon Fuel Standard – Carbon Intensity Lookup Tables (2012) http://www.arb.ca.gov/fuels/lcfs/lcfs.htm
[52] U.S. EPA, "List of Municipal Solid Waste Landfills," accessed on July 11, 2013 online at http://www.epa.gov/osw/nonhaz/municipal/landfill/section3.pdf.

energy to power 500,000 homes, and several of these facilities are in California (although Altamont is the only one that is currently generating LNG for transportation use).[53]

With these low-carbon intensity ratings, types of RNG such as LFG and digester gas are perfectly positioned to help meet ARB's Low Carbon Fuel Standard (LCFS). The LCFS incentivizes production and sale of low-carbon transportation fuels by establishing declining carbon intensity (CI) levels that fuel producers and importers must meet each year for their fuel pools, with a 2020 target of 10 percent lower than the average CI of fuel sold in California in 2010.[54] The CI scores for various fuels are set forth in the LCFS regulation, along with annual CI targets. A fuel that has a CI below the target in a given compliance period generates credits; conversely, a fuel with a CI above the target will generate a deficit that must be "reconciled" by purchasing credits or other means defined in the regulation.

Compared to the 2020 diesel replacement target under the LCFS, the volumes of RNG currently produced in California are relatively small. However, strong potential exists for these volumes to grow much larger. Moreover, because RNG varieties such as landfill and digester gas are biofuels with low carbon intensity ratings, a relatively small volume of these fuels can generate a large percentage of the credits needed to comply with the LCFS. In fact, according to an April 2013 "status review" of the LCFS since it took effect in 2011, "biofuels made from waste materials comprised less than one percent of biofuel volumes, but generated 10 percent of biofuel credits, due to their low-carbon intensity."[55]

If the state maximized its biomethane potential, it could displace 27 percent of the diesel currently sold in the California for on-road vehicles.

Maximizing the market penetration of RNG requires research to identify technical, commercial, financial, market, and regulatory barriers to its production. The State of California continues to aggressively support efforts by industry to develop and improve RNG production technology. ARB has approved projects that can help determine the technological and commercial feasibility of producing large quantities of RNG fuels for use in California.[56] The CEC recently released a Program Opportunity Notice (PON) titled "Renewable Natural Gas Transportation Fuel Production Systems with Value Added Co-Products/Benefits." The purpose of the solicitation was to accelerate research, development, and demonstration (RD&D) of advanced technologies that produce RNG transportation fuels "through the use of technologies that are novel, innovative, and generate economically significant co-products and/or co-benefits for California." In early 2013, CEC announced that $2.4 million in funding was being awarded to four different projects that met PON requirements for either bench scale projects, working demonstration units, or prototype development projects.[57]

It is clear that RNG can play a major role as an important alternative transportation fuel for California's

[53] Kerry Kelly, Director of Federal Affairs for Waste Management, "Landfill Gas to Renewable Energy – A Primer," undated Power Point presentation to the American Biogas Council, accessed online on July 12, 2013 at: http://www.americanbiogascouncil.org/pdf/briefing15may12_wasteManagement.pdf.

[54] See Title 17 CCR 95482, http://www.arb.ca.gov/regact/2009/lcfs09/finalfro.pdf

[55] University of California, Davis, "Status Review of California's Low Carbon Fuel Standard, Spring 2013," Research Report – UCD-ITS-RR-13-06, April 30, 2013.

[56] California Air Resources Board, "The Feasibility of Renewable Natural Gas as a Large-Scale, Low-Carbon Substitute," agenda item, June 27, 2013, http://www.arb.ca.gov/board/books/2013/062713/prores1320.pdf.

[57] California Energy Commission, "Notice of Proposed Awards: Renewable Natural Gas Transportation Fuel Production Systems with Value Added Co-Products/Benefits, February 27, 2013, accessed online at http://www.energy.ca.gov/contracts/PON-12-506_NOPA.pdf.

transportation sector. Resources in California for production of RNG are vast and widely available. These include landfills, waste water treatment facilities, dairy/cattle operations, and other types of agricultural waste. Looking at LFG alone, there are hundreds of landfills in California that produce significant volumes of biomethane each day. In addition, given the size of agriculture and animal husbandry in the state, the capacity to produce RNG from animal and plant waste adds substantially to the potential biomethane resource base.

While current renewable methane production in California is small when compared to the total natural gas use in the state, the potential volume of renewable methane that could be produced from organic waste is significant. The California Biomass Collaboration estimates that the state has the capacity to produce about 106 billion cubic feet of biomethane annually by 2030.[58] Although a fraction of the total natural gas used in the state, if this volume of biomethane was used as a transportation fuel in HDVs, it would displace more than 27 percent of the total taxable diesel consumption in California, or about 840 million diesel gallon equivalents (DGE).[59] The use of such volumes of biomethane in heavy-duty natural gas trucks would dramatically lower the carbon footprint of the sector, and be more than enough to reduce the last increment of GHG emissions to enable the described pathway technologies to achieve the state's 2050 climate protection goals.

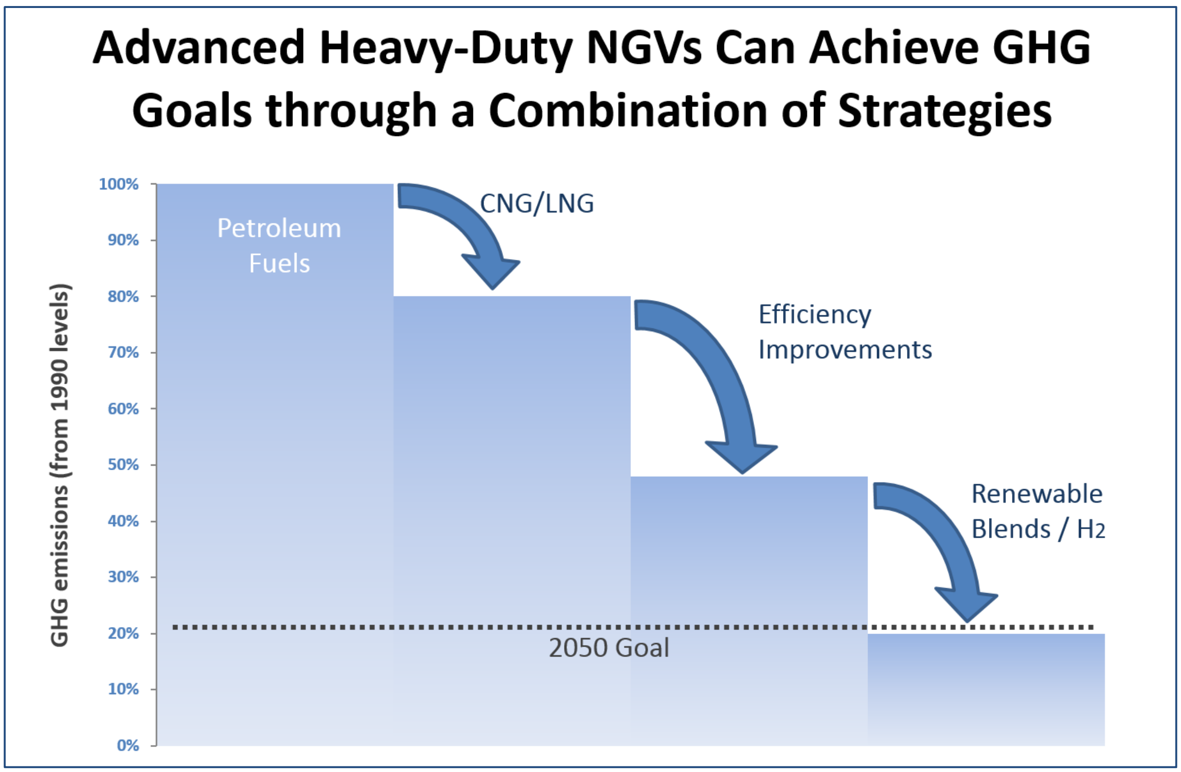

Figure 16 – Major deployments of high-efficiency heavy-duty natural gas vehicles fueled by renewable methane-hydrogen blends can be a pathway to meet California's 2050 GHG-reduction goal.

[58] A Preliminary Roadmap for the Development of Biomass in California. California Biomass Collaboration; December 2006, California Energy Commission Report CEC-500-2006-095, p.11.

[59] According to the CEC, total taxable diesel consumption in California was 3.075 billion gallons in 2007. Assuming that a cubic foot of biomethane contains the same energy content as pipeline gas (1020 BTU) and a gallon of diesel has 128,700 BTU, then the 27 percent figure is derived by dividing 108.12 billion BTU from biomethane by 385.8 billion BTU in total diesel consumption.

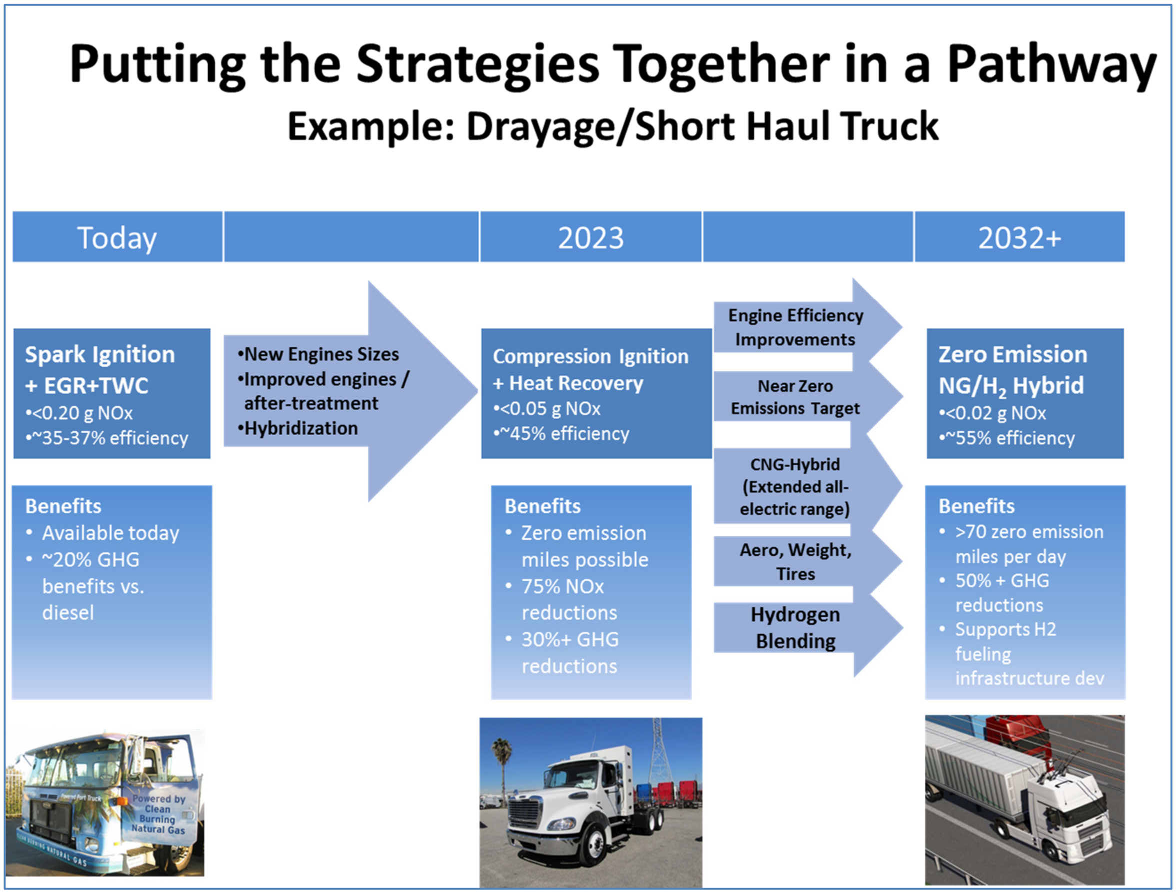

Figure 17 – Example pathway to zero-NOx equivalency for the drayage trucking sector

Examples of HDV Applications for Pathways to Zero-NOx and Low-GHGs

Figure 17 provides an example pathway to (full fuel cycle) zero-NOx and low-GHG emissions for a specific heavy-duty trucking application: drayage trucks. As shown, through a combination of technologies and techniques (improved engine technologies, drivetrain hybridization, advanced fuel blends, fuel efficiency improvements, etc.), the typical Class 8 heavy-duty drayage truck rated at 80,000 pounds gross vehicle weight rating (GVWR) will progressively emit lower levels of NOx and GHGs. By the 2030 timeframe, natural gas trucks in this demanding sector will emit about 0.02 g-bhp-hr of NOx, or the equivalent of the power plant NOx emissions for a battery-electric truck. Through high system efficiencies due to electric drive and advanced engine technologies, they will also emit low levels of GHGs.

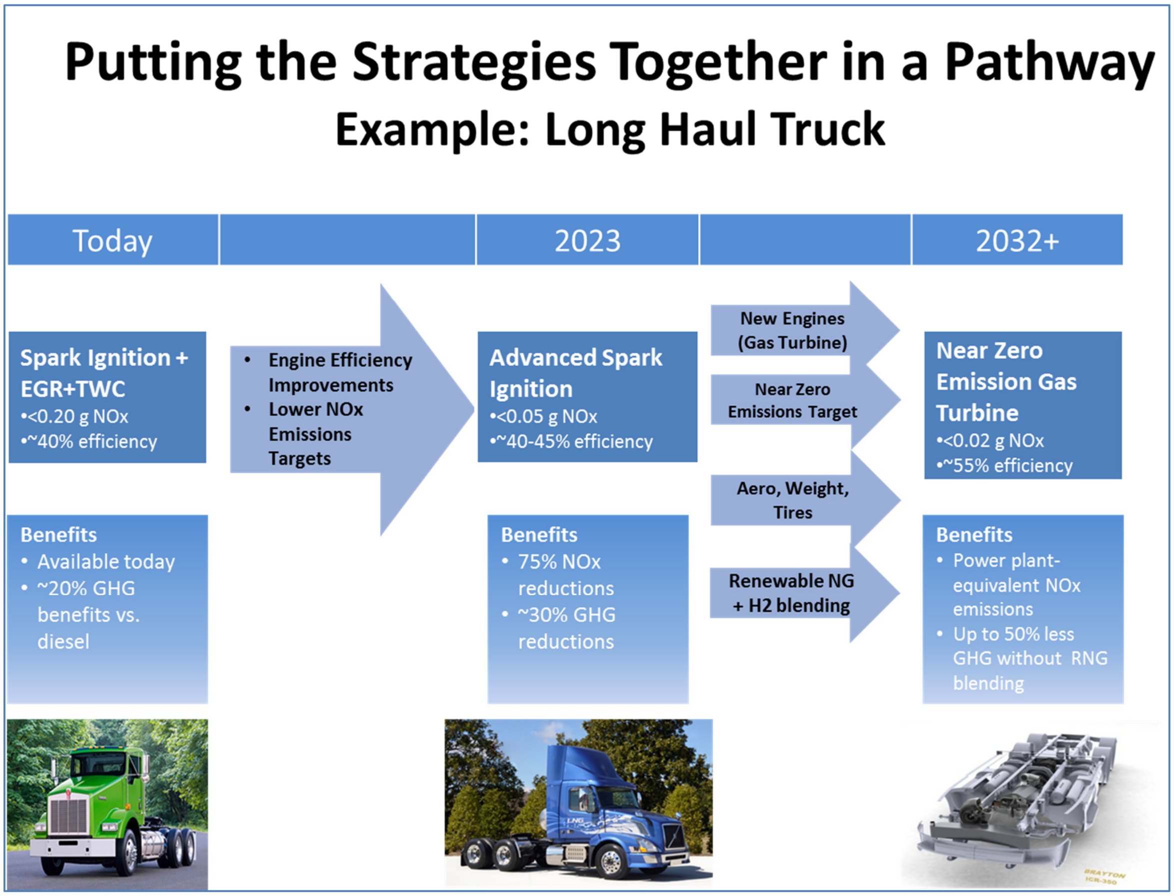

Figure 18 – Example pathway to zero-NOx equivalency for the long haul trucking sector

Figure 18 provides a potential pathway for long haul trucks to power plant-equivalent NOx emissions and GHG reductions of 50 percent (before any GHG benefits from the use of RNG). Natural gas turbines are a potential enabling technology to achieve low-NOx emissions, while the combination of low carbon natural gas and vehicle efficiency improvements provide GHG reductions.

For additional examples of current demonstrations of pathway technologies, please see Appendix A.

Recommended Actions

California disparately needs both the NOx and the GHG emission reductions that will result from the early deployment of these technologies. Both to ensure and accelerate the development of these super low-emission natural gas-fueled HDVs, supportive public policies can and should be promulgated. The suggested actions for such policies can be grouped into seven categories, all of which target the pathway technologies detailed above:

- Promulgate performance-based emission standards;
- Develop and implement of optional low-emission standards;
- Fund research and development (R&D);
- Encourage early demonstration projects;
- Foster public-private partnerships to encourage accelerated development and commercialization;
- Incentivize commercialization; and
- Incentivize fleet purchase requirements.

This section will review some of the rules, regulations, emission standards, and incentive programs that can hasten the arrival and mass market penetration of these near-zero and power plant emission-equivalent technologies.

Develop and Promulgate Performance-Based Emission Standards

Regulators have used both technology-forcing mandates and performance-based standards to push vehicle and engine manufacturers to build and sell cleaner transportation technology. Compelling the market to purchase specific kinds of vehicles such as BEVs and FCVs has had mixed success. As an alternative approach, establishment of very challenging new emission standards that are achievable with combustion engines compels manufacturers to develop the advanced engine technologies needed to continue selling their existing products in progressively cleaner versions.

This performance-based approach to setting emission standards does not eliminate incentive for manufacturers to develop commercially viable BEVs and FCVs. The need to make and sell zero-tailpipe-emission vehicles will continue to be as great as ever, and will be equally promoted by tough performance standards. Yet, by setting fuel-cycle equivalency as the basis for emission standards, and allowing technology developers the freedom to create and innovate, the state is much more likely to expeditiously achieve the necessary emission reductions from the HDV sector.

This approach, adoption and implementation of performance-based standards, has consistently been successful at the federal, state, and local level. Clearly, the best forward strategy for California policy makers is to focus on technology-forcing through a conventional command-and-control methodology, while avoiding adoption of rules that effectively prescribe specific technologies and/or fuels. In tandem, this must be supplemented with renewed and revised incentive programs to help defray the incremental costs of super clean technologies in their early years of development.

Develop and Implement Optional Low-Emission Standards

One of the best examples of a performance-based standard has been optional low-emission standards. Optional standards provide the context and incentive for engine makers to engineer technologies that are above and beyond what is required. California has enjoyed a great deal of success in the past with optional emission standards that are tougher than the contemporary emission standard. The Optional Low NOx emission Standard that existed in the late 1990s and early 2000s did much to encourage engine manufacturers to push the envelope in regards to the environmental footprint of their products, through use of cleaner fuels and advanced engine technologies.

An optional emission standard provides engine manufacturers with an official target for certification. Although many natural gas and even some diesel engines are testing at emissions levels below the 2010 standards, currently there is no protocol available for manufacturers to certify engines to a lower standard over the entire test cycle. Without a formal standard to certify to, engine manufacturers cannot prove to air quality regulators that engines that test to a lower emission rate are “officially” providing any emission reductions; at least, they cannot claim any reductions that could be counted toward a surplus emission reduction required to receive State Implementation Plan (SIP) credit, generate emission reduction credits or qualify for funding from grant programs that require demonstration of “real” emission reductions.[60]

It is very expensive for an engine manufacturer to certify an engine. Without a certification standard and the instructions to conduct the testing, there is no inducement for engine manufacturers to push emissions performance lower. The promulgation of an optional low-emission standard would incentivize heavy-duty natural gas engine manufacturers to invest in and perfect the near-zero-emission technologies that they are currently researching. The existence of an optional low-emission standard would enable the cleanest technologies officially to generate surplus emission reductions. Not only would this qualify their products for grant funding, but it would also verify to potential customers concerned about emissions that they can purchase cleaner technology. This would entice engine makers to accelerate their product development schedules, as well as would encourage the early introduction of these very low, near-zero-emission heavy-duty engine technologies.

ARB recently approved new Optional Low-NOx Standards (OLNS) for heavy-duty engines that will encourage engine manufacturers to introduce and “showcase” new ultra-low-NOx technologies. The new standards take a three-tiered approach. Beginning with 2015 model year engines, OLNS’s of 0.10 g/bhp-hr, 0.05 g/bhp-hr, and 0.02 g/bhp-hr will be implemented. These represent NOx reductions of 50 percent, 75 percent, and 90 percent from the current 0.2 g/bhp-hr standard.[61] To incentivize fleets to purchase HDVs with engines certified to the OLNS, ARB is considering adjustments to HDV fleet rules, e.g., the Truck and Bus Regulation. In addition, ARB staff is exploring modifications and updates to existing incentive programs, e.g., Carl Moyer, to give preference to engines certified to the OLNS.

This “round two” OLNS in 2013 can provide engine manufacturers with a clear market signal and target to achieve for certification. Many natural gas engines (and even some diesel engines) are already testing at NOx and PM emission levels below the 2010 standards. However, there have been no standards or protocols available to date to certify heavy-duty engines to emissions levels below current

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[60] The Clean Air Act requires states with non-attainment areas to develop a State Implementation Plan (SIP). The SIP both describes the air pollution problem and a plan to reduce emissions so that the polluted air shed can meet NAAQS. Surplus emission reductions are created when states can show that they are implementing programs that will generate emission reductions above and beyond those measures described in their SIP. Surplus emission reductions must be verifiable, which can only be achieved through officially sanctioned testing procedures and protocols. Optional low- emission standards establish these methods, giving regulators confidence that the claimed surplus emission reductions are real.

[61] Although, as of this writing, the ARB had not yet updated its website to reflect passage of the proposed rule in the December 12, 2013 board meeting, the staff presentation can be found at http://www.arb.ca.gov/board/books/2013/121213/13-11-1pres.pdf. The details about the proposed rule can be found at http://www.arb.ca.gov/regact/2013/hdghg2013/hdghg2013.htm.

standards. Consequently, engine manufacturers cannot claim these as "official" emission reductions that are officially deemed "surplus" and qualified for SIP credit or grant funding.

ARB's promulgation of the OLNS will send an unambiguous message to engine manufacturers: expand and accelerate your commercialization efforts for ultra-low-NOx HDV technologies. It will encourage early introduction of near-zero-emission heavy-duty engine technologies, yielding substantial benefits to millions of Californians who are currently exposed to unhealthful levels of diesel exhaust.

The ultimate OLNS standard should be the air quality equivalent to a zero-emission HDV, i.e., no direct vehicle emissions, taking into account the NOx emissions generated by electricity production required to recharge a comparable heavy-duty BEV. An updated assessment may be needed to determine if this is equivalent to 0.02 g/bhp-hr. Phase-in of an OLNS should be as aggressive as possible. The interim OLNS of 0.05 g/bhp-hr should be adopted to push for engine certifications and deployments as soon as the next five years.[62]

Direct Funding to R&D

The ARB, CEC, air districts, and even transportation agencies have been provided substantial resources to promote R&D of cleaner, more energy efficient transportation technology. Coupled with the development of tougher performance-based and optional low-emission standards, a policy is needed for state agencies to re-focus their scarce research and development funding and to encourage private investment in the pathway technologies described herein. Investment in pathway technologies is more likely to yield air quality and climate protection benefits sooner and more cost-effectively than other options. Thus, the state should develop and aggressively pursue an R&D agenda that targets the emission reduction and efficiency improvement technologies enumerated in the prior section.

Develop Policies and Incentives to Encourage Early Demonstration Projects

In order to ensure that R&D resources are well spent, regulators should also work to provide funding for the early demonstration of pathway technologies. Demonstration projects help manufacturers determine whether the new products they develop actually work in common duty cycles as designed, and enable potential customers to determine whether these experimental designs can meet their everyday performance needs. The earlier new technologies are successfully demonstrated, the more likely manufacturers will be to make the investment to produce them on a commercial scale, which is necessary for much needed near-zero-emission vehicles to gain market share and contribute to California's air quality and climate protection goals. Such demonstrations require the development of robust measurement and monitoring programs to collect the data necessary to determine if the trial technologies are performing, both environmentally and operationally, as intended.

Encourage Public-Private Partnerships

Both R&D and early demonstration projects will rely on collaboration and cooperation between public agencies and the private sector. These public-private partnerships are necessary in order to bring the resources, expertise, and experience necessary both to develop and evaluate the new technologies that are promoted by the state's clean air and climate protection policies. Most of the R&D and demonstration projects that receive state funding will involve partnerships between the private entities

[62] California Air Resources Board, "Proposed Optional Low NOx Standards for Heavy Duty Engines, Extended Engine Warranties, and Heavy Duty Zero-Emission Vehicles Certification", presentation for public workshop, March 2013.

that ultimately seek to commercialize products and the government that wishes to promote them.[63] State policy should be to encourage and expand the utilization of public-private partnerships focused on the research, development, demonstration, testing, and commercialization of pathway technologies.

The state cannot and will not be the entity that actually creates and commercializes the near-zero and zero-emission equivalent heavy-duty engine technologies needed to meet future air quality and climate protection goals. The private sector ultimately will design, develop, and produce the products that consumers will purchase to replace the dirtier vehicles that they drive today. But government can play a critical role in supporting the efforts of the private sector, particularly through the development of public-private partnerships in which public resources and supportive permitting can help accelerate the commercialization of needed technology.

Develop and Implement Incentives for Commercialization

Many of the new technology funding programs that have been created in California over the last several decades have focused on accelerating the retirement of older, higher-emitting motor vehicles for replacement with new vehicles that meet or exceed the most current emissions standards. Examples of such funding programs include the Carl Moyer Air Quality Standards Attainment ("Moyer") program, AB 2766, AB 118, and the Proposition 1B Goods Movement Emissions Reduction program. It is becoming more difficult to find heavy-duty applications that can deliver surplus NOx reductions through such programs. To successfully encourage further development and rapid deployment of next-generation near-zero and zero-emission equivalent technologies, it may be necessary to modify funding formulas and/or dedicate a significant portion of the resources in these programs toward pathway technologies capable of meeting new benchmarks for low-NOx and low-GHG emissions. This will help to spur early deployment of heavy-duty engines that meet the optional low-NOx standard, the near-zero-emission standard, or even the zero-equivalent emission standards.

Modifications to Cost-Effectiveness Formulas

There is reasonable certainty on the part of heavy-duty natural gas engine manufacturers that over the next several years they can achieve, and perhaps go beyond, the 0.02 g/bhp-hr NOx emissions level. However, much less clarity currently exists for manufacturers regarding whether a <u>business case</u> exists to pursue ultra-low-NOx emission levels. It is too soon for manufacturers to know the incremental cost of an HDV equipped with an engine certified to 0.02 g/bhp-hr NOx, but preliminary estimates range from $3,000 to $5,000 per heavy-duty NGV. This is well in line with past NOx-reduction milestones, e.g., the incremental cost of about $10,000 for SCR on diesel engines, to meet the 2010 NOx standard. Technology-forcing through classic command-and-control regulations differs markedly, however, from *voluntary* development and sales of "optional" ultra-clean HDVs. Heavy-duty engine and vehicle OEMs are well aware that their customers will not pay more simply to help California achieve surplus emissions reductions.

Clearly, there is a need to change the scale for valuing NOx reductions as the heavy-duty engine standards progress toward the very low level of 0.02 g/bhp-hr. California must be willing to pay more to reduce the last remaining mass of NOx emitted by new HDVs. Under current Carl Moyer program cost-effectiveness metrics, there just are not enough remaining emission reductions compared to a 0.2 g/bhp-hr baseline engine. If incentive programs like Carl Moyer are going to be relevant in the future, significant revamping of the cost-effectiveness metrics and formulas are needed. It is likely that a more

[63] In some instances, research may be conducted by academic institutions or government-funded laboratories, but it is rare that such projects do not involve private interests.

multi-media approach will be required that adopts a comprehensive approach addressing a cross section of California's environmental goals. For example, monetization of other significant societal benefits such as petroleum displacement, use of low-carbon and renewable fuels, and reduction of GHG emissions within the calculation of cost effectiveness would provide a more holistic incentive for much needed ultra-low emission technologies.

In the near and medium term, heavy-duty BEVs and FCVs are likely to be significantly more expensive to purchase and operate than natural gas technologies. As noted earlier, if the past is prologue, it could be decades before we see significant numbers of heavy-duty BEVs and FCVs in commercial use. Yet, the need for more immediate reductions in criteria, toxic and greenhouse gas emissions is acute. Hence, it is important to develop incentives now that encourage the proliferation of the cleanest and most cost effective technologies sooner; such incentives will also assist in the development of the BEV and FCV technologies in the long run as these technologies can apply and benefit as well.

As a specific example, the Carl Moyer Program could be modified to provide greater funding amounts for applications involving the purchase and deployment of HDVs equipped with ultra-low-emission engines. Simply put, it is becoming more expensive to achieve a given mass of emission reduction from the heavy-duty vehicle sector. Although heavy-duty natural gas engines are significantly cleaner than in-use or new diesel engines, the masses of available reductions from vehicle replacement projects are substantially lower than when the Carl Moyer Program first began in 1998. This diminished emission reduction benefit on a mass basis has also been reflected in poorer cost-effectiveness calculations, resulting in incentive programs such as Moyer that primarily focus on grants for diesel-to-diesel replacement projects, generally in off-road mobile source sectors.

To adjust for these changes, California's various mobile source incentive programs should be reviewed for possible implementation of one or more of the following remedies:

a) Provide a multiplier to the emission reductions that are delivered by a pathway technology. For instance, if a fleet seeks to purchase a truck equipped with a 0.05 g/bhp-hr engine, then for purposes of determining the cost-effectiveness and the dollar value of the grant, the total reduction is multiplied by some factor that would both ensure that the project met the cost-effectiveness test, and would receive a grant of sufficient substance as to incentivize the purchase. In such a program, the multiplier would be even greater for proposals to deploy 0.02 g/bhp-hr, fuel cell, and battery electric (zero tailpipe emissions) HDVs.

b) Integrate GHG emission reductions into the calculations of cost effectiveness. In the case of pathway technologies, incentive program administrators should develop a mechanism to both enhance the cost effectiveness calculation as well as the total incentive amount by adding a value for the volume of GHGs that will be reduced by the deployment of the technology.

There are a number of other proposals that can be implemented by the state which would encourage the commercialization of ultra-low emission NGVs. Most of these incentives can be applied to any low emission technology, and not only to natural gas technologies. The key would be to apply these new incentives only to technologies that met the 0.05g and 0.02g and lower standards.

Establishment of Rebate Programs for Pathway Technologies

Another approach to incentivizing near-zero and power plant emission equivalent heavy-duty vehicles could be through the creation of program that rebates either all or a portion of the premium a buyer pays for such vehicles. Rebate programs have been popular in other states, such as Texas, where government is trying to encourage the purchase of cleaner vehicles but does not want the administrative burden of managing a grant program. The rationale for taking the rebate approach over grants is outlined below.

Rebates differ from the grant programs described above in that a rebate typically provides greater certainty to the buyer that they will receive the incentive. The reason for this is that in grant programs an applicant, even of the most cost effective deployment project, still must submit an application that competes against other applicants for funding. The applicant will not know if they qualify for a grant, nor will they know if they will get the entire amount that they applied for, until months after their application is submitted. In addition, for most diesel replacement grant programs in the state there are typically many more applicants than there are resources to award. An otherwise excellent applicant can find that they will go unfunded because their application was submitted a few moments after the application of another qualified applicant. This uncertainty is a disincentive to participation.

Although they do not eliminate uncertainty, rebate programs work differently than grant in that the state establishes a pre-determined list of qualifying technologies as well as a tally of the balance in the rebate account. The applicant can then determine if the qualifying pathway technology will receive a rebate and whether there are still resources in the account to apply for. They submit their simplified application (or the dealer submits the application on their behalf) and they can learn from the administrators of the program within a more reasonable timeframe (usually measured in days rather than months) whether they will receive a rebate from the state for their qualifying purchase. This approach typically is favored by applicants as application processes are simplified, take less time and decisions can be made in a shorter time.

Under a rebate program, the state does not distribute a check to the applicant until such time as the applicant can prove that they have submitted a purchase order for the qualifying vehicle or that they take delivery of the technology. Rebate programs also usually place fewer burdens on program administrators, as they do not have to evaluate applications, rank them, and then enter in to complex contracts for the distribution of the grant.

Establishment of a Voucher Program

Other types of creative thinking may be needed and effective for the promotion of pathway technologies. For example, the OLNS concept can be combined with a voucher program that provides a fixed grant amount per vehicle that meets the emission reduction targets established in the OLNS. Another approach could enable a natural gas version of the California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) program to provide a $25,000 voucher incentive for any HDV with an engine certified to 0.05 g/bhp-hr NOx, and $45,000 for any HDV powered by a certified 0.02 g/hp-hr NOx engine. These are the kinds of ideas that will be necessary for the state to develop and implement in order to increase the velocity of ultra-low emission HDVs commercialization.

Moratorium on the Collection of State Excise Taxes

California charges excise tax on every gallon of fuel sold in the state for use in an on-road vehicle, with some limited exceptions for public agencies. The same is true for vehicles that are fueled with alternative fuels, such as propane and natural gas. In order to support the early adoption of pathway technologies, the state could provide buyers of such technology a holiday from the payment of state excise taxes on the fuel that they by for a set period. This “road tax holiday” can start the moment that the buyer takes possession of the qualifying vehicle, and can expire after a period determined by policy makers to be sufficient to incentivize the purchase of the ultra-clean heavy-duty vehicles. The incentive could be structured so that the owner of the pathway technology is eased gradually back to full payment of the excise tax. For instance, during year one and two of ownership, the fleet operator avoids paying 100 percent of the excise tax, while in year three they enjoy a 75 percent reduction, 50 percent in year four and 25 percent in year five. By the sixth year of ownership they are paying the same excise tax as any other fuel consumer in the state. A positive aspect of this incentive is that it not only encourages the purchase of the near-zero and power plant emission equivalent heavy-duty vehicles, but it also encourages their deployment, as fleet operators maximize the use of those ultra-clean vehicles over those for which the owner has to pay excise tax.

Moratorium on the Collection of State Sales Taxes

Another financial incentive for pathway technologies could be the avoidance of sales taxes either on the capital cost of the ultra-low-emission vehicle, on the fuel purchased for its operation, or on both. Regarding sales taxes on capital equipment, this moratorium could apply to the entire purchase price of the qualifying vehicle, or only to the incremental portion of the purchase of any vehicle. At the very least, policy makers should consider eliminating the sales tax on the incremental cost of qualifying vehicles, as the additional sales tax that buyers must pay for cleaner technologies is a disincentive for their purchase.

A holiday from the collection of state sales tax on fuel purchased for qualifying vehicles is a complimentary incentive. Although a small portion of the sales tax burden a fuel buyer bears (most of sales taxes in California are collected by local governments), it can add up to significant money when a fleet purchases hundreds of thousands, or millions of gallons, of fuel per year. This program could be similar to the incentive described above for an excise tax moratorium, with a gradual phase-in of the sales tax over a similar period.

Establishment of a Fuel Tax Credit

In order to help develop the market for low-emission alternative fueled vehicles, the 2005 Federal Transportation Bill established a tax credit for the purchase of qualifying fuel when used in an appropriately-equipped vehicle.[64] Although his fuel tax credit has since expired, it proved to be an effective incentive to promote the use of cleaner, alternative fuels. In order to incentivize the purchase of the kinds of ultra-low-emission pathway technologies described herein, as well as similarly beneficial battery electric and fuel cell-powered HDVs, the state could establish a fuel tax credit for the fuel purchased for use in qualifying vehicles. Under such a scenario, at the end of the year the owner of the pathway technology would submit, with their state tax return, an application to receive a tax credit for every gallon equivalent of fuel that was purchased during the tax year and delivered into the qualifying vehicle. The state would then either credit this amount from applicant's state tax bill, or refund the applicant the difference. Like the other financial incentives described in this section, the fuel tax credit would have a shelf life, and expire either after a specific date, or after the state determines that there has been sufficient stimulus of the market for pathway technologies such that the tax credit is no longer needed as an incentive.

Reduce DMV Fees for Alternative Fuel Vehicles

Alternative fuel vehicles suffer an additional disincentive related to Department of Motor Vehicles (DMV) fees. Such fees are based on the purchase price of the vehicles, and are re-set every year based

[64] The law was official known as the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (Public Law 109-59; SAFETEA-LU).

on the projected residual value of the vehicle over time. Since alternative fuel vehicles are more expensive, the registration and license fees charged by the DMV are inherently higher for the vehicles that the state is trying to encourage consumers to purchase. To avoid this DMV fee penalty for cleaner vehicles, the initial fee and subsequent annual adjustments could be based on the lower-value of the conventionally fueled vehicle. This would reduce the cost to consumers, and would remove this clean technology purchase disincentive.

Develop and Implement Requirements for Public and Private Fleets to Purchase and Deploy Pathway Technologies

Another way to accelerate the commercialization of near-zero and power plant emission equivalent technologies is through the establishment of fleet mandates. Such requirements can work when the mandate is for a technology which, in the long run, will result in cost savings for the operator or when the purchase is supported with public resources. Such requirements will not work with the technology is too expensive to purchase or operate, or when the technology cannot perform the required duty cycle of the target fleet. An example of a successful fleet mandate is the SCAQMD's fleet rules, which encouraged the development and commercialization of a number of cleaner vehicle models during a period when conventional fuel prices were relatively low. In order to encourage the mass market penetration of these super low emission heavy-duty vehicles, policy makers could consider the use of targeted, carefully crafted fleet requirements. One could be a purchase requirement, patterned after the SCAQMD's program, in which the state requires fleets of a certain size to begin to purchase the requisite technologies once those technologies have achieved certain performance standards. Another could come in the form of a development condition, in which the state requires the use of certain kinds of technology when a public agency or a private interest seeks to engage in an activity that will require the use of heavy-duty vehicles and equipment.

Although it may seem contradictory to suggest the establishment of a purchase requirement, the policy that is being suggested herein differs significantly from the technology forcing measures depicted above. First, the purchase requirement described here is not for a particular technology, i.e. an electric, fuel cell or natural gas powered vehicle. It is for vehicles equipped with engines that meet a particular emissions performance standard, in this case 0.05 and 0.02 g/bhp-hr of NOx. Second, the requirements suggested below could be met by any technology that meets this emissions performance standard. To be effective, the purchase requirements represented below must allow fleet managers to choose the type of near-zero and power plant equivalent emission technology best suited for their operations; what matters to the state is that these super low emission technologies are introduced sooner, their commercialization happens faster, and that their market dominance occurs quicker and emission reductions sooner.

Fleet Purchase Mandates

One mechanism to stimulate growth in the market is for the state to establish a purchase requirement for all public fleets. This could include all state, county, and municipal agencies, as well as all special purpose agencies, e.g. transit, water and air districts, and all public or private utility fleets (defined broadly to include electric, gas, water, telephone and cable companies). Such a measure could be structured in a variety of ways. One would be similar to the fleet mandate first established by the SCAQMD in 2000, which required all covered fleets to purchase only vehicles that met specified criteria after a particular date. Another approach could emulate the ARB's purchase requirements, such as the ZBus program, which stipulate that a certain percentage of a fleet's new acquisitions must be near-zero or power plant emission-equivalent vehicles by date certain. Either approach would send signals to fleet operators and manufacturers that the state seeks to stimulate the purchase and use of ultra-low-emission technologies.

The state should use the resources in order to not overburden cash-strapped public agencies with the cost of purchasing technologies that are likely to be more expensive than their dirtier, conventionally-fueled counterparts, the state could and should use the resources from the auction of GHG allowances. As noted, not only would these ultra-clean vehicles reduce emissions of smog-forming chemicals and toxic air contaminates, but they would also reduce emissions of GHGs. This is exactly the kind of emission reduction expenditure envisioned by the ARB when it formulated the cap and trade program, and the Greenhouse Gas Reduction Fund.[65]

Development Conditions

The placement of conditions on development differs from fleet purchase mandates in that the party that seeks to develop a project is likely to be adding to the inventory of pollutants through the construction activities of project development and increased traffic and energy consumption. Typically, the development of any project that is large enough to trigger an environmental review will entail both temporary (during construction) and permanent increases to the volume of pollution in the state's air. In order to address these increases, developers are often encouraged to utilize the cleanest available construction equipment, reduce construction dust, employ vehicle miles travelled reduction programs, and other mitigations. Going forward, it can become the policy of the state that, when considering the adoption of mitigation measures, developers should be encouraged to employ near-zero and power plant emission-equivalent vehicles.

In other arenas, it may be feasible to go a step further. One area where the state may have a great deal of leverage is in the potential energy development of the Monterey Shale. This vast 1,750 square mile geologic formation is believed to contain approximately 15.4 billion barrels of recoverable oil.[66] To develop this resource will require the use of horizontal drilling and hydraulic fracturing of the rock ("fracking"). It will also require the utilization of billions of gallons of brine water (presuming that the state will not allow the use of fresh water) pumped from the brackish water formation in the west side of the San Joaquin Valley. To successfully exploit this resource, oil companies will need to deploy hundreds, if not thousands, of trucks. Under normal circumstances, these trucks would be fueled with diesel, but the state can make it a requirement that, if a company is going to work in the Monterey Shale play, they must use trucks equipped with engines that meet the ultra-low-emission standards discussed herein. That would dramatically increase the likelihood that these technologies will be commercialized rapidly.

Encourage Expansion of RNG Production and Consumption

As more of the heavy-duty transportation sector (including trucks, buses, rail, and marine) move from diesel fuel to compressed or liquefied natural gas, renewable natural gas becomes an increasing attractive GHG reduction strategy. RNG has the potential to provide among the lowest carbon intensity of all the transportation fuel pathways.[67] Methane from renewable sources is easily used in NGVs; thus renewable natural gas can become a "drop-in" bio-fuel.

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[65] See http://www.arb.ca.gov/cc/capandtrade/auctionproceeds/auctionproceeds.htm.
[66] http://news.nationalgeographic.com/news/energy/2013/05/130528-monterey-shale-california-fracking/.
[67] See ARB, LCFS Carbon Intensity Lookup Tables, http://www.arb.ca.gov/fuels/lcfs/lu_tables_11282012.pdf.

There are several keys to expanding the production of RNG to make it cost competitive as a feedstock for transportation fuel. One key is the development of cost-effective ways to clean up the fuel to meet the state's specifications for its natural gas pipeline system. Another key is bringing down the cost of producing RNG. Improvements in technology, standardization, as well as economies of scale will help in this regard.

In addition, the matter of who bears the cost of this cleanup is another question that bears consideration. A key element to this equation is who will pay for "conditioning" RNG for integration into the state's network of natural gas transmission and distribution. If all of the costs for cleaning up RNG are placed on the end-user, renewable gas may be too expensive to compete with conventional gas. If the costs of conditioning the gas are viewed as a social good, RNG can be made more cost-effective for end-users, particularly in the transportation sector. Policy makers should consider the passage of policies that encourage the use of this important resource.

Conclusion

It is crucial for California to clean up its smog, reduce the exposure of its citizens to toxic diesel exhaust, and reduce the state's emission of pollutants that contribute to climate change. Although tremendous progress has been made addressing the state's air quality problems, more must be done, and more must be done more quickly. Current air quality and climate protection efforts fall short of achieving the necessary emission reductions of smog-forming gases and GHGs, condemning a majority of the state's residents to decades more of air that does not meet health standards.

Dr. Carl Moyer said it best: "It's the trucks, stupid!" California's ozone pollution almost entirely comes from transportation. Trucks, buses, and other equipment with heavy-duty diesel engines are the largest source of smog-forming gases in the transportation sector. Heavy-duty diesel technologies are also the largest source of toxic air contaminants, and a major emitter of GHGs. No plan to reduce smog or protect the climate can succeed without a robust, comprehensive, and effective strategy to drastically cut emissions from heavy-duty engines.

To address this, policy makers have tried many strategies, but the focus of their approach has been clear. For nearly 25 years, the emphasis of the state's air quality planning has been to force the development of transportation technologies that will produce vehicles that emit no pollutants. Air quality regulations have been premised on the assumption that the only way to meet ever-tightening NAAQS has been to mandate the technologies with zero-tailpipe emissions, and that such a strategy would also help reduce GHG emissions.

Unfortunately, in 25 years this strategy has only produced a couple of commercially successful BEV and FCVs in the light-duty market, and both did not come to market until recently.[68] No BEV or FCV technologies have emerged in the heavy-duty vehicle sector that have survived beyond the demonstration phase without heavy government subsidy. Given the expected high financial cost of these technologies for the foreseeable future, California's leadership must work to find new ways of achieving the emission reductions needed from transportation. Natural gas-powered HDVs can provide an immediate and cost-effective solution to achieve these much-needed emission reductions in the near-term, and can serve as the foundation for heavy-duty emission reduction strategy for the long-term.

Natural gas has long been the dominant alternative to diesel in HDVs. There are dozens of companies that produce heavy-duty engines, vehicles, storage, and dispensing equipment for natural gas, and more that produce, transport, and distribute natural gas to transportation end-users. Natural gas HDVs are mature, commercially successful technologies, the proliferation of which is growing rapidly because of the low cost of this fuel that has resulted from the shale gas revolution. End-users are demanding natural gas trucks, buses, and other heavy-duty and high-horsepower equipment, because fleet operators recognize that, even with higher capital and market entry expenses, converting to natural gas yields reduced life-cycle costs.

[68] See Angelo Young, "Are The Nissan Leaf And The Tesla Model S The Only Two Electric Vehicles That Matter?" International Business Times, August 8, 2013; http://www.ibtimes.com/are-nissan-leaf-tesla-model-s-only-two-electric-vehicles-matter-1378329.

Today, thousands of heavy-duty NGVs are on California's roadways, logging millions of miles with very low emissions. These commercially proven natural gas HDVs are more than just a "bridge technology" to the future of California's near-zero-emission heavy-duty transportation sector; <u>they are part of its foundation</u>. Heavy-duty NGVs are the only mainstream, commercially proven technology that is clearly evolving toward achieving ultra-low emissions, i.e., equivalent to (or below) power plant emissions from recharging a heavy-duty BEV. More importantly, their development is already underway.

It is critical that California policy makers develop a dynamic, aggressive, and all-inclusive suite of policies that promote the rapid introduction of near-zero and power plant emission-equivalent HDVs. Policies that focus on environmental performance are more likely to result in a wider array of cost-effective choices sooner. Natural gas-fueled transportation technologies are poised to deliver the emission reductions required to reach the state's air quality and climate protection objectives sooner and more economically than other alternatives. Coupled with continued promotion of zero-emission technology, particularly in those sectors of the vehicle population where the most progress is being made, an air quality plan that encourages the rapid development and massive deployment of near-zero and power plant emission-equivalent NGVs can propel California down the path toward its environmental and economic goals.

Appendix A – Current Demonstrations of Pathway Technologies

Many of the technologies identified as part of the pathway to near-zero/zero-emission equivalent heavy-duty vehicles are being developed and demonstrated today. Examples of demonstration programs are provided in this appendix.

Plug-in Hybrid Natural Gas Drayage Truck

US Hybrid is working to develop and demonstrate a Class 8 drayage truck that features a plug-in hybrid drive train with a CNG-fueled Cummins Westport ISL G engine. Objectives of the project include technical and market validation of the pre-commercial platform in preparation for a "full-scale, commercial vehicle production launch." The vehicle will feature an all-electric, zero-emission range of 30 miles, while operating at very low emissions when powered by natural gas. By combining the hybrid system and natural gas engine, the vehicle will eliminate idling and extend the applicability of the 8.9L natural gas engine to drayage applications with heavier loads, while targeting a 30 percent reduction in fuel consumption. According to US Hybrid, the key challenge is not technology, but building a vehicle with low life-cycle costs of ownership.

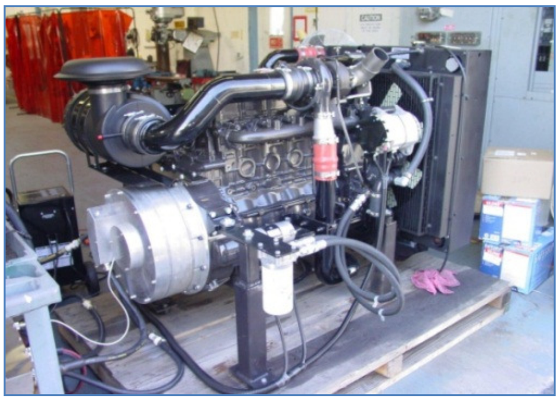

Figure A-1 – Engine integrated with hybrid system

Project partners include the US Hybrid, Gas Technology Institute, California Energy Commission, Southern California Gas Company, Cummins Westport, Freightliner, Calko Transport, and UC Riverside.

Potential Benefits

- Utilizes clean, natural gas ISL-G engines that already provide low-NOx emissions
- Hybrid system eliminates idling, thereby reducing emissions
- Combines fuel efficiency improvements and natural gas potentially to achieve more than 40 percent GHG reduction
- Compatible with renewable natural gas

Gas Turbine Hybrid Trucks

Capstone Turbines and Brayton Energy, two developers of gas turbine engines, are engaged in the development and demonstration of gas turbine hybrid trucks ranging in size from Class 3 to Class 8 trucks.

Brayton Energy Class 8 Turbine Hybrid

Brayton Energy is working to demonstrate an advanced natural gas turbine powering a hybrid Class 8 truck for long haul applications. The advanced design of the gas turbine is expected to provide up to 44 percent thermal efficiency, a significant improvement over traditional microturbines that is competitive with modern diesel engines. The gas turbine will also provide very low-NOx emissions (0.05 g/bhp-hr), a 75 percent reduction from the current diesel engine standard.

Project partners include Brayton Energy, California Energy Commission, Southern California Gas Company, Kenworth, and FedEx.

Potential Benefits

- Gas turbine provides a 75 percent reduction in NOx compared to today's diesel engines
- Natural gas provides GHG reductions versus diesel fuel
- Fuel flexible and compatible with renewable natural gas

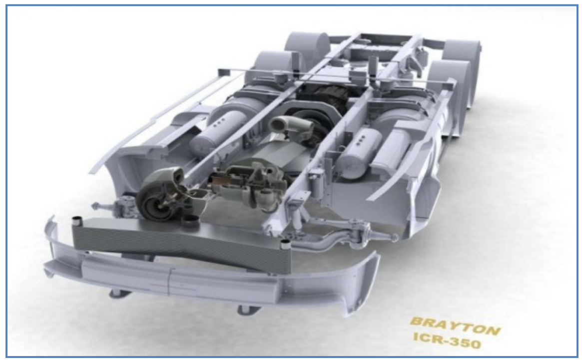

Figure A-2 – Brayton Energy gas turbine in a long haul truck chassis (Source: ICRTec)

Capstone Turbines Hybrid Trucks

Capstone has initiated demonstration projects with its C30 (30 kW) and C65 (65 kW) gas turbines in Class 3 to Class 7 trucks. These trucks will be the first to incorporate what Capstone is calling the "Capstone Drive Solution, which includes the Capstone microturbine along with liquid cooled power electronics, permanent magnet traction drive motor and vehicle power control system."[69] Capstone is teaming with Kenworth and the South Coast AQMD to demonstrate a Class 7 truck with a 10 mile all-electric range and a diesel-fueled microturbine. A smaller Class 4 truck fueled by natural gas is also being demonstrated in partnership with Wrightspeed utilizing an Isuzu NPR truck chassis.

Figure A-3 – Capstone gas turbine and Wrightspeed hybrid system in an Isuzu truck chassis (Source: Capstone Turbine Corporation)

Project partners include Capstone, Kenworth, South Coast AQMD, Wrightspeed, and Isuzu.

Potential Benefits

- Gas turbine could achieve NOx emissions rates that are lower than power plant equivalent-emissions
- Hybrid system could double the vehicle's fuel efficiency
- Eliminates exhaust treatment systems
- Fuel flexible and compatible with renewable natural gas

[69] Capstone Turbines press release, "Capstone to Demonstrate Heavy Duty Hybrid-Electric Drive System with Major U.S. Truck OEM," http://www.capstoneturbine.com/news/story.asp?id=581.

Next Generation Refuse Truck and Transit Bus Engine

Doosan and Southwest Research Institute are developing a next-generation natural gas engine with the goal of achieving near-zero-emissions without sacrificing the performance and efficiency of a 2010 diesel engine. The development effort will demonstrate several technologies for natural gas engines, including advanced ignition systems, improved in-cylinder fuel mixing, and advanced knock and misfire detection systems on a modified Doosan 11 liter engine.

Figure A-4 – Natural gas refuse truck

Project partners include Doosan, Southwest Research Institute, National Renewable Energy Laboratories, California Energy Commission, South Coast AQMD, and Southern California Gas Company.

Potential Benefits

- A 75 percent reduction in NOx compared to today's diesel engines
- No loss in engine performance or efficiency
- Natural gas provides GHG reductions versus diesel fuel
- Compatible with renewable natural gas
- Potential to study natural gas/hydrogen blends in later phases

Catenary Hybrid Trucks

Siemens and the South Coast AQMD are partnering to demonstrate an electrified roadway system for heavy-duty trucks based on an overhead catenary system. The demonstration will include natural gas, diesel, and battery-electric trucks operating on all-electric power when connected to the catenary system. Each truck will also be equipped with a battery pack for 10 or more miles of zero-emission range when not connected to the catenary system. Natural gas and diesel-fueled trucks will be capable of operating in a hybrid mode when the battery pack is depleted, extending the range of the trucks when not connected to the catenary system. The system is a potential technology for the I-710 zero-emission truck corridor.

Project partners include South Coast AQMD, Siemens, California Energy Commission, Port of Los Angeles, Port of Long Beach, Volvo, and Transpower.

Potential Benefits

- Unlimited zero-emission miles when connected to the catenary system or operating on the on-board battery
- Hybrid system eliminates idling and can improve vehicle efficiency when operating off of the catenary system
- Fuel neutral system
- Natural gas trucks are compatible with renewable natural gas

Figure A-5 – Siemens catenary truck concept (Source: Siemens)

Appendix B – Pathway Technologies for Off-Road Applications

Historically, on- and off-road vehicles have shared many of the same technologies. The most obvious examples of this technology sharing are diesel and gasoline engines. As emission standards for off-road engines have become more stringent, many of the emission control technologies used in on-road vehicles, such as exhaust gas recirculation, oxidation catalysts, and diesel particulate filters have also migrated to non-road applications. Fuel efficiency technologies including electronic fuel injection and turbocharging are additional examples. In fact, the overall trend for technology development in non-road applications is to adopt technologies that were first deployed in on-road applications. Many of the pathway technologies described for on-road vehicles are likely to follow this same trend and cross over to off-road applications, or in some cases, are already available in off-road applications.

Figure B-1 – Typical trend of technology development and deployment across equipment sectors

Advanced Engines

Engine advances often cut across all sectors because they tend to provide some combination of improved fuel efficiency, pathways to compliance with emissions regulations, improved performance, and/or reduced lifecycle costs. Not all engine advances are equally desirable in each sector; however, the broad range of technologies being developed, increasing diesel and gasoline fuel prices, and increasingly stringent emission regulations support the position that many new technologies will be deployed in each sector. Fundamental improvements such as reductions in friction and parasitic losses, improved sensors and controls, and increased use of turbocharging are prime examples of technologies that provide benefits across engine types, fuels, and end-use sectors.

Advanced After Treatment

The off-road market has already seen the adoption of some on-road exhaust after treatment technologies, including three way catalysts and exhaust gas recirculation. Improvements to catalyst formulations and tighter integration of after treatment technologies are examples of technologies that are likely to migrate from on-road to off-road sectors.

Hybridization

Many examples exist of the transfer of hybrid technologies between on-road and non-road applications. Hybrid-electric and hybrid-hydraulic technologies developed for heavy-duty trucks, buses, and semi-tractors are now being applied to cargo handling equipment such as terminal tractors and construction and earth-moving equipment. Further, many of the components used in these systems are similar, regardless of the end-use sector. This makes these technologies well positioned to benefit from advances in key components such as energy storage systems and control systems.

Vehicle Integration

Improved vehicle integration is already producing significant benefits in the heavy-duty on-road sector, as evidenced by programs like U.S. EPA's SmartWay program. However, the key technologies envisioned under the strategy of vehicle integration described in this paper are the least likely to transfer to the off-road sector. This is simply because the key vehicle integration improvements in the areas of vehicle weight, aerodynamics, and rolling resistance are less likely to be applicable to off-road vehicles, or would produce little benefits in terms of emissions or costs.

Fuels, Storage, and Infrastructure

As vehicles and engines transition to natural gas, there are clear cross-sector benefits to improvements in natural gas fuels, storage, and infrastructure. The fuel tanks, stations, and support equipment used to supply natural gas to the on-road sector are often the same products used to supply the growing off-road market. Hence, technological advances in the on-road sectors provide a directly translatable advance to off-road equipment using this same equipment.

Renewable natural gas (RNG) is an important, low carbon resource across the U.S. Placed into pipelines, RNG can be widely distributed. Captured and used at the point of production, RNG can fuel heavy-duty equipment, including refuse trucks and earth moving equipment. Finally, RNG created through methanation can act as an energy carrier for renewable energy sources such as solar, wind, and biomass. This presents the opportunity to bring renewable fuels to applications such oceangoing vessels, which would be infeasible to power with other energy carriers such as hydrogen or batteries.

Example Pathways for Off-Road Port Applications

Ports naturally function as intermodal hubs, connecting many different types of equipment – both on-road and non-road. The increasing development and deployment of natural gas-fueled trucks, cargo handling equipment, locomotives, and oceangoing vessels highlight ports as a nexus of cross-sector natural gas activity. The following three examples highlight potential pathways for marine vessels, locomotives, and cargo handling equipment to achieve significant long-term reductions in GHGs and criteria air pollutants, based on the use of natural gas technologies that can leverage the benefits of pursuing on-road technology pathways.

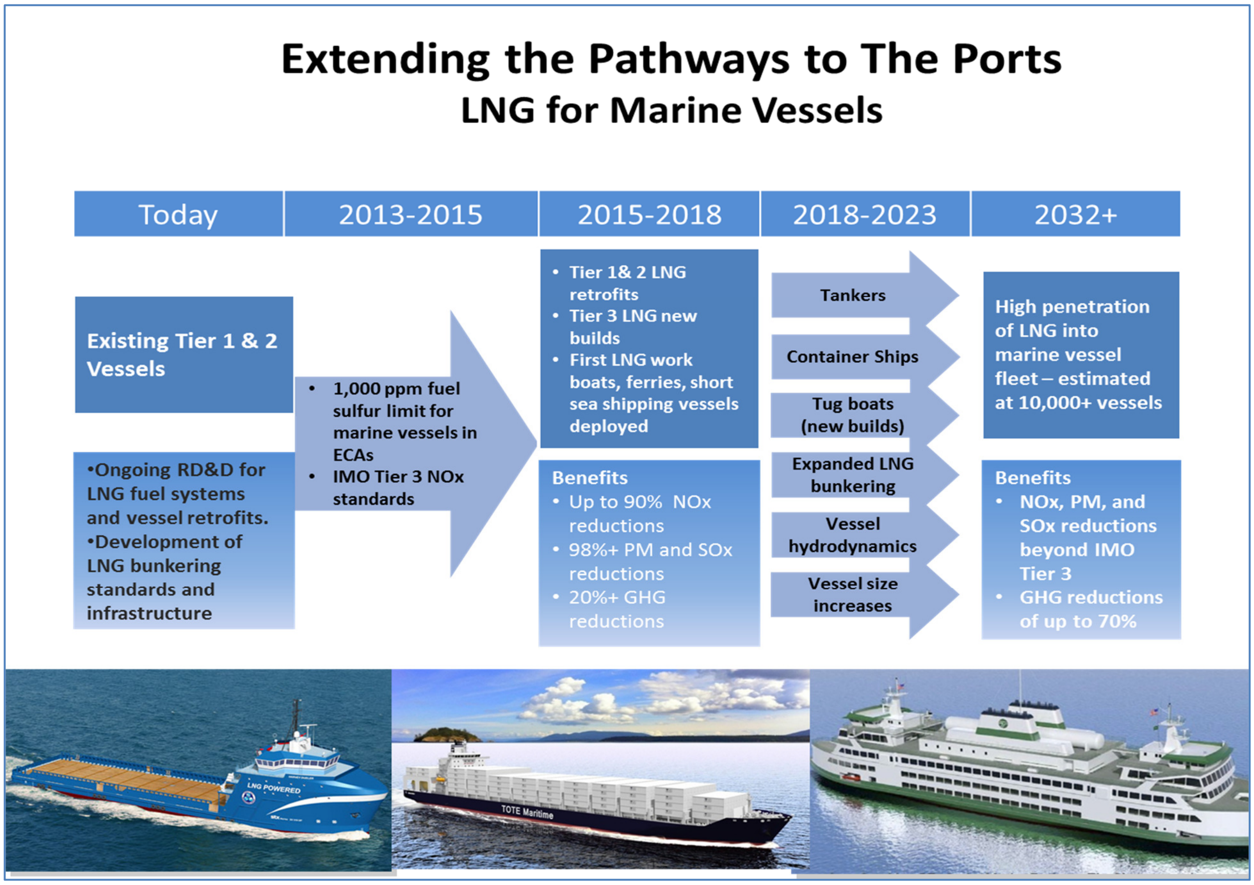

Figure B-2 – A possible pathway to emissions and GHG reductions for marine vessels

LNG has long been used to power very large LNG bulk carriers. Now, ongoing RD&D efforts are poised to deliver North America's first LNG-fueled work boats, ferries, and short sea shipping vessels over the next couple of years. According to MAN, one of the world's largest manufacturers of marine engines, vessels running on LNG reduce NOx by 90 percent, and PM and SOx reductions of more than 98 percent compared to today's vessels. The lower carbon intensity of LNG provides an estimated 20 percent GHG reduction compared to heavy fuel oil or marine distillates. LNG is predicted to expand into other vessel types including container ships, tankers, and tug boats – bringing emissions and GHG benefits to vessels that cannot be feasibly powered by hydrogen or electricity. Other improvements such as vessel hydrodynamics (i.e., aerodynamics for ships) and the continuing trend of increasing vessel size could combine to provide GHG reductions of 70 percent or more from LNG vessels.

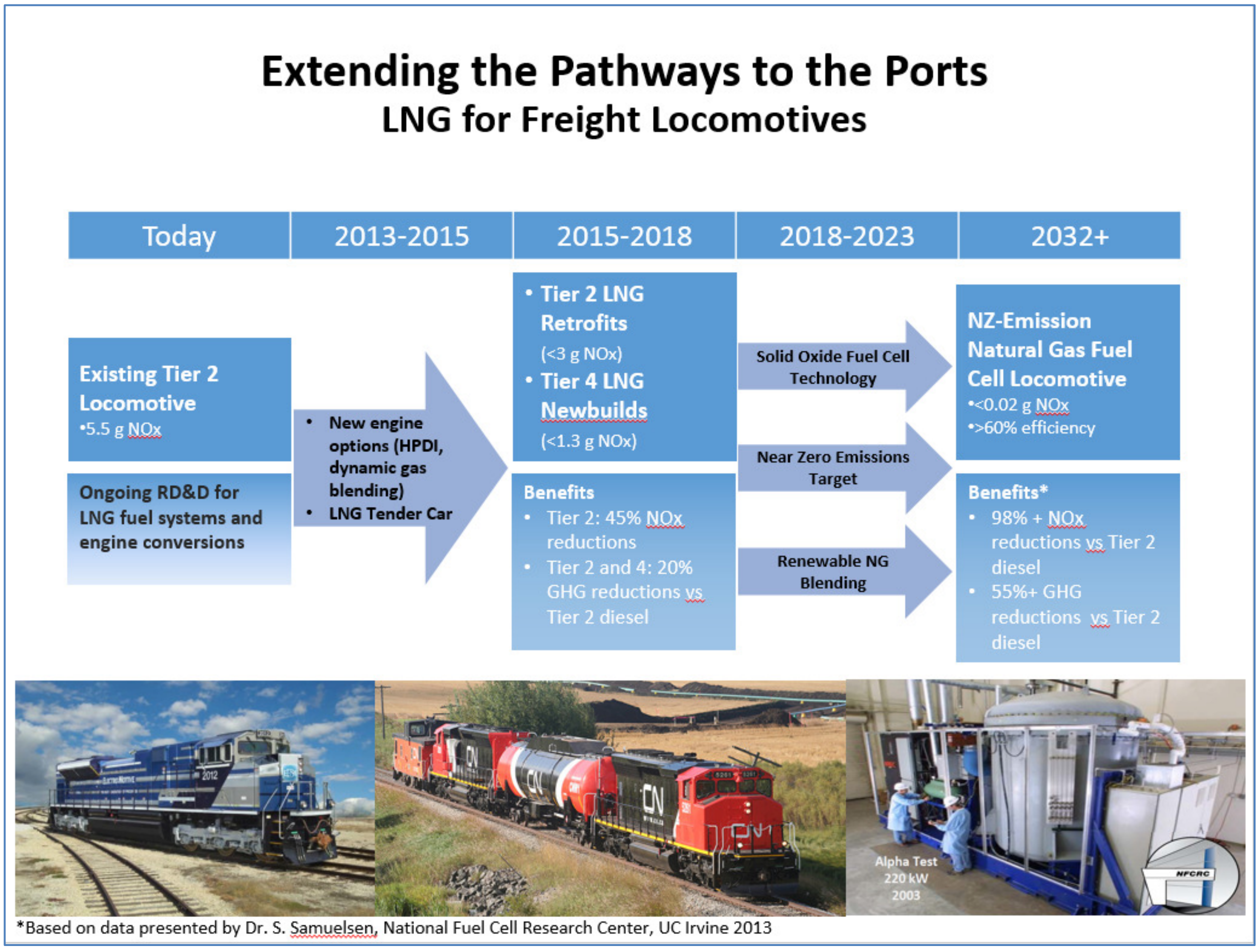

Figure B-3 – A possible pathway to emissions and GHG reductions for locomotives

Today's average Tier 2 locomotive emits roughly four times more NOx than the most advanced Tier 4 locomotives. However, the long life of locomotives means that Tier 2 technologies are likely to be with us for a very long time. Retrofitting these existing locomotives with natural gas can immediately reduce NOx emissions by 45 percent and can provide twice the NOx reductions that would be gained from replacing a Tier 4 locomotive with a zero-emission locomotive. The legacy fleet of locomotives should be a top priority for NOx reductions and natural gas offers an economically attractive way to achieve these reductions. Whether applied to Tier 2 or Tier 4 locomotives, natural gas is a less carbon intense fuel than diesel and offers a 20 percent GHG reduction over diesel. Beyond 2023, advanced technologies like solid oxide fuel cells could nearly eliminate NOx emissions and cut GHG emissions by over 50 percent while operating on natural gas. Blending renewable natural into the fuel mix could push GHG reductions close to 100 percent.

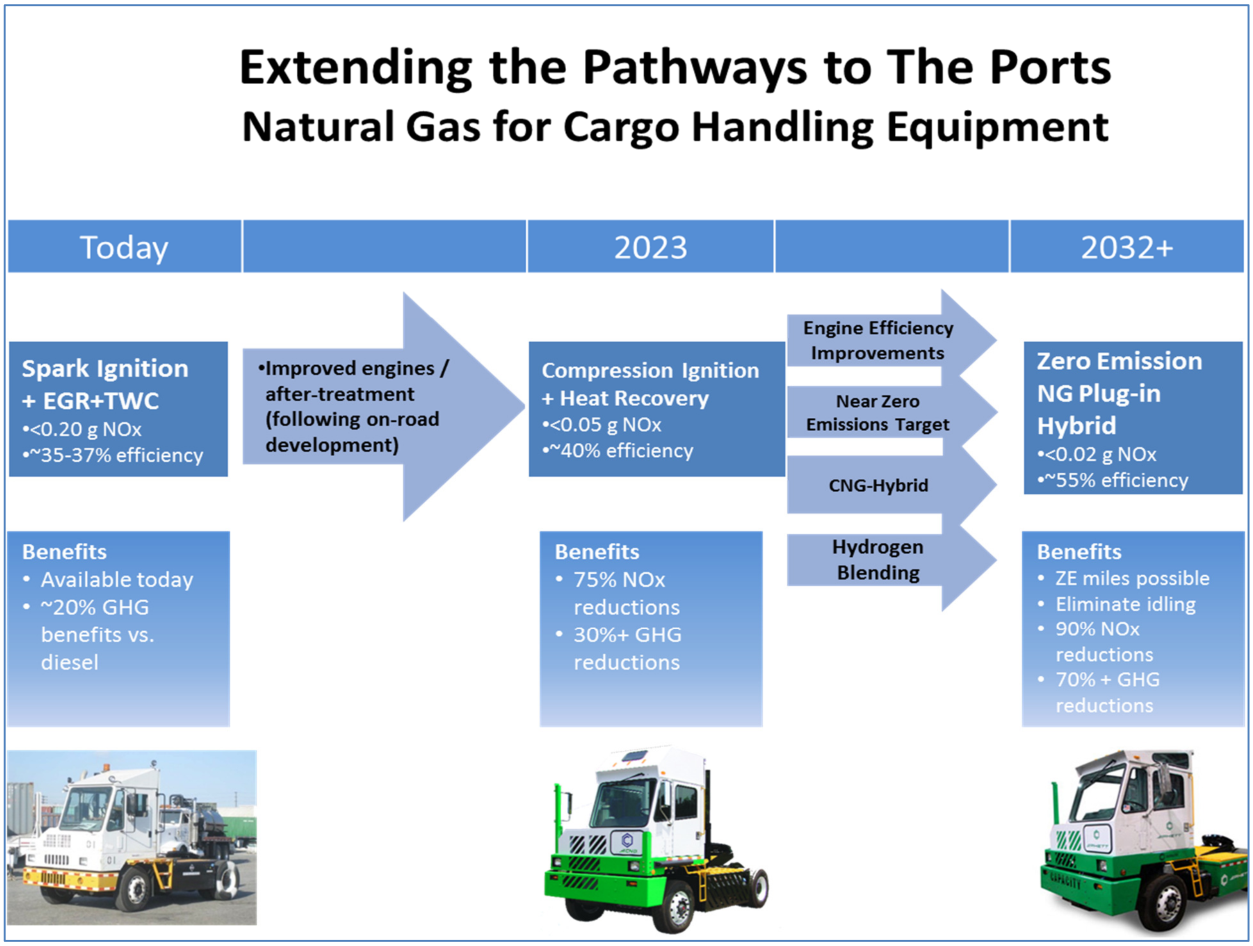

Figure B-4 – A possible pathway to emission and GHG reductions for cargo handling equipment

Manufacturers of cargo handling equipment, such as terminal tractors, already offer natural gas options that meet today's most stringent heavy-duty on-road and off-road emission standards. These vehicles utilize the same Cummins ISL G engine used in on-road trucks and are expected to follow the same technology development pathway as on-road natural gas engines, ultimately achieving 90 percent NOx reduction below today's standards. Hybridization will also provide significant benefits with zero-emission operations and fuel consumption reductions in this sector that is characterized by high idle times and significant low speed operation.

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