

# GAME CHANGER

TECHNICAL WHITE PAPER

## EXECUTIVE SUMMARY

NEXT GENERATION HEAVY-DUTY  
NATURAL GAS ENGINES FUELED  
BY RENEWABLE NATURAL GAS

PREPARED FOR



PREPARED BY



Gladstein, Neandross & Associates

## GAME CHANGER:

### Next Generation Heavy-Duty Natural Gas Engines Fueled by Renewable Natural Gas

Abstract and Executive Summary

April 2016

#### Authorship and Uses

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## ABSTRACT

One fuel-technology platform meets all the commercial feasibility and logistics tests to immediately begin this transformation: near-zero-emission heavy-duty NGVs fueled by increasing volumes of ultra-low-GHG renewable natural gas.

This White Paper explores the need—and leading approaches—to immediately start deploying zero-emission and near-zero-emission heavy-duty vehicle (HDV) technologies on a wide-scale basis in the United States. Expeditious action is needed to reduce smog-forming emissions from HDVs to restore healthful air quality—as is legally required under the federal Clean Air Act—for approximately 166 million Americans who reside in areas with exceedingly poor air quality. At the same time, to combat global climate change, the United States must aggressively reduce greenhouse gas (GHG) emissions from HDVs, which are the fastest growing segment of U.S. transportation for energy use and emissions.

In many regions of the U.S., these goals cannot be achieved without a systematic transformation of today's diesel-fueled HDVs—particularly high-fuel-use heavy-heavy-duty vehicles (HHDVs)—to zero- or near-zero-emission technologies operated on low-carbon fuels. Four unique fuel-technology combinations currently hold the most promise to successfully achieve this transformation. These are: two types of advanced low-emission internal combustion engines (fueled increasingly by renewable natural gas or renewable diesel); and two types of electric-drive systems (powered by batteries or hydrogen fuel cells). Over the long term (several decades), it is likely that all four of these HDV architectures will contribute to meeting air quality and climate change goals.

However, air quality regulators have recognized that meeting air quality goals will require the immediate deployment of zero- and/or near-zero-emission HDVs, especially in the most-impactful HHDV applications like on-road goods movement trucking. This White Paper documents that only one fuel-technology platform meets all the commercial feasibility and logistics tests to immediately begin this transformation: near-zero-emission heavy-duty NGVs fueled by increasing volumes of ultra-low-GHG renewable natural gas (RNG).

In 2015, Cummins Westport certified the world's first heavy-duty engine at near-zero-emission levels (90 percent below the existing federal standard). To complement the NOx reductions provided by this landmark engine, conventional (fossil) natural gas provides significant GHG-reduction benefits. However, RNG completes the game-changing proposition by providing the lowest carbon intensity of any heavy-duty transportation fuel available in the market today. RNG can immediately provide deep GHG emission reductions when used in either in-use or new heavy-duty NGVs. Expanded RNG production in America can offer an array of environmental and economic benefits; these include enhanced job creation, improved air quality, and a number of environmental waste stream management improvements that will accrue at local levels.

Near-zero-emission natural gas engines using RNG provide a commercially proven, broad-based and affordable strategy to immediately achieve major reductions in emissions of criteria pollutants, air toxins and GHGs from America's on-road HDV sector. The 9-liter near-zero-emission engine being deployed today offers broad, immediate applicability in several HDV sectors that power our freight and public transportation systems (transit buses, refuse haulers, and short-haul delivery trucks). By 2018, Cummins Westport will certify and commercialize a near-zero-emission version of its existing 12-liter natural gas engine designed for HHDV applications. This 12-liter engine provides diesel-like performance for tractor-trailer trucks hauling

With nearly the full range of HDVs covered, the combination of new near-zero-emission natural gas engine technology and RNG provide the single best opportunity for America to achieve immediate and substantial NOx and GHG emission reductions in the on-road heavy-duty transportation sectors.

80,000 pounds over long distances and up steep grades, as routinely needed for goods movement trucking throughout our nation's interstate highway system. Notably, when near-zero-emission HHDVs with this engine begin to roll out in 2018, some large operator fleets will already be using significant volumes of ultra-low-GHG RNG to supplement (or entirely replace) fossil gas use.

With nearly the full range of HDVs covered, the combination of new near-zero-emission natural gas engine technology and RNG provides the single best opportunity for America to achieve immediate and substantial NOx and GHG emission reductions in the on-road heavy-duty transportation sectors. Equally important, major reductions of cancer-causing toxic air contaminants can immediately be realized in disadvantaged communities adjacent to freeways and areas of high diesel engine activity, where relief is most urgently needed.

While the opportunity and potential benefits to widely deploy near-zero-emission heavy-duty NGVs are quite large, significant challenges must be systematically and expediently addressed. This White Paper describes recommended actions for government and industry stakeholders that will help meet these challenges and immediately begin broad deployments of near-zero-emission heavy-duty NGVs, using progressively greater volumes of ultra-low-GHG RNG. First and foremost, national, state and local incentive funding programs should be established or strengthened that 1) subsidize the higher costs to produce and deploy these new-generation heavy-duty NGVs, and 2) help produce and transport RNG, where the economics and logistics are most conducive. Recommendations are provided about how to allocate available incentive funds toward deployments that can immediately and cost effectively achieve large reductions for key pollutants.



## EXECUTIVE SUMMARY

### America's Immediate Need for Zero- and Near-Zero Emission Heavy-Duty Vehicles

The dominance by fossil petroleum fuel in America's transportation sector—particularly the near-total use of diesel fuel by the largest “heavy-heavy duty vehicles” (HHDVs)—has many major adverse environmental consequences, with high corresponding economic costs.

Nationwide, on-road heavy-duty vehicles (HDVs) contribute approximately 50 percent of America's smog-precursor emissions and 20 percent of our transportation-related greenhouse gas (GHG) emissions. Heavy-duty trucks—primarily used to transport freight and goods—are the second largest and fastest-growing segment of the U.S. transportation system for both energy use and emissions of harmful pollutants. Despite significant progress to gradually move towards cleaner alternative fuels such as natural gas, propane, hydrogen, and electricity, America's transportation sector continues to rely heavily on combusting two fossil petroleum fuels: gasoline and diesel. Only a very small, albeit growing, percentage of energy consumed in the U.S. transportation sector comes from alternative or renewable sources.

The dominance by fossil petroleum fuel in America's transportation sector—particularly the near-total use of diesel fuel by the largest heavy-heavy duty vehicles (HHDVs)—has many major adverse environmental consequences, with high corresponding economic costs. HHDVs emit disproportionately high levels of smog-causing pollutants that cause millions of Americans to regularly breathe unhealthful air. They emit high levels of toxic air contaminants (TACs) such as cancer-causing diesel particulate matter (DPM); this disproportionately impacts minority populations living in economically disadvantaged communities, which are often located adjacent to freeways or within areas of high diesel engine activity. Finally, HHDVs are also major emitters of greenhouse gases (GHGs), which cause global climate change.

Under the federal Clean Air Act, air quality officials in areas that don't meet health-based National Ambient Air Quality Standards (NAAQS) must develop and implement emissions-reduction strategies that demonstrate how attainment will be achieved according to set time lines, most of which are in the next 5 to 10 years. The greatest ongoing air quality challenge is to attain NAAQS for ozone and fine particulate matter (“PM2.5”) in our nation's most-polluted air sheds; these include California's South Coast and Central Valley air basins, the greater Houston area, Phoenix and much of the Boston-Washington corridor. The key to achieve NAAQS for both ozone and PM2.5 is to aggressively control oxides of nitrogen (“NOx”) emissions from HHDVs. This must be done while also controlling other key pollutants, including GHGs and TACs.

Over the last two decades, America has made major advancements to reduce on-road HDV emissions of NOx, DPM, other TACs, and GHGs. Solid progress has been made to phase in lower emission diesel trucks and cleaner, alternative fuels to power a wide array of HDV types. In particular, today *approximately 65,000 heavy-duty natural gas vehicles (NGVs)* are being operated throughout the U.S., *avoiding combustion of an estimated 400 million diesel gallons annually*. While this represents less than one percent of the nation's in-use HDV fleet, the market accelerated in the last five to 10 years as Waste Management, Frito Lay, UPS, Anheuser-Busch, Procter & Gamble and many other large national corporations have made considerable commitments to the adoption of heavy-duty natural gas vehicle trucks and/or renewable natural gas fuel. In some cases, large heavy-duty fleets have achieved 100 percent conversion to NGV operations (e.g., the Los Angeles County Metropolitan Transit Authority, with approximately 2,300 CNG transit buses in operation). Heavy-duty natural gas

To meet health and environmental goals, America's heavy-duty transportation system needs a full transformation to the cleanest-available HDV technologies and fuels, as soon as they are developed and commercialized.

truck sales have represented approximately 2 to 3 percent of total market volume in recent years, while annual NGV sales in the refuse and transit sectors have been 60 and 30 percent respectively.

Despite these important advancements, faster and far-greater progress is required. To meet health and environmental goals, America's heavy-duty transportation system needs a full transformation to the cleanest-available HDV technologies and fuels, as soon as they are developed and commercialized. In areas with the most severe air quality problems—such as southern and central California, Phoenix and the greater Houston area—restoration of healthful air quality will require immediate, systematic phase in of HDVs that provide *zero-emission or near-zero-emission levels of NOx*.

### Key Related Policy Goals Involving Heavy-Duty Vehicles

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Consumption of energy, creation of local air pollution, and emissions of GHGs that exacerbate global climate change are all closely related in today's U.S. HDV sector. There are many federal, state and local policies converging in this nexus that are collectively helping to drive America's gradual transition towards advanced, clean HDV technology. Examples of key interrelated objectives involving the HDV transportation sector include the following:

- Reduce regulated pollutants (e.g. NOx) to attain National Ambient Air Quality Standards
- Reduce usage of petroleum-based diesel fuel
- Increase production and use of low-carbon renewable fuels
- Increase fuel economy of heavy-duty NGVs while reducing GHG emissions
- Reduce upstream leakage of emissions of methane (a GHG and Short-Lived Climate Pollutant)
- Reduce emissions of black carbon (a Short-Lived Climate Pollutant)
- Replace, retrofit or repower in-use HDVs that pre-date state-of-the-art emission controls

California has the nation's most-aggressive goals to address these types of energy and environmental policy issues. The California Air Resources Board (CARB) and other state and local transportation authorities have clearly laid out the state's need for early, wide-scale deployment of zero- and near-zero-emissions HDVs, especially in the most-impactful HHDV applications like on-road goods movement trucking.

### Four Leading Fuel-Technology Pathways

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Four unique fuel-technology combinations currently hold the most promise to successfully transform America's HDV transportation sector to zero and near-zero emissions using low-carbon non-petroleum fuels. These are: two types of low-emission internal combustion engines (fueled by renewable natural gas or renewable diesel); and two types of electric-drive systems (powered by batteries or hydrogen fuel cells). Each of these HDV pathways offers unique opportunity and challenges regarding their potential to help transform America's on-road HDV fleet. Over the long term (several decades), it is likely that all four of these HDV architectures will contribute to meeting air quality and climate change goals.

The essential need is for zero- and/or near-zero-emission technologies and fuels to deeply penetrate into the urban HDV and on-road transportation sector in less than 10 years.

However, the actual role that each will ultimately play largely depends on how soon and to what degree they can be commercially deployed on a wide-scale, especially in high-impact HHDV applications. The essential need is for zero- and/or near-zero-emission technologies and fuels to deeply penetrate into the urban HDV and on-road transportation sector in less than 10 years. As air quality regulators have widely recognized, early deployment is needed for hundreds of thousands of HDVs (especially HHDVs) using the cleanest available fuel-technology platforms. Lesser deployments will be insufficient in many U.S. cities to achieve health-based NAAQS, or drive down GHG emissions from the transportation sector as needed to mitigate global climate change.

The table below briefly describes each of the four leading HDV fuel-technology pathways, differentiated by their technology and fuel type, emissions profiles, and estimated timeline for initial commercial deployment to power significant numbers of on-road HDVs. As summarized below (and further documented in this White Paper), only one fuel-technology pathway and strategy provides the ability to immediately begin broadly providing extremely low NOx and GHG emissions in high-impact HDV sectors. This pathway involves early deployment of commercially available near-zero-emission heavy-duty NGVs using progressively higher blends of renewable natural gas (RNG), as highlighted by the **green dotted lines**.

**Table 1: Four leading fuel-technology pathways for zero-emission or near-zero-emission HDVs**

Prime Mover Technology	Assumed Fuel / Energy Source	Proven Regulated Emissions Profile ( <i>Direct HDV Emissions</i> )	Proven GHG Emissions Profile	Timeline for Commercialization as HD ZEVs or NZEVs
<b>Low-NOx Diesel Internal Combustion Engine</b> (possible hybridization with electric drive, plug-in capability)	<b>Renewable Diesel</b> (increasing blends with fossil diesel)	<b>Baseline:</b> meets 2010 federal heavy-duty emissions standard (modest NOx reduction using RD)	<b>Very Low:</b> RD has an excellent combination of low carbon intensity fuel / high engine efficiency	<b>Unknown</b> (lower-NOx engines expected by about 2018, but achievement of near-zero emission levels will be very challenging)
<b>Low-NOx Natural Gas Internal Combustion Engine</b> (possible hybridization with electric drive, plug-in capability)	<b>Renewable Natural Gas</b> (increasing blends with fossil gas)	<b>Near-Zero-Emission:</b> engine(s) certified to 90% below existing (2010) federal—NOx standard	<b>Extremely Low:</b> ultra-low or negative carbon intensity fuel options / good engine efficiency	<b>Immediate</b> for 9 liter HDV applications (trucking, refuse, transit); <b>2018</b> for HHDV 12L applications
<b>Battery Electric Drive</b> (possible hybridization with range extending fuel cell, other options)	<b>Grid Electricity</b> (increasing percentages made from renewables)	<b>Zero Emission:</b> meets CARB's definition (no direct-vehicle emissions)	<b>Very Low:</b> excellent combination of low carbon intensity fuel / very high drivetrain efficiency	<b>10 to 20 Years</b> in HHDV applications; <b>Immediate</b> for use in short-range MHDV and transit applications
<b>Fuel Cell Electric Drive</b> (likely hybridization with batteries for regenerative braking and peak power)	<b>Hydrogen</b> (increasing percentages made from renewables)	<b>Zero Emission:</b> meets CARB's definition (no direct-vehicle emissions)	<b>Very Low:</b> excellent combination of low carbon intensity fuel / very high drivetrain efficiency	<b>10 to 20 Years</b> in HHDV applications; <b>Potentially Near-Term</b> for use in short-range MHDV and transit applications

## Game Changer: Commercially Mature Near-Zero-Emission Heavy-Duty NGVs

These three CWI low-NOx engines can collectively power a full range of on-road HDV applications where heavy-duty natural gas engines are already available across a wide range of leading OEM truck chassis product offerings.

Near-zero-emission heavy-duty NGVs provide a game-changing proposition because they can immediately begin transforming America's diesel-dominated freight movement system. In September 2015, CWI's 8.9 liter ISL G NZ engine became the world's first heavy-duty engine certified to meet CARB's lowest-tier optional low-NOx emission standard of 0.02 g/bhp-hr NOx. This "next-generation" heavy-duty natural gas engine is now commercially available in a broad range of HDV sectors that power our freight and public transportation systems (transit buses, refuse haulers, and short-haul delivery trucks). In 2017 CWI is expected to also certify with CARB and EPA a near-zero-emission version of its 11.9 liter ISX12 G engine, with commercial product to be available immediately after certification is achieved. This will expand on-road applications of near-zero emissions HDVs into HHDTs used in high-fuel-use goods movement applications, including for-hire long-haul trucking. CWI is also expected to certify its 6.7-liter ISB6.7 G engine to CARB's 50 percent optional low-NOx level (0.1 gbhp-hr), and make it commercially available in limited applications by 2017. (Note: other heavy-duty engine manufacturers are also working to certify and commercialize near-zero-emission heavy-duty gaseous fuel engines.)

The figure below summarizes the important low-NOx credentials of these three CWI engines, and their immediate-to-near-term timeframes for commercial rollout.

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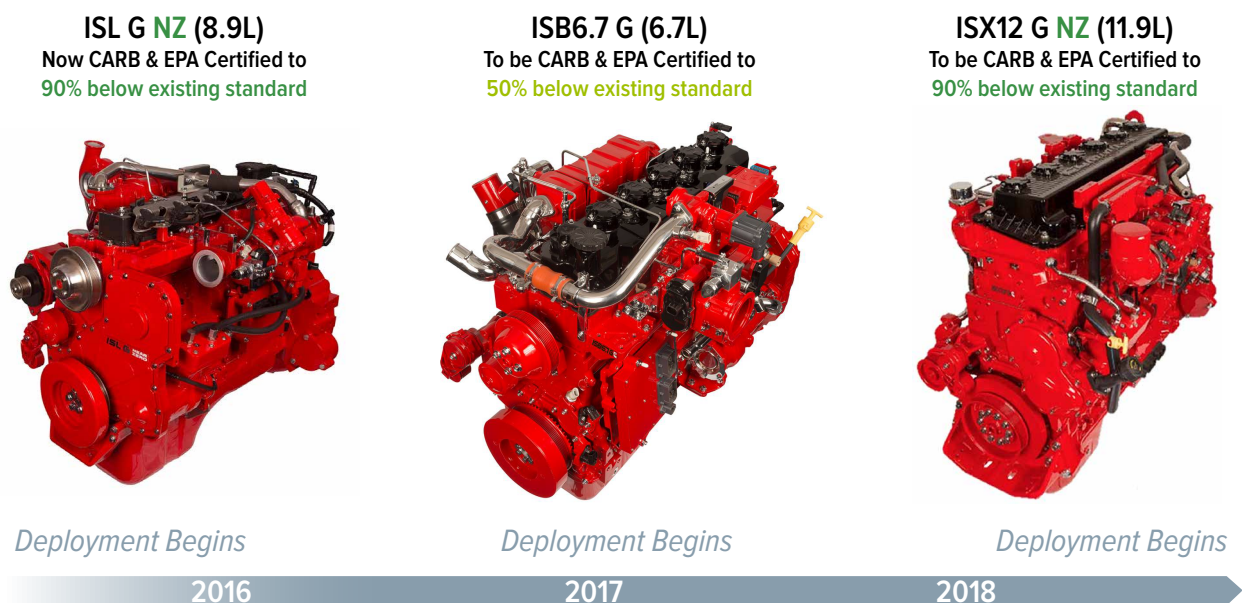


Figure 1: CWI heavy-duty ultra-low-NOx engines: anticipated timeline for certification and deployment



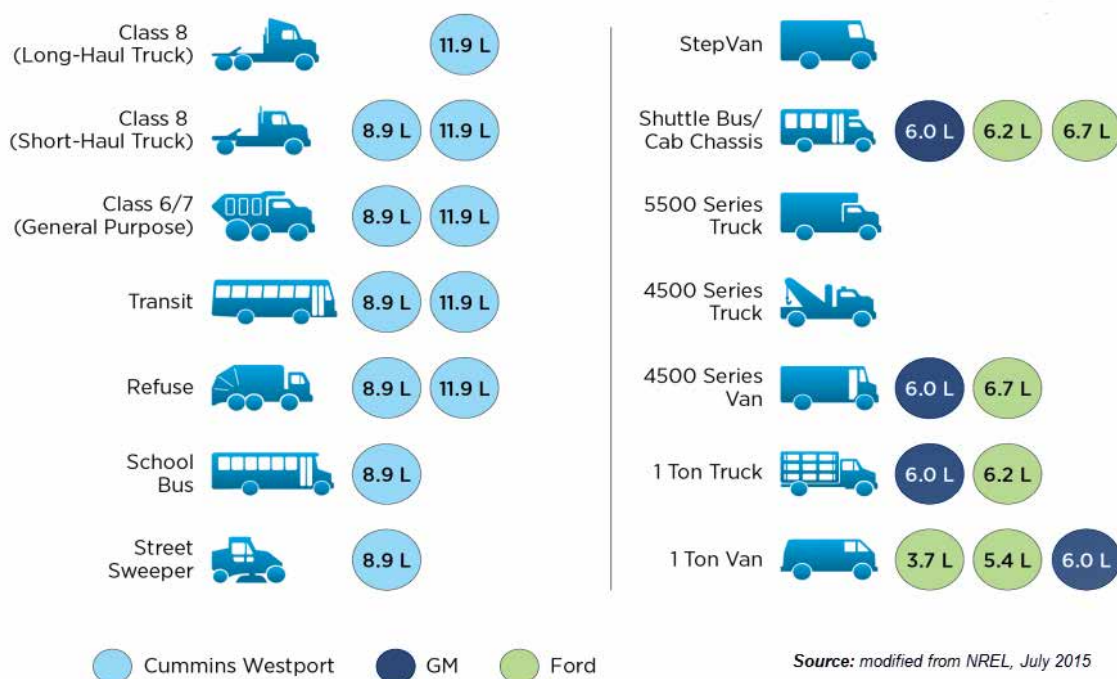


Figure 2: Existing HDV applications and engine sizes that can utilize CWI's ultra-low-NOx engines

Designation of CWI's NZ engine technology as being "near-zero-emission" may significantly undervalue its relative importance as a long-term, sustainable ultra-low-emission option for America's HDV transportation sector.

As shown in the left side of the figure above, CWI's 8.9-liter and 11.9-liter natural gas engines are now offered in many types of HDVs. Its 6.7-liter natural gas engine will work in many smaller trucking applications that currently offer natural gas models (right side). Collectively, these three heavy-duty natural gas engines can deliver up to 90 percent NOx reductions in virtually every on-road HDV application by 2018, beginning with immediate deployments of the 8.9-liter engine.

### Equivalent NOx Emissions as Low as Heavy-Duty Battery Electric Vehicles

Designation of CWI's NZ engine technology as being "near-zero-emission" may significantly undervalue its relative importance as a long-term, sustainable ultra-low-emission option for America's HDV transportation sector. Based on an analysis further described in this White Paper, HDVs powered by engines certified to 0.02 g/bhp-hr emit smog-forming NOx at levels as low as, or lower than, NOx emissions associated with generating the electricity used to charge heavy-duty battery-electric vehicles (BEVs). This is due to the relatively high NOx emissions rates from today's power plants—particularly in regions that rely heavily on coal-based generation. However, even in states like California, Oregon and Washington—where the average "grid mix" is fairly clean due to higher reliance on clean renewable energy sources and natural gas power generation—HDV engines emitting at 0.02 g/bhp-hr NOx compare very favorably to heavy-duty BEVs for extremely low NOx emissions.

## Market Momentum Achieved Over Decades

Today, an estimated 65,000 heavy-duty NGVs are displacing diesel fuel on America's roadways. This accomplishment is unique in America's HDV transportation sector for any low-emission alternative fuel.

This game-changing proposition for clean HDV transportation did not emerge suddenly, or in a vacuum. As described in this White Paper, NGV stakeholders, OEMs, end users and government agencies have made very large investments over the last two decades to make natural gas a mainstream transportation fuel. A wide array of public and private heavy-duty fleet operators and NGV industry stakeholders have spent *tens of billions of dollars* to purchase NGVs, build fueling infrastructure, upgrade maintenance facilities, train personnel and otherwise work to expand this still-developing market. Notably, invested public funds such as those that help end users “buy down” the incremental costs of NGVs often contribute to local and regional economies.

Today, many different manufacturers collectively produce a wide array of NGV and/or engine models for U.S. markets. In the HDV sector, nearly 20 U.S. truck and bus OEMs have allocated a significant amount of human and financial capital and other company resources to develop and offer NGV products on a national commercial scale. With continued market growth, leading heavy-duty truck OEMs have begun to enter into Tier 1 supplier arrangements and long-term partnerships with key component suppliers. In some cases, leading OEMs have made direct equity investment in component supplier businesses, thus indicating an expected growth of the market in forward years. These partnerships and collaborations are focused on improving the utility and lifecycle economics of heavy-duty NGVs by driving down costs; increasing on-board fuel storage capacities; shortening production and delivery timelines; and improving vehicle performance, operational reliability, maintenance and service, parts availability, and overall up-time and efficiency. The development of Tier 1 supplier arrangements - which require several years of consistent market growth - is a clear sign of a maturing marketplace for heavy-duty NGVs.

In aggregate, the alignment taking place in the sector points to a very strong, robust and increasingly integrated market for NGV technologies. It is important to recognize that it took two full decades of major ongoing efforts by a spectrum of stakeholders—combined with about five years of a very compelling fuel price spread benefitting end users—to achieve this unprecedented level of commercialization for a clean alternative fuel HDV technology. The result is that heavy-duty NGVs have emerged as a proven mainstream alternative to conventional diesel HDVs.

Today, on-road heavy-duty NGVs in the truck, transit and refuse sectors are fully commercialized, successful technologies. They have displaced very significant volumes of diesel. Commercial offerings have been growing, in response to the compelling price advantage natural gas has offered over diesel, combined with government incentives offered in states like Pennsylvania, Texas, California, Colorado and others. This has resulted in high demand for these products from heavy-duty fleet owners. An estimated 65,000 heavy-duty NGVs are now displacing diesel fuel on America's roadways every day. Despite relatively high capital and market entry expenses, end users have been able to achieve compelling life-cycle cost savings that provide attractive payback on investments.

This accomplishment is unique in America's HDV transportation sector for any low-emission alternative fuel. Only natural gas has reached—or even come close to reaching—this “critical mass” of investments, product offerings from mainstream OEMs, fueling station networks, training programs, incentive offerings, stakeholders,

and vehicle deployments. Notably, no mainstream heavy-duty OEMs have announced plans to commercialize any other type of heavy-duty alternative fuel vehicle (AFV) technology. No other type of alternative fueling stations exist that are specifically designed to accommodate HDVs, with the exception of proof-of-concept systems for a few select transit applications.

### Corporate Sustainability as a Driver for Heavy-Duty NGVs

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Beginning in late 2014, the price of diesel has dropped from record levels, thereby narrowing the price spread between it and compressed natural gas (CNG) and liquefied natural gas (LNG). Thus, life-cycle economics have not been a strong driver for fleet managers to switch their heavy-duty diesel vehicles over to NGVs. However, growing confidence in the major environmental benefits of commercially proven heavy-duty NGVs is providing an impetus for fleets to continue to make this transition. This is exemplified by the many major American corporations—both shippers and carriers—now investing in heavy-duty natural gas trucks as foundations of their sustainability policies, and in the interest of long-term fuel diversity and price stability. For example, UPS has already built 23 LNG and CNG fueling operations across 10 states. UPS's March 2016 announcement indicates it will soon build another 12 CNG stations. Increasingly, the company is investigating and using RNG to displace fossil natural gas at these stations. In Memphis and Jackson (Mississippi), UPS will use an estimated 1.5 million DGEs per year of LNG made from landfill gas to fuel up to 140 of its HDVs. Many other similar examples are described in this White Paper.

### Renewable Natural Gas: the Second Element for Transforming HDV Transportation

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RNG is the second  
element of this  
game-changing  
fuel-technology  
pathway.

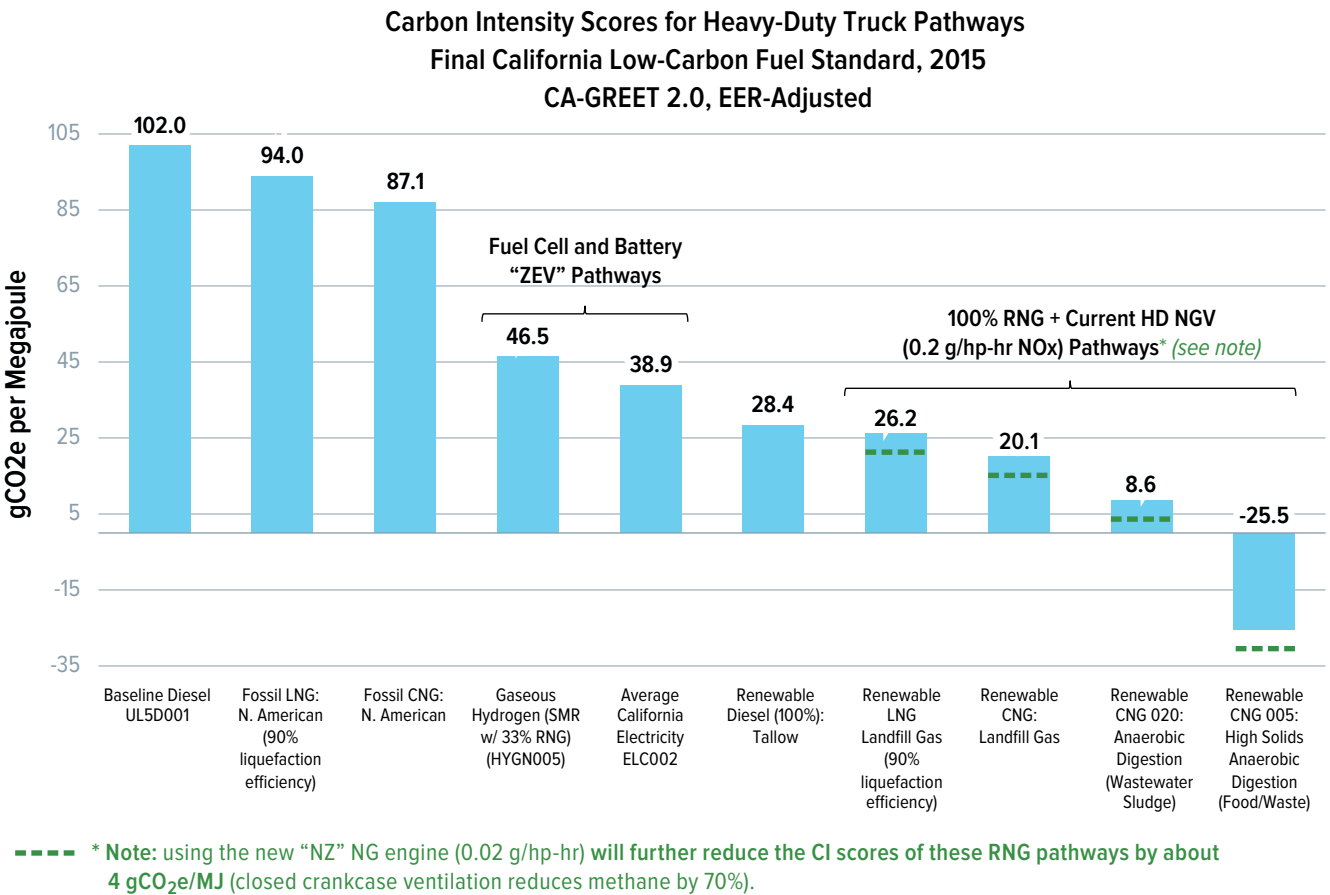
RNG is the second element of this game-changing fuel-technology pathway. RNG is a gaseous mixture of methane and other compounds that is produced from renewable sources, using either biological or chemical processes. Producing RNG is a highly sustainable process from multiple pathways. Various forms of waste streams that are otherwise environmental hazards requiring costly treatment or processing are instead converted to energy-rich, locally-produced renewable energy sources that ultimately displace higher-pollution non-renewable fuels. This simultaneously generates significant economic value and multiple other benefits. Even if RNG is not used as a transportation fuel (and is instead used to produce electricity), it can offer several important societal benefits; these include reduction of upstream methane leakage and flaring, mitigation of catastrophic wildfire, and improvements to agricultural processes and yields. Moreover, RNG production facilities can help create local jobs and economic development in virtually any community across America.

The most important benefits of RNG relate to its potential use to fuel hundreds of thousands of near-zero-emission heavy-duty NGVs. Used together to replace conventional diesel HDVs, this fuel and engine technology can immediately and uniquely begin delivering 90 percent (or greater) reductions in NOx emissions for the large U.S. fleet of on-road HDVs. Simultaneously, RNG will provide deep GHG reductions (80 percent or greater), due to the very low (and in some cases negative) carbon intensity values of various production pathways. This is clearly illustrated in the figure below, which compares preliminary “carbon intensity” (CI) values (in grams per mega joule of “CO<sub>2</sub> equivalent” GHGs) for eight different heavy-duty transportation fuel pathways.

RNG will provide deep GHG reductions (80 percent or greater), due to the very low (and in some cases negative) carbon intensity values of various production pathways.

According to this illustrative data from CARB, when fossil CNG or LNG are combusted in currently available spark-ignited heavy-duty engines, they provide CI reductions of approximately 15 and 9 percent, respectively (relative to the baseline diesel pathway). The CI values of CNG and LNG are decreased substantially when RNG replaces fossil natural gas as the feedstock. As the last four bars of the graph show, numerous RNG pathways provide very significant CI reductions relative to the diesel baseline. These range from a 75 percent reduction for “Renewable LNG: Landfill Gas,”<sup>1</sup> to a 125 percent reduction for “Renewable CNG: High Solids Anaerobic Digestion.” Moreover, an additional CI benefit (approximately 4 gCO<sub>2</sub>e/MJ) is achieved for each of these RNG types when combusted in CWI’s near-zero-emission engine. This is attributable to the engine’s closed crankcase ventilation system, which reduces “downstream” methane emissions by 70 percent. All four RNG pathways in CARB’s illustrative data have lower CI values than the “Average California Electricity” pathway (CI value of 31.0 gCO<sub>2</sub>e/MJ) assumed to recharge heavy-duty BEVs, and the “Gaseous Hydrogen

<sup>1</sup> This reflects the relative CI advantage in the LCFS today for fossil CNG and LNG compared to baseline diesel. This is likely to change over time, based on LCFS credit generation and other factors.



Source: California Air Resources Board, “LCFS Illustrative Fuel Pathway Carbon Intensity Determined using CA-GREET2.0,” discussion presented by staff on 9/17/15 and/or CARB LCFS Final Regulation Order, Table 6; note that “HSAD pathway is EER-adjusted by the CARB formula (-22.93 base CI divided by EER of .9), even though this improves its CI score.

Figure 3: Comparative carbon intensity (CI) scores for heavy-duty truck pathways (CARB, 2015)



(SMR with 33% RNG)” pathway (CI value of 46.5 gCO<sub>2</sub>e/MJ). Future changes to the grid mix and/or hydrogen-production processes will likely result in lower CI values for these two ZEV pathways.

CARB has noted that it is technically and economically feasible to deploy approximately 400,000 near-zero-emission HDVs by 2030, and this “large-scale deployment” of low-NO<sub>x</sub>, very-low-PM goods movement trucks “will provide the largest health benefit of any single new strategy” under consideration by California.

The middle bar of this figure shows that a “Renewable Diesel (100%) – Tallow” pathway can also provide low-CI transportation fuel. Renewable diesel (which is chemically different than “biodiesel”) is a “drop-in” replacement for conventional diesel. Growing numbers of HDVs in California and other regions are now using this renewable diesel fuel as a substitute for conventional diesel. It can provide compelling GHG reductions and modest criteria pollutant benefits in today’s diesel engines. To date, however, no heavy-duty diesel engine (using conventional or renewable diesel) has been certified below the existing NO<sub>x</sub> standard of 0.2 g/bhp-hr. Engine manufacturers have detailed challenging “NO<sub>x</sub>-GHG” tradeoff issues that must be resolved before heavy-duty diesel engines can be certified to the 0.02 g/bhp-hr NO<sub>x</sub> level, which as noted has already been achieved by CWI’s ISL G NZ natural gas engine. Heavy-duty diesel engines certified to 0.02 g/bhp-hr NO<sub>x</sub> are not expected to be developed and available until at least the mid-2020 timeframe. This assumes that challenging NO<sub>x</sub>-GHG tradeoff issues can be resolved, as necessary for low-NO<sub>x</sub> diesel engines to also comply with tightening federal fuel efficiency / GHG standards.

Heavy-duty natural gas engines appear to offer another important advantage over diesel engines: their ability to maintain low NO<sub>x</sub> emissions during in-use operation. Based on a body of test data, CARB has found that 2010-compliant heavy-duty diesel engines with advanced emissions controls can exhibit NO<sub>x</sub> “control challenges” during in-use operation in low temperature, low speed duty cycles. To date, in-use heavy-duty NGVs have not exhibited this problem with their emissions control technology, which is generally less complex than diesel technology. This has helped CWI achieve very-low NO<sub>x</sub> certification levels that still offer good margin, to meet very challenging requirements from CARB / EPA to maintain low NO<sub>x</sub> emissions throughout the useful life of the engine.

### Concurrence from Air Quality Regulators

Concluding that “combustion technology will continue to dominate” the on-road HDV sector over the next 15 years, CARB has found that low-NO<sub>x</sub> trucks are “the most viable approach” to meet California’s mid- and longer-term goals to attain NAAQS for NO<sub>x</sub> and PM<sub>2.5</sub>. CARB has noted that it is technically and economically feasible to deploy approximately 400,000 near-zero-emission HDVs by 2030, and this “large-scale deployment” of low-NO<sub>x</sub>, very-low-PM goods movement trucks “will provide the largest health benefit of any single new strategy” under consideration by California. To simultaneously meet GHG and petroleum-use-reduction targets, CARB will target approximately 55 percent of fuel demand for these trucks to be met with renewable fuel. As noted, only heavy-duty natural gas engine technology has been certified (by either CARB or EPA) for commercial sale at the near-zero-emission level, starting with CWI’s ISL G NZ engine. In CARB’s own words, “these advanced natural gas vehicles are expected to deliver near term opportunities to reduce NO<sub>x</sub> emissions, and with the use of renewable natural gas, could also deliver deep GHG emission reductions.” CARB concludes that “deployment of 350,000 electric trucks over the next 15 years would require technology development and cost that are well beyond what will be needed to deploy low-NO<sub>x</sub> trucks.”

The opportunity to rapidly achieve large-scale gains from commercially available heavy-duty NGVs using RNG does not diminish the important need for, and/or potentials of, heavy-duty ZEV technologies such as battery-electric and fuel vehicle vehicles. In certain MHDV and bus applications, there is good potential within the next decade to deploy increased numbers of heavy-duty ZEVs to meaningfully reduce NOx and GHG emissions.

CARB's plans to deploy large numbers of near-zero-emission HDVs in California are urgently geared towards attaining the ozone NAAQS by 2023 in the South Coast and Central (San Joaquin) Valley areas, which both face extremely tough challenges to drastically reduce ozone. Over just seven years, these air basins require very large NOx reductions from high-impact heavy-heavy-duty goods movement trucks and other HHDVs. At the same time, state and local goals for GHG reductions must also be met. The major tool that air quality regulators have in these two areas is to maximize government incentives towards immediate replacement of in-use diesel HHDVs with commercially available near-zero-emission heavy-duty NGVs using RNG.

### **The Need to Deploy All Feasible Zero-Emission and Near-Zero-Emission HDV Options**

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The opportunity to rapidly achieve large-scale gains from commercially available heavy-duty NGVs using RNG does not diminish the important need for, and/or potentials of, heavy-duty ZEV technologies such as battery-electric and fuel vehicle vehicles. In certain MHDV and bus applications, there is good potential within the next decade to deploy increased numbers of heavy-duty ZEVs to meaningfully reduce NOx and GHG emissions. Based on broad consensus about current heavy-duty ZEV technology, these are medium-fuel-use, return-to-base applications having daily range requirements less than about 100 miles. This has been widely acknowledged by air quality regulators at the Federal, state, and local levels. For example, to the greatest extent feasible, California's South Coast Air Quality Management District seeks to immediately deploy battery-electric and plug-in hybrid trucks, which can help provide valuable NOx, GHG and TAC reductions in short-range, medium-heavy-duty goods movement applications.

It is clear that America must continue to push for the cleanest on-road HDV fuel and technology pathways. All four heavy-duty ZEV and NZEV fuel-technology pathways described in this White Paper are needed for our nation to meet daunting energy and environmental challenges, while continuing to transport freight efficiently and competitively. It will be essential to avoid over-reliance on any single fuel-technology combination, or "picking winners" in unsure markets.

### **Renewable Natural Gas: Opportunity and Challenges**

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This White Paper provides further discussion and specific recommendations about how to unlock our nation's major resources to produce RNG as a transportation fuel. Key areas of importance include the need to better recognize and monetize the diverse societal benefits that can be gained through management of environmental waste streams to produce RNG and use it as a substitute fuel for HDVs. The implications go well beyond transforming America's heavy-duty transportation sector. Expanded production and use of RNG for HDVs can be important catalysts for building our nation's overall markets for sustainable, environmentally benign renewable fuels (such as renewable hydrogen and electricity).

Due to the availability  
of federal and state  
monetary incentives,  
RNG is an affordable and  
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HDV transportation sector.

Producing RNG is significantly more expensive than conventional (fossil) natural gas. However, transportation is a high-value use for RNG, due to the availability of federal and state monetary incentives (as described in this White Paper). The net result is that currently, RNG is an affordable and increasingly important ultra-clean fuel for the HDV transportation sector. In 2015, approximately 80 million DGEs of RNG were consumed by heavy-duty NGVs in California and across the U.S. Some companies are producing RNG onsite at landfill or dairy operations, and using it to power their own large fleets of heavy-duty NGVs. Because there is no “blend wall” for RNG; it can be used as a drop-in fuel in today’s existing heavy-duty natural gas engines at any mixture with conventional natural gas, up to 100 percent RNG. That means an estimated 65,000 in-use medium- and heavy-duty NGVs that are currently moving goods and people on America’s highways could potentially start using RNG, where locally available and price competitive. In areas across the U.S. where affordable RNG is not yet available—or as RNG is gradually blended into the natural gas mix—heavy-duty NGVs using fossil natural gas will still provide very important GHG-reduction benefits compared to conventional diesel HDVs.

RNG is widely available in California, and it currently fuels more than half of the state’s NGVs. However, RNG production specifically for the purpose of fueling heavy-duty NGVs is relatively limited in America. Several barriers and challenges remain before national production on a large scale will occur. However, with concentrated focus and strong development efforts, the potential to greatly expand RNG production in the U.S. is significant. Studies from a range of sources (including the U.S. government) estimate that there are sufficient technically recoverable feedstocks in the U.S. to produce enough RNG to displace tens of billions of diesel gallons. This is enough RNG to fuel large portions of America’s heavy-duty on-road goods movement sector.

### **Importance of Proportional Incentives for Immediately Deployable Heavy-Duty NZEVs**

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The use of economic incentives by government agencies has long been an important tool to control environmental pollution and drive the use of energy alternatives to petroleum. Incentive funds have been extremely important in accelerating commercialization of alternative fuel HDVs, and their replacement of older in-use diesel vehicles. Notably, government agencies that allocate public funds to incentivize low-emission HDV purchases as an air quality improvement strategy must carefully consider the magnitude, type and timeline of air quality benefits that can be achieved. The associated emissions reductions must be real, quantifiable, enforceable, and surplus. In addition, incentive allocations must meet standardized criteria for cost effectiveness. Finally, to achieve the fastest results, they should be focused on HDV technologies and fuels that are fully commercialized and immediately ready for wide scale deployment.

To provide a tangible example of the effectiveness of public investments in near-zero emission heavy-duty NGVs and RNG, this White Paper provides an analysis that compares the relative costs and air quality benefits of spending \$500 million to help purchase three different HDV options.

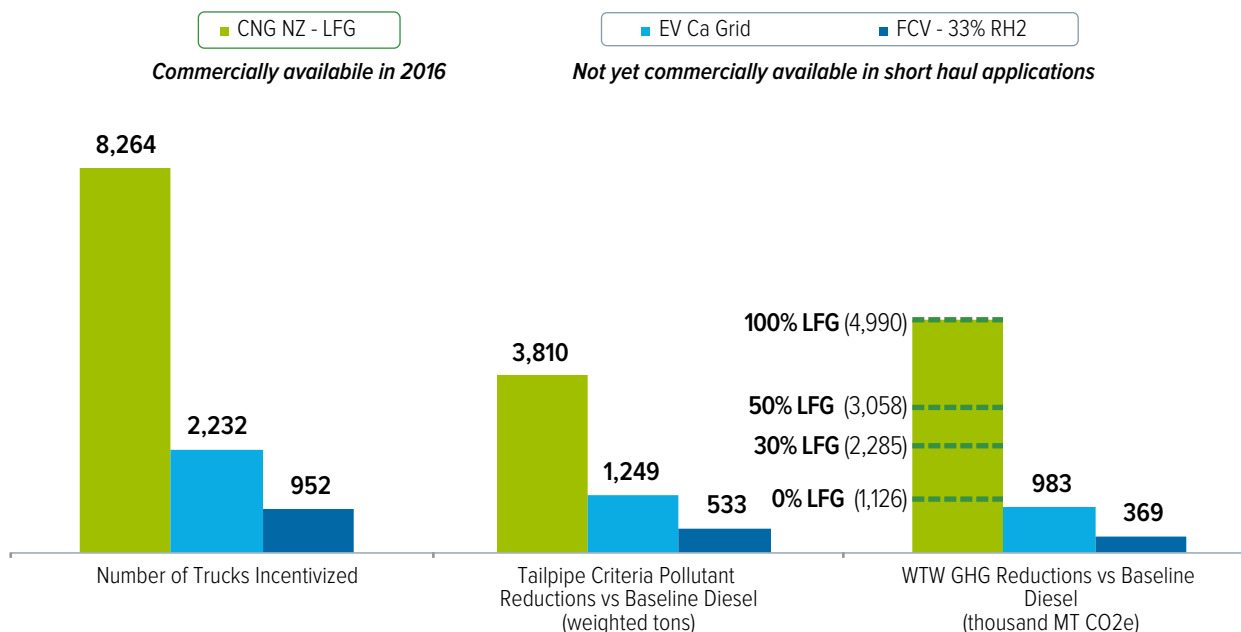
The combination of near-zero-emission heavy-duty NGVs and increasing volumes of ultra-low-GHG RNG fuel provides an extremely cost effective option for immediately achieving major NOx and GHG reductions from America's on-road HDV sector.

As the figure below demonstrates, a \$500 million investment would help deploy roughly 4X more near-zero-emission CNG trucks than battery-electric trucks, and 9X more compared to fuel cell trucks. As a result, roughly 3X and 8X more tailpipe criteria pollutants would be reduced respectively. And finally, using the \$500 million to buy down near-zero-emission CNG trucks that operate on 100 percent RNG from landfill gas (CNG NZ - LFG) would provide roughly 5X and 14X GHG reductions, respectively, compared to the battery-electric truck (EV CA Grid) and the fuel cell truck (FCV 33% RH2). Even at a 0 percent LFG blend (i.e., 100 percent fossil CNG), purchasing heavy-duty NGVs still achieves the highest level of well-to-wheels (WTW) GHG reductions due to the greater numbers of low-GHG natural gas trucks that can be purchased for the same amount of money.

As this analysis demonstrates, the combination of near-zero-emission heavy-duty NGVs and increasing volumes of ultra-low-GHG RNG fuel provides an extremely cost effective option for immediately achieving major NOx and GHG reductions from America's on-road HDV sector. Therefore, the best application of public incentive dollars for reducing mobile source air pollution is to maximize allocations towards immediate deployments, which can begin with return-to-base trucks, transit buses and refuse haulers. Within two years, deployments can begin in high-impact HHDV applications like regional and long-haul trucking. Focused investment in ultra-low NOx natural gas trucks and RNG to fuel those trucks will achieve the

### Short Haul Truck Incentives

What does \$500 million buy?



Incentive amounts based on incremental purchase cost of advanced heavy-duty short haul trucks over baseline diesel truck

Based on emissions and vehicle activity data from CARB EMFAC 2014

Weighted emissions =  $\text{NOx} + 20 \times \text{PM}_{10} + \text{ROG}$

GHG emissions based on illustrative fuel pathways calculated by ARB Staff using CA-GREET 2.0

Cost effectiveness uses Moyer program capital recover factors based on typical retention period of first owner

Figure 4: Hypothetical comparison of trucks and benefits and benefits based upon a \$500 million investment



The best application of public incentive dollars for reducing mobile source air pollution is to maximize allocations towards immediate deployments of heavy-duty near-zero-emission NGVs, which can begin with return-to-base trucks, transit buses and refuse haulers.

greatest volumes of key pollutant reductions at the lowest cost, in the fastest timeframe possible, and in the neighborhoods most in need of relief from diesel engine emissions.

The importance of robust public incentives to help rapidly deploy near-zero-emissions HDVs cannot be overstated. It does not appear that there will be any regulatory mechanism to mandate deployment of near-zero-emissions HDVs in California, or nationally, prior to 2024. Incentives are the only mechanism to spur early deployments, which CARB and other regulators have clearly emphasized to be essential for goal attainment over the next decade. Further, in the absence of EPA action, it will possibly take much longer for states not adopting CARB's standards to begin deployment of near-zero-emission NGVs. Finally, current low diesel prices—combined with the newly commercialized engine's incremental cost—make it harder for HDV diesel fleets to switch to heavy-duty near-zero-emissions NGVs.

Government agencies such as CARB and EPA have made tangible progress to ensure that their incentive funds for clean HDV technologies account for the emergence of this fuel-technology combination. Notable efforts are being made to ensure that such awards focus as much as possible on near-term, large NOx and GHG reductions. However, increased stakeholder awareness and actions are needed to help ensure that even greater amounts of incentive funds are allocated for large-scale deployment of commercially ready near-zero-emission heavy-duty NGVs. It is the high-impact HHDV applications—where there are no foreseeable commercial pathways to achieve zero emissions for one to two decades—that most need incentive funds to immediately deploy large numbers of heavy-duty NGVs.

Large-scale NOx reductions, as needed for NAAQS attainment in many American cities, cannot be achieved without such deployments. Heavy-duty NGVs, which already provide significant GHG reductions when using fossil natural gas, can achieve deep GHG reductions by using RNG, where available. Thus, incentives are also needed to increase RNG production, distribution and end use. This will take time on a national scale, but fossil natural gas will continue to offer important GHG reductions relative to diesel, as RNG is increasingly blended into the natural gas fuel mix and further drives down GHG emissions from the HDV transportation sector.

## WHITE PAPER RECOMMENDATIONS

This White Paper provides an overview of major opportunities in America for wide-scale use of near-zero-emission heavy-duty NGVs fueled increasingly by RNG. To fully realize such potential, there are opportunities that should be pursued, and challenges that need to be addressed, in two key areas: 1) heavy-duty near-zero-emission natural gas engines and vehicles, and 2) RNG production and end use. The White Paper recommendations for both areas are summarized below.

### **Recommendations for Heavy-Duty Near-Zero-Emission Natural Gas Engines and Vehicles**

1. All stakeholders should work together to develop and implement new strategies to educate potential HDV fleet buyers on important emerging information about near-zero-emission heavy-duty NGVs (commercialized make/models, benefits, costs, performance, availability of incentive programs, etc.).
2. CARB, EPA, interested local air districts and industry stakeholders should join together to conduct a rigorous, peer-reviewed comparative analysis on the full-fuel-cycle emissions of existing heavy-duty ZEV and NZEV technologies.
3. All stakeholders in areas with unhealthful air quality should encourage EPA to adopt national optional low-NOx standards for heavy-duty engines that are harmonized with those adopted by CARB.
4. EPA should establish a national template for HDV incentive programs that “leapfrog” to deployment of HDVs meeting (or beating) the near-zero-emission level of 0.02 g/bhp-hr NOx. Using this template, key national agencies (DOE, EPA, NHSTA) should join together to implement new clean HDV incentive programs in populated areas of the U.S. with high on-road diesel engine activity.
5. Key government agencies (federal, state and local) should continue and expand funding to manufacturers for advanced natural gas engines, HDVs and on-board fuel systems
6. CARB, the California Energy Commission (CEC) and other California agencies should review policies for HDV incentive programs to determine if adjustments can expedite awards and help ensure that they are proportional to the magnitude and expediency of NOx-reduction benefits. They should work together to devise and implement a multifaceted strategy in California that allows pooling of different incentive programs to provide major annual funding for rapid deployments.

### **Recommendations for RNG Production and End Use**

7. Appropriate national, state and local agencies should join with the biofuels industry to develop and implement focused outreach and education efforts that provide important emerging information about the production of RNG and its use in heavy-duty near-zero-emission NGVs.
8. CARB and CEC should further study the potential future dynamics between the supply and demand for RNG as a transportation fuel in California.
9. Relevant federal and state agencies (especially in California) should work together to establish new policies and programs that specifically support the production of RNG as a transportation fuel.

10. Air quality and energy regulatory agencies should continue to recognize and support fossil natural gas as a lower-carbon-intensity transportation fuel.
11. Key federal and California agencies, utilities, and other stakeholders should immediately work together to identify and discuss remaining obstacles to injecting RNG into common carrier natural gas pipelines.
12. EPA and other federal agencies should take action to increase volume obligations for Advanced Cellulosic Fuels under the federal RFS.



Gladstein, Neandross & Associates

2525 Ocean Park Boulevard,  
Suite 200  
Santa Monica, CA 90405

1 Park Plaza, 6th Floor  
Irvine, CA 92614

1270 Broadway, Suite 1009  
New York, NY 10001

T: (310) 314-1934

[www.gladstein.org](http://www.gladstein.org)