

GAME CHANGER

TECHNICAL WHITE PAPER

FULL REPORT



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

Authorship and Uses

This report was prepared by the clean transportation and energy consulting firm of Gladstein, Neandross & Associates (GNA). The opinions expressed herein are those of the authors and do not necessarily reflect the policies and views of any project co-sponsor. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by cosponsoring organizations or Gladstein, Neandross & Associates.

No part of this work shall be used or reproduced by any means, electronic or mechanical, without first receiving the express written permission of Gladstein, Neandross & Associates (GNA).

Acknowledgements

Preparation of this report was performed under co-funding by the South Coast Air Quality Management District and private-sector co-sponsors that include Clean Energy Fuels, Southern California Gas Company, Pacific Gas and Electric Company, the California Natural Gas Vehicle Partnership, the American Gas Association, and Agility Fuel Systems. GNA gratefully acknowledges the essential support of, and content contributions from, these organizations.

Many individuals from GNA made significant contributions to the complete process to prepare and finalize this report, including:

Jonathan (Jon) Leonard, Senior Vice President (lead author / editor)
Erik Neandross, Chief Executive Officer (author / editor)
Cliff Gladstein, President
Patrick Couch, Vice President, Technical Services
Tan Grimes, Creative Manager
Alexis Wiley, Communications and Marketing Manager

Additionally, the following experts served as subcontractors to GNA, and made significant contributions to the preparation of this report. However, GNA is solely responsible for all content in this final document. These subcontractors do not necessarily agree with all of the report's findings, conclusions, or recommendations.

Julia Levin, Bioenergy Association of California
Philip Sheehy, ICF
Jeff Rosenfeld, ICF
John Curtis, independent expert

GNA also gratefully acknowledges the cooperation of Cummins Westport Inc. (CWI) in the preparation of report content related to its "NZ" heavy-duty natural gas engines and technology.

PREPARED FOR



PREPARED BY



List of Terms

ACRONYM	DEFINITION
ADF	Alternative Diesel Fuel
AQMP	Air Quality Management Plan
ARB	California Air Resources Board (Also "CARB")
AB	Assembly Bill
BEV	Battery Electric Vehicle
CO₂	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
DPM	Diesel Particulate Matter
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
HDE	Heavy-Duty Engine
HDV	Heavy-Duty Vehicle
HHDV	Heavy-Heavy-Duty Vehicle
HSAD	High Solids Anaerobic Digester
MHDT	Medium-Heavy-Duty Truck
HHDT	Heavy-Heavy-Duty Truck
ICCT	International Council for Clean Transportation
LFG	Landfill Gas
LCFS	Low Carbon Fuel Standard
LNG	Liquefied Natural Gas
MPO	Metropolitan Planning Organization
MTP	Metropolitan Transportation Plan
NAAQS	National Ambient Air Quality Standards
NGV	Natural Gas Vehicle
NMOG	Non-Methane Organic Gases
NO_x	Oxides of Nitrogen
OEM	Original Equipment Manufacturer
PPB	Parts Per Billion
PPM	Parts Per Million
NZEV	Near-Zero-Emission Vehicle
PM	Particulate Matter
PM_{2.5}	PM smaller than 2.5 microns in size
RD	Renewable Diesel
RNG	Renewable Natural Gas
SCAQMD	South Coast Air Quality Management District
SCAB	South Coast Air Basin
SIP	State Implementation Plan
SJVAB	San Joaquin Valley Air Basin
SJVAPCD	San Joaquin Valley Air Pollution Control District
TWC	Three-Way Catalyst
ULSD	Ultra-Low Sulfur Diesel
ZEV	Zero-Emission Vehicle

Table of Contents

Abstract 1

Executive Summary 3

1. Problem Statement: Societal Impacts of U.S. Transportation Sector 18

 1.1. Dominance of Fossil Petroleum Fuels..... 18

 1.2. Poor Air Quality Impacting Millions of Americans 20

 1.3. Climate Change and Greenhouse Gases 22

2. The Major Role of “Heavy-Heavy-Duty” Vehicles and Trucks 24

 2.1. Overview of Heavy-Duty Trucking 24

 2.2. Focus on HHDTs in High-Fuel-Use Goods Movement Applications 24

 2.2.1. Fuel Use and Emissions..... 24

 2.2.2. Alternative Fuels Conducive to HHDT Applications 25

 2.3. Closer Look: HHDTs in California Goods Movement..... 27

3. Policy Goals and Objectives for U.S. On-Road HDV Transportation 31

 3.1. Petroleum Displacement and Increased Energy Diversity..... 31

 3.1.1. Federal Initiatives and Policies..... 31

 3.1.2. California’s Initiatives and Policies..... 32

 3.2. Improvement of Ambient Air Quality 35

 3.2.1. Heavy-Duty Engine Emission Standards to Reduce NOx Emissions 35

 3.2.2. Reduction of Health Risks from Diesel Exhaust 37

 3.2.3. Accelerated Deployment of Zero- and Near-Zero-Emission HDTs..... 39

 3.3. Reduction of Greenhouse Gases / Climate Pollutants 41

 3.3.1. Federal Efforts, Policies and Initiatives 41

 3.3.2. California’s Efforts, Policies and Initiatives 43

 3.3.3. Other State and Regional GHG-Reduction Initiatives 49

 3.4. Increased Use of Renewable Fuels and Energy 50

 3.4.1. Federal Renewable Fuel Standard (RFS 2) 50

 3.4.2. California Renewable Portfolios Standard (RPS)..... 51

 3.4.3. Other States and Regions 51

 3.5. Transportation Planning and Economic Development 52

 3.5.1. Federal Efforts and Initiatives 52

 3.5.2. California’s Sustainable Freight Action Plan 53

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

- 3.6. Achievement of Environmental Sustainability Goals by HDV End Users 56
- 3.7. Summary of Key Policy Goals and Timelines 56
- 4. Leading Approaches for Zero- and Near-Zero Emission HDVs..... 60
 - 4.1. Overview of Key Fuel and Technology Pathways..... 60
 - 4.2. Heavy-Duty “Zero-Emission Vehicle” (ZEV) Technology 61
 - 4.2.1. The Attraction—and Uncertainty—of ZEV Technologies..... 61
 - 4.2.2. Technology Assessment Summary: Heavy-Duty BEVs 63
 - 4.2.3. Technology Assessment Summary: Heavy-Duty FCVs 64
 - 4.2.4. Addressable Market for NOx Reductions from Heavy-Duty ZEVs..... 64
 - 4.3. Heavy-Duty “Near-Zero-Emission Vehicle” (NZEV) Technology 68
 - 4.3.1. California’s Optional Low-NOx Emissions Standard..... 68
 - 4.3.2. Technology Assessment Summary: Low-NOx Heavy-Duty Engines 68
 - 4.4. Emergence of Commercially Viable Heavy-Duty Natural Gas NZEVs..... 70
 - 4.5. Potential for Commercialization of Heavy-Duty Diesel NZEVs 70
 - 4.6. California’s Estimated Mix of Heavy-Duty NZEVs and ZEVs..... 72
 - 4.7. The Need for All Heavy-Duty ZEV and NZEV Pathways..... 74
 - 4.8. Key Determinants and Factors for Large-Scale Market Penetration 76
- 5. Current Status of Heavy-Duty NGV Technology and Deployments 78
 - 5.1. Overview of NGV Populations and Key End-Use Sectors..... 78
 - 5.2. Fuel Volumes Used in Transportation..... 79
 - 5.3. Commercial Maturity and Availability 81
 - 5.3.1. Overview 81
 - 5.3.2. Heavy-Duty Engine and Vehicle Offerings 81
 - 5.3.3. Gaps and Expected New Commercial Offerings 82
 - 5.3.4. Growing Partnerships Among Key NGV Industry Players 83
 - 5.4. Overview of Life-Cycle Economics 84
 - 5.5. Growing Use of Heavy-Duty NGVs to Meet Corporate Sustainability Goals..... 85
 - 5.6. Market Projections for Heavy-Duty NGVs and Fueling Stations 88
- 6. Game Changer: Near-Zero-Emission Heavy-Duty NGVs 91
 - 6.1. Low-NOx Certification Status and Commercialization Plans..... 91
 - 6.2. Engine Efficiency and GHG Emissions 92
 - 6.3. Comparative NOx Emission Levels from Other On-Road HDV Engines 93
 - 6.4. Comparative NOx Emission Levels from Heavy-Duty BEVs..... 94
 - 6.4.1. Background and Introduction 94

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

- 6.4.2. Limitations and Caveats 95
- 6.4.3. Methodology and Findings 96
- 6.5. Growing Production and Use of Ultra-Low-GHG RNG for Transportation..... 97
 - 6.5.1. RNG Production and Supply for Petroleum Displacement 97
 - 6.5.2. Current RNG Use as a Heavy-Duty Transportation Fuel 99
- 6.6. Continuity of Progress and Avoidance of Stranded Investments 101
- 6.7. Ability to Maintain Regional Integration and Connectivity..... 102
- 6.8. Role in Lowering the Carbon Intensity of High-Impact HDV Sectors 103
 - 6.8.1. California Comparisons for Transportation Fuel Pathways 103
 - 6.8.2. National CI Comparisons for Transportation Fuel Pathways 105
- 6.9. Immediately Available, Affordable Emissions Reductions 106
 - 6.9.1. What Can \$500 Million Buy?..... 106
 - 6.9.2. Cost Effectiveness Considerations 107
 - 6.9.3. Urgency to Address Ambient Air Quality Needs 109
- 6.10. Potential for Expansion into High-Horsepower Off-Road Sectors 110
- 6.11. Synergy with Advancement of Heavy-Duty ZEVs..... 111
- 6.12. Industry Efforts to Reduce Upstream Methane Emissions 112
- 7. RNG for NGVs: Supply, Costs, Opportunities and Challenges..... 114
 - 7.1. Introduction 114
 - 7.2. Major Production Pathways 114
 - 7.2.1. Digestion / Decomposition of Organic Waste..... 115
 - 7.2.2. Gasification and Methanation of Woody Biomass 116
 - 7.2.3. Electrolysis and Methanation Using Renewable Power 116
 - 7.3. A Closer Look at Biogas Feedstocks 117
 - 7.4. Overview of RNG’s Direct Benefits for Climate Change and Air Quality..... 118
 - 7.4.1. Reduction of Full-Fuel Cycle GHG Emissions from HDVs 118
 - 7.4.2. Reduced Emissions of Black Carbon, DPM and TACs 120
 - 7.5. Overview of Other Societal Benefits Associated with RNG Production..... 121
 - 7.5.1. Reduction of Landfilling 121
 - 7.5.2. Reduction of Catastrophic Wildfires 122
 - 7.5.3. Improvements in Agriculture 123
 - 7.5.4. Creation of Local Jobs and Economic Development 124
 - 7.6. Current Status of RNG for Transportation (Production, Cost and Price) 125

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

- 7.6.1. Overview of Existing Biogas Production Facilities..... 125
- 7.6.2. Case Study: CR&R Refuse Trucks in Perris California 126
- 7.6.3. Cost to Produce RNG 128
- 7.7. Feedstock Potential for Expanded RNG Production in America 131
 - 7.7.1. National Potential from Biogas Production 131
 - 7.7.2. National Power-to-Gas Potential 133
 - 7.7.3. California’s Potential for In-State RNG Production 134
- 7.8. Current Policy Framework for Increased RNG Production for Transportation..... 136
 - 7.8.1. Federal Policies 137
 - 7.8.2. California Policies..... 137
- 7.9. Current Barriers to Increased Production and Use of Transportation RNG..... 139
 - 7.9.1. Lack of Market Supply and Demand Certainty for Biogas 139
 - 7.9.2. Existing or Potential Competing Uses for Biogas Feedstock and RNG 140
 - 7.9.3. Requirements for Biomethane Pipeline Access and Transmission 141
 - 7.9.4. General Lack of Knowledge by Policy and Decision Makers 142
- 7.10. Summary: Production, Supply and Cost of RNG for Transportation..... 143
- 8. Importance of Proportionally Allocated, Cost-Effective Incentives..... 145
 - 8.1. Introduction..... 145
 - 8.2. Addition of Near-Zero-Emission Natural Gas Engines into the Equation..... 146
 - 8.3. The Best (and Most-Immediate) “Bang for the Buck” 147
 - 8.4. Tensions between Goals to Reduce NOx and/or GHG..... 148
 - 8.5. Summary: Major Incentive Increases Needed for Heavy-Duty NGVs..... 151
- 9. White Paper Conclusions..... 152
 - 9.1. Heavy-Duty Diesel Engines and Trucks: Workhorses, at a High Price..... 152
 - 9.2. Game Changing Ultra-Low NOx Engine Technology for Wide-Scale HDV Use..... 152
 - 9.3. RNG Completes the Game Changing Equation 153
 - 9.4. Checking the Boxes of Key National, State and Local Policy Goals..... 153
 - 9.5. Challenges and Opportunities 155
 - 9.6. The Need for Immediate Action 156
- 10. White Paper Recommendations..... 157
 - 10.1. Heavy-Duty Near-Zero-Emission Natural Gas Engines and Vehicles 157
 - 10.1.1. Education, Outreach and Further Study 157
 - 10.1.2. Policies, Legislation and Regulations 158
 - 10.1.3. Incentives for Manufacturing and/or Deployment..... 159

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

- 10.2. RNG Production and End Use 160
 - 10.2.1. Education, Outreach and Further Study 160
 - 10.2.2. Policies, Legislation, Regulations and Incentives 161
- 11. Appendix 1: Details of Power Plant NOx Equivalency Analysis..... 162
 - 11.1. Introduction and Background 162
 - 11.2. Electrical Grid Sub Regions 163
 - 11.3. Determining a Vehicle-Equivalent NOx Emission Rate 163
 - 11.4. Regional Power Plant Emissions Equated to Heavy-Duty Engine Standards 164
 - 11.5. Marginal vs Average NOx Emissions 165
 - 11.6. Future NOx Emissions Scenarios as the U.S. Grid Gets Cleaner..... 166
 - 11.7. A Note Regarding “Off-Cycle” Emissions 168
- 12. Appendix 2: Assumptions for Section 6 Cost-Effectiveness..... 169
- 13. Appendix 3: Control of Upstream Methane Emissions..... 170
 - 13.1. Industry Efforts to Reduce Methane Leakage 170
 - 13.2. Rare Events Causing Large Methane Leakage 172
- 14. Appendix 4: Potential Role of Renewable Diesel Fuel 174
 - 14.1. Introduction 174
 - 14.2. Advantages and Uses..... 174
 - 14.3. Acceptance by Heavy-Duty Engine and Vehicle Manufacturers 175
 - 14.4. Production, Feedstock and Supply..... 175
 - 14.5. Expanding End Users..... 176
 - 14.6. Cost and Price 177
 - 14.7. Constraints and Challenges..... 177
 - 14.8. Criteria Pollutant Emissions 178
 - 14.9. GHG Emissions and Carbon Intensity..... 178
 - 14.10. Potential for Expansion of U.S. RD Production Capacity..... 179
 - 14.11. Summary: RD as a Pathway to Near-Zero NOx and Low GHG Emissions..... 179

List of Figures

Figure 1. Petroleum use in the U.S. by major sector, 1949-2014 (U.S. EIA, September '15) 18

Figure 2. U.S. transportation petroleum use (quadrillion Btu/year) 1949-2014 (EIA)..... 19

Figure 3. Estimated U.S. counties in nonattainment for ozone NAAQS of 0.07 ppm (70 ppb) 21

Figure 4. Heavy-duty truck (HDT) population and average miles traveled (VMT) in SCAB..... 27

Figure 5. NOx reductions (tons per day) needed in SCAB to meet ozone NAAQS..... 29

Figure 6. CARB’s “sample path” to 50% petroleum reduction 33

Figure 7. History of EPA and CARB heavy-duty engine standards for NOx and PM..... 35

Figure 8. SCAQMD MATES IV map: cancer risk from air toxics in greater Los Angeles 38

Figure 9. Reports serving as the foundation for California’s Sustainable Freight Action Plan..... 55

Figure 10. California’s timeline to achieve NAAQS (bottom) and GHG targets (top). 57

Figure 11. Award trends (CA HVIP) for heavy-duty BEVs by weight, range and vocation 65

Figure 12. CARB projections for California’s mix of HHDT populations over next 35 years 73

Figure 13. Impact of California-only vs 50-state low-NOx standard on SCAB NOx targets..... 74

Figure 14. 2013-2014 NGV Production and Sales (NGVAmerica, 2015) 79

Figure 15. Trends in consumption of natural gas for transportation (U.S. and top areas)..... 80

Figure 16. Agility’s CNG fuel system installed on FCA Transport truck..... 83

Figure 17. UPS driver filling a CNG package delivery truck..... 85

Figure 18. Ryder LNG truck at fueling station..... 86

Figure 19. Frito-Lay’s fleet of CNG delivery trucks 87

Figure 20. Anheuser-Busch CNG tractor for beer delivery 87

Figure 21. Various market projections (and average) for heavy-duty CNG vehicles 89

Figure 22. CWI heavy-duty ultra-low-NOx engines: anticipated timeline for certification and deployment 91

Figure 23. Existing NGV applications and engine sizes that can utilize ultra-low-NOx NG engines..... 92

Figure 24. Comparison of GHG emissions (CO₂e) for CWI ISL-G and ISL-G NZ engines 93

Figure 25. Comparative NOx and PM test levels for recently certified heavy-duty engines 94

Figure 26. Santa Monica’s transit fleet now operates entirely on RNG (liquefied biomethane)..... 99

Figure 27. Natural gas / RNG volumes generating credits for CA LCFS, 2011 to present 100

Figure 28. Comparative C.I. scores for heavy-duty truck pathways (CARB, 2015) 104

Figure 29. Hypothetical comparison of truck deployments and benefits based on a \$500 million investment..... 107

Figure 30. Criteria pollutant reduction cost effectiveness by HDV type and application 108

Figure 31. GHG reduction cost effectiveness by HDV type and application 109

Figure 32. Breakout of national methane emissions by source (U.S. EPA)..... 113

Figure 33. Landfill-based RNG production near Dallas (Fleets & Fuels) 126

Figure 34. CR&R facility to produce RNG for CNG refuse trucks / pipeline use (Photo: CR&R)..... 127

Figure 35 Annual GHG emissions from fleet of refuse trucks using HASD RNG blends..... 127

Figure 36. 2015 credit value history in U.S. RFS (D5 RINs) and California’s LCFS 129

Figure 37. U.S. biomethane potential (landfills, animal waste, wastewater, IIC sources)..... 132

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

Figure 38. Technical potential of biomethane production in California (UC-Davis 2014) 136
Figure 39. U.S. intrastate and interstate natural gas pipeline system..... 140
Figure 40. Methane emitted per natural gas produced in the U.S. (EPA, 2015 inventory) 171

List of Tables

Table 1. Core concepts and priority elements (HDV-related) for GGRF 2nd Investment Plan 46
Table 2. SLCP emissions and proposed targets for reductions by 2030 48
Table 3. Summary of key policy initiatives relevant to clean HDV technology..... 58
Table 4. HDV fuel / technology pathways with best potential to meet NOx and GHG targets 60
Table 5. Summary: CARB’s key technology assessment findings on heavy-duty battery-electric vehicles 63
Table 6. Summary: CARB’s key technology assessment findings on heavy-duty FCVs..... 64
Table 7. Summary: CARB’s key Technology Assessment findings on low-NOx diesel engines 69
Table 8 Summary: CARB’s key Technology Assessment findings on low-NOx NG engines 69
Table 9. Technology Readiness Levels (TRLs) for Commercializing HHDTs (Volvo) 76
Table 10. Commercially available heavy-duty natural gas truck models, by OEM 82
Table 11. Summary of Major Pathways to Produce RNG 115
Table 12. Summary of feedstocks for production of biogas (for potential upgrading to RNG) 117
Table 13. Carbon intensity values (gCO2e/MJ) for representative fuel pathways 119
Table 14. Clean Energy’s U.S. production facilities for RNG from landfill gas 125
Table 15. Estimated annual biomass and RNG potential in California (UC-Davis)..... 135
Table 16. ARFVTP Funding Summary 2009 – 2015 138
Table 17. Policy goals met by heavy-duty near-zero-emission NGVs + RNG 154
Table 18. 15 EPRI REGEN sub-regions and their states..... 163
Table 19. Typical electrical efficiencies / losses for a Class 8 battery-electric truck..... 164
Table 20. Vehicle-equivalent NOx emission rates under future “cleaner-grid” scenarios 167
Table 21. Assumptions used to derive graphs in Section 6.9 (see page 106) 169
Table 22. Projected U.S. renewable diesel production capacity in 2020 (CARB, 2015)..... 179

Abstract

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. Expedient 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 NO_x 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 80,000 pounds over long distances and up steep grades, as routinely needed for goods movement trucking throughout our nation's interstate highway system. 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.

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

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

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 unhealthy 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 has accelerated in recent 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 truck sales have

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

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

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

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.

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

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

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**.

Four leading fuel-technology pathways for zero- or near-zero emission HDVs

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

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

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

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.)

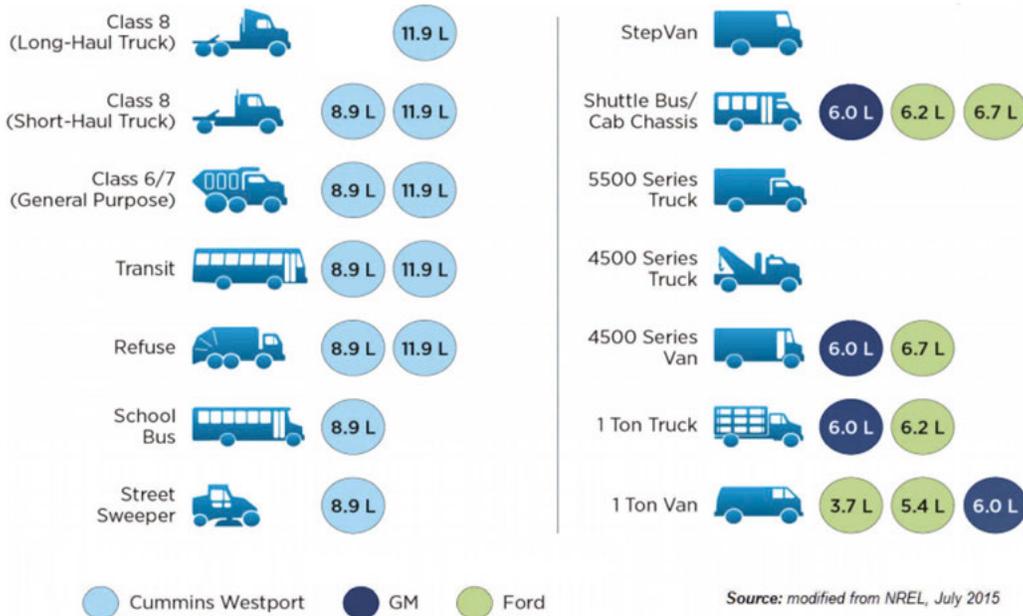
The figure below summarizes the important low-NOx credentials of these three CWI engines, and their immediate-to-near-term timeframes for commercial rollout.



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

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

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



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

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.

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

Market Momentum Achieved Over Decades

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. 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

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

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

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

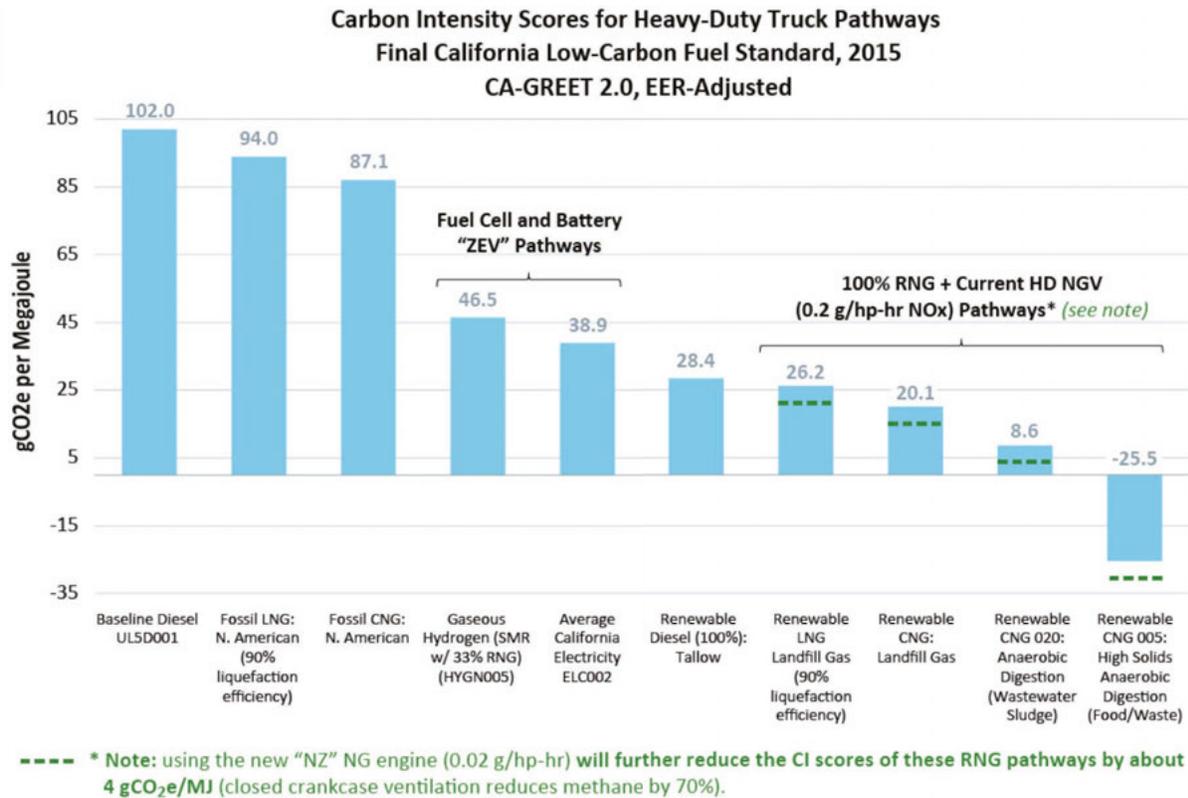
RNG is the second element of this game-changing fuel-technology pathway. RNG is a gaseous mixture of methane and other compounds that is produced from renewable sources, using either biological or chemical processes. Producing RNG is a highly sustainable process from multiple pathways. Various forms 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

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

preliminary “carbon intensity” (CI) values (in grams per mega joule of “CO2 equivalent” GHGs) for eight different heavy-duty transportation fuel 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).¹ 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,” to a 125 percent reduction for “Renewable CNG: High Solids Anaerobic Digestion.” Moreover, an additional CI benefit (approximately 4 gCO_{2e}/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_{2e}/MJ) assumed to recharge heavy-duty BEVs, and the “Gaseous Hydrogen (SMR with 33% RNG)” pathway (CI



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.

Comparative carbon intensity (C.I.) scores for heavy-duty truck pathways (CARB, 2015)

¹ 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.

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

value of 46.5 gCO₂e/MJ). Future changes to the grid mix and/or hydrogen-production processes will likely result in lower CI values for these two ZEV pathways.

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_x standard of 0.2 g/bhp-hr. Engine manufacturers have detailed challenging “NO_x-GHG” tradeoff issues that must be resolved before heavy-duty diesel engines can be certified to the 0.02 g/bhp-hr NO_x 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_x are not expected to be developed and available until at least the mid-2020 timeframe. This assumes that challenging NO_x-GHG tradeoff issues can be resolved, as necessary for low-NO_x 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_x 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_x “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_x certification levels that still offer good margin, to meet very challenging requirements from CARB / EPA to maintain low NO_x 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_x trucks are “the most viable approach” to meet California’s mid- and longer-term goals to attain NAAQS for NO_x and PM_{2.5}. 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_x, 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_x 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_x trucks.”

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

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

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

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).

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

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

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.

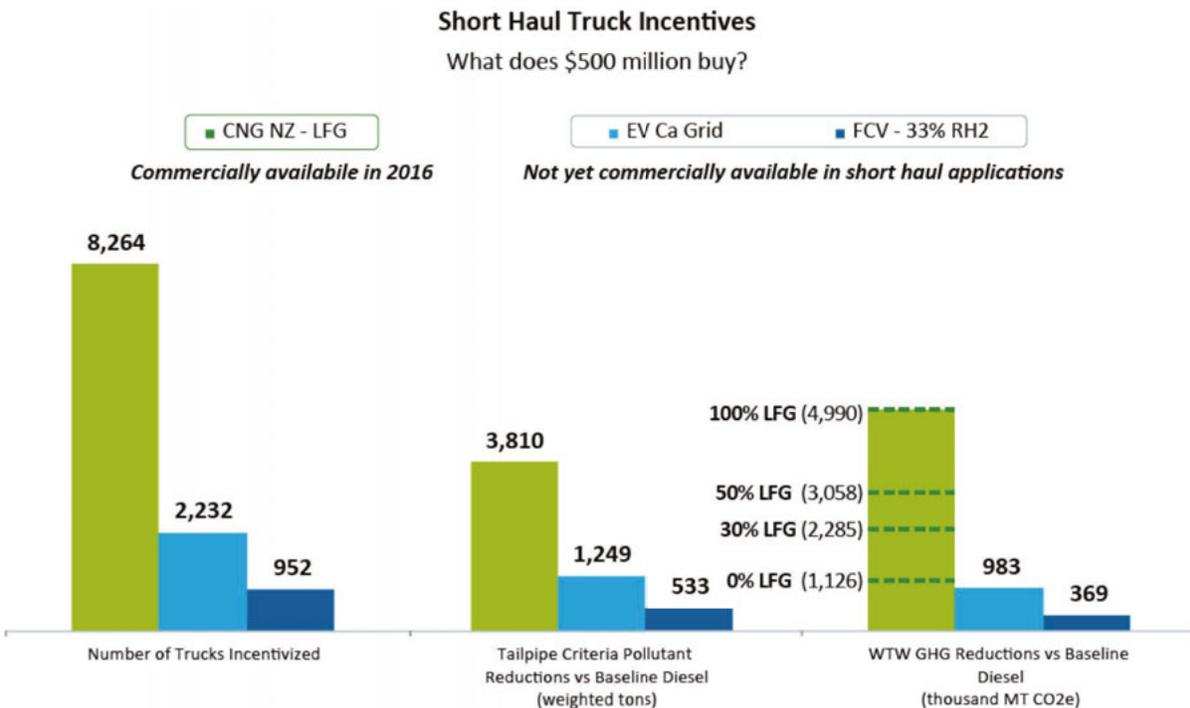
Importance of Proportional Incentives for Immediately Deployable Heavy-Duty NZEVs

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.

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

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.



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 = NOx + 20*PM10 + 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

Hypothetical comparison of truck deployments and benefits based on a \$500 million investment

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 HDDV applications like regional and

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

long-haul trucking. Focused investment in ultra-low NOx natural gas trucks and RNG to fuel those trucks will achieve the 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.

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

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.

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

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.

1. Problem Statement: Societal Impacts of U.S. Transportation Sector

1.1. Dominance of Fossil Petroleum Fuels

The United States is the world's largest consumer of transportation-related energy, accounting for 25 percent of global energy demand to transport goods and people. Approximately 28 percent of America's total energy consumption is for transportation. The U.S. transportation sector consumes approximately 14.2 million barrels of petroleum fuel *each day*; the next largest use of petroleum fuel is by the industrial sector, at about 4.7 million barrels per day (Figure 1). Energy consumption in the U.S. transportation sector has increased more than 300 percent over the last 65 years.²

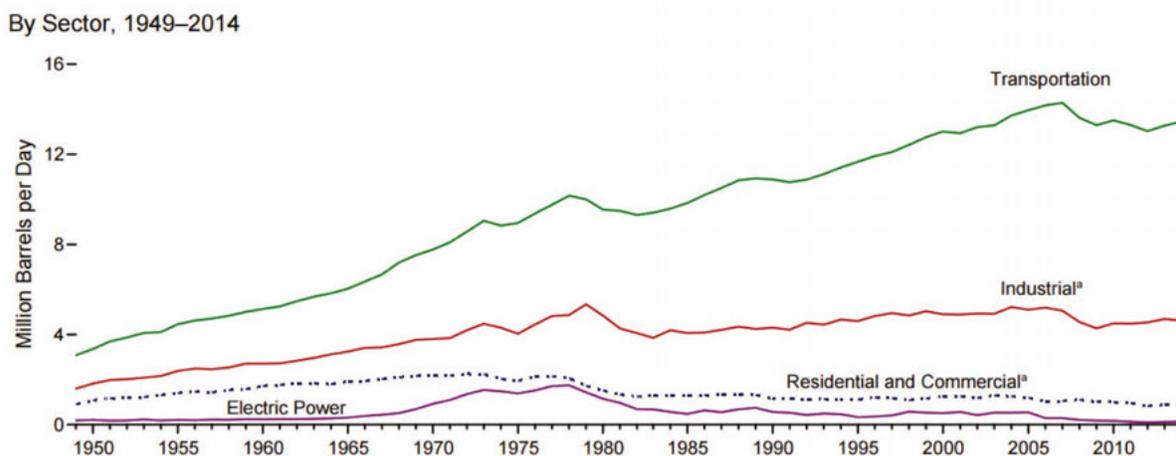


Figure 1. Petroleum use in the U.S. by major sector, 1949-2014 (U.S. EIA, September '15)

As Figure 2 indicates, roughly 27 quadrillion British Thermal Units (Btu) of energy are consumed annually to power America's transportation sector. Approximately 92 percent is consumed as petroleum fuel, equating to about 211 billion gallons of gasoline and diesel fuel each year. Heavy-duty vehicles (HDVs) are second only to passenger cars in the consumption of transportation fuels. In particular, on-road HDVs used for "goods movement" annually consume approximately 18 percent of American's total transportation energy. In 2014, heavy-duty trucks transported more than nine billion tons of freight while consuming 37 billion gallons of petroleum fuel.³ (See Section 2 for additional details.)

² U.S. Energy Information Administration, Monthly Energy Review, September 2015, <http://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf>

³ American Trucking Association, "Reports, Trends & Statistics," accessed online February 14, 2016, http://www.trucking.org/News_and_Information_Reports_Energy.aspx

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

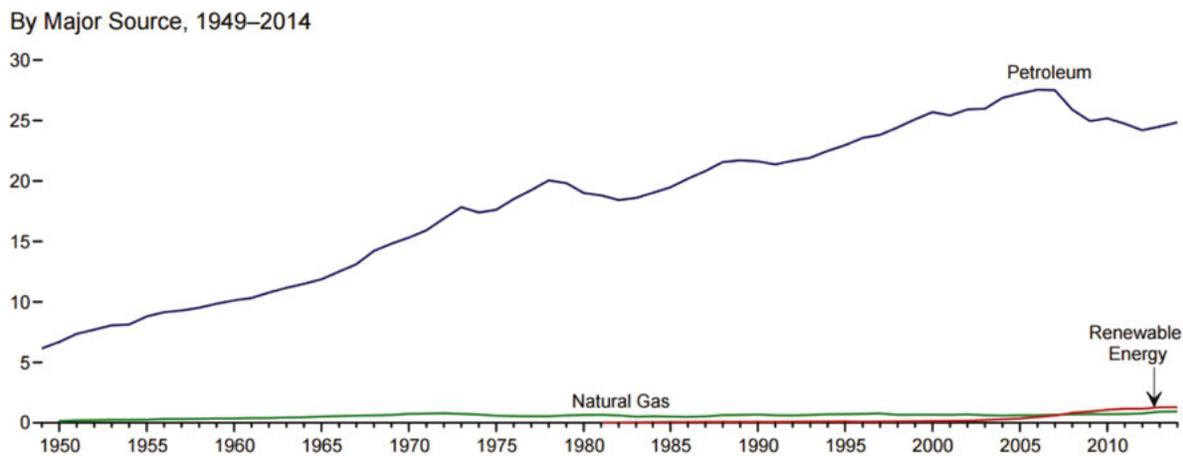


Figure 2. U.S. transportation petroleum use (quadrillion Btu/year) 1949-2014 (EIA)

The U.S. has made very significant progress over the last two decades to deploy HDVs using “alternative fuels” such as natural gas, hydrogen, propane and electricity. Most notably, increasing deployments of heavy-duty natural gas vehicles (NGVs) have displaced large volumes of diesel fuel, improved urban air quality, reduced human exposure to cancer-causing diesel exhaust, and lessened America’s dependence on imported petroleum fuels. An estimated 65,000 heavy-duty NGVs are currently operating across America in refuse, transit and other HDV applications.⁴ Heavy-duty NGVs have enabled these important accomplishments while meeting essential customer needs for vehicle performance, range, reliability, durability, life-cycle costs, warranty coverage and other parameters.

Despite this major progress, America’s transportation sector continues to heavily rely on combusting two fossil petroleum fuels, gasoline and diesel; minimal displacement has been realized through use of cleaner alternative transportation fuels such as natural gas. In 2014, natural gas represented about three percent of the total energy used by the U.S. transportation sector. Only a very small—albeit growing—percentage of energy consumed in the U.S. transportation sector comes from renewable sources.⁵ As further described in this report, California is making major inroads to greatly increase use of renewable transportation fuels.

This dominance by fossil petroleum fuel in America’s transportation sector—particularly the near-total use of diesel fuel by the largest HDVs—has major adverse economic and environmental consequences, as further described below.

⁴ U.S. EPA, “Proposed Rulemaking for Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles – Phase 2: Draft Regulatory Impact Analysis,” June 2015, <http://www3.epa.gov/otaq/climate/documents/420d15900.pdf>.

⁵ U.S. EIA, “Use of Energy in the United States Explained,” http://www.eia.gov/Energyexplained/?page=us_energy_transportation.

1.2. Poor Air Quality Impacting Millions of Americans

To protect public health, the Federal Clean Air Act (CAA) requires the U.S. Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards (NAAQS) for six principal air pollutants, known as “criteria pollutants.” These are: 1) carbon monoxide, 2) lead, 3) nitrogen dioxide, 4) ozone, 5) fine particulate matter, and 6) sulfur dioxide. (For a detailed description of each of these criteria pollutants and the various types of NAAQS, see EPA’s webpage at <http://www3.epa.gov/ttn/naaqs/criteria.html>.)

Of the six criteria pollutants, ozone is the most pervasive and hardest to control. Ground-level (tropospheric) ozone is not directly emitted into the air (in significant quantities); it is created secondarily through photochemical reactions between oxides of nitrogen (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight. While there are many sources of these two ozone precursor emissions, motor vehicle exhaust is among the largest part of the problem.

Attainment of the NAAQS for fine PM is also highly dependent on controlling motor vehicle emissions. Fine PM is a byproduct of engine combustion; it is regulated as both PM₁₀ (particulate matter smaller than 10 microns in diameter) and PM_{2.5} (particulate matter smaller than 2.5 microns in diameter). Motor vehicles directly emit fine PM, but it is also formed secondarily in the atmosphere from precursor emissions that include NO_x.

The majority of on-road HDVs are powered by diesel engines. In addition to NO_x and fine PM, diesel engines emit a complex mixture of harmful gases and vapors. Diesel particulate matter (DPM) and many other constituents of diesel exhaust are considered to be toxic air contaminants (TACs). TACs are a broad category of air pollutants for which no NAAQS exists, but they cause or contribute to increases in human mortality and/or serious illness. According to the California Office of Environmental Health Hazard Assessment (OEHHA), motor vehicles emit “at least forty different” TACs.⁶ Notably, as described later, modern emission controls and improved diesel fuel have combined to greatly reduce—but not eliminate—public health risks from exhaust emitted from post-2006 on-road diesel HDVs.

An estimated 166 million people (52 percent) in the United States live in counties that have unhealthful levels of either ozone or particle pollution.⁷ Under the CAA, air quality officials in nonattainment areas must develop and implement an emission-reduction strategy demonstrating how the area will be brought into attainment, in a timely manner. The greatest ongoing challenges are to attain the ozone and PM_{2.5} NAAQS in California’s two most polluted airsheds,

More than half (166 million, or 52 percent) of the people in the United States live in counties that have unhealthful levels of either ozone or particle pollution.

-American Lung Association, “State of the Air 2016,” <http://www.lung.org/our-initiatives/healthy-air/sota/?referrer=https://www.google.com/>

⁶ California Office of Environmental Health Hazards Assessment. “Adoption of Air Toxics Hot Spots Program Guidance Manual for Preparation of Health Risk Assessments,” March 6, 2015, accessed online at http://oehha.ca.gov/air/hot_spots/hotspots2015.html.

⁷ American Lung Association, “State of the Air 2016,” undated, <http://www.lung.org/our-initiatives/healthy-air/sota/?referrer=https://www.google.com/>.

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

the South Coast Air Basin (SCAB) and the San Joaquin Valley Air Basin (SJVAB).

The SCAB includes the greater Los Angeles area. While air quality has dramatically improved since peak-pollution years in the 1950s, the SCAB remains in “extreme” nonattainment for the ozone NAAQS, and “moderate” nonattainment for the PM_{2.5}. In fact, the SCAB is generally acknowledged to have the worst air quality in North America. This is due to the very large number of emissions sources that exist in this 10,743 square mile area, combined with natural conditions (geography, climatology, meteorology) that are conducive to formation and retention of air pollution. For similar reasons, the nearby SJVAB is also in extreme non-attainment for ozone—and in serious nonattainment for PM_{2.5}.

Of course, unhealthy ambient air is not just a California problem. An estimated 241 counties across America do not meet the newly adopted federal ozone NAAQS of 0.07 ppm (70 ppb), as further described in Section 3.2. These ozone nonattainment counties are dispersed all over the U.S. For example, as can be seen in Figure 3, America’s northeastern seaboard from Virginia to Massachusetts is largely in nonattainment for federal ozone standards

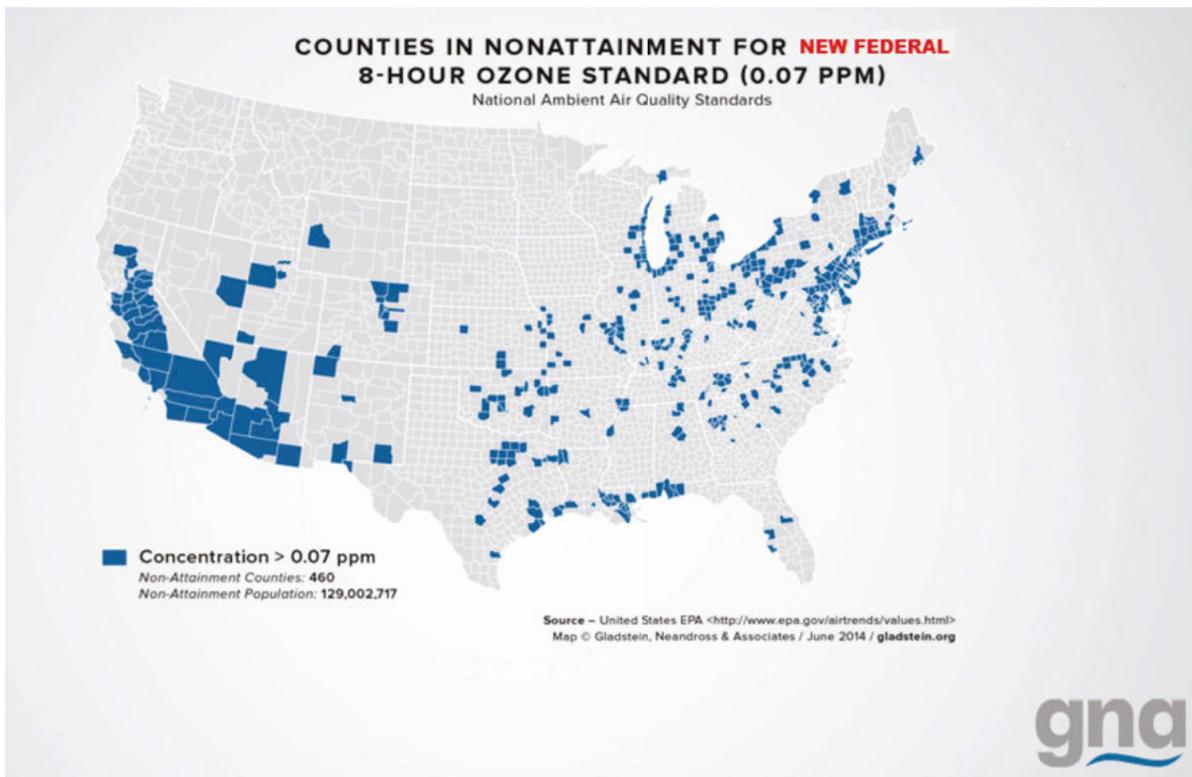


Figure 3. Estimated U.S. counties in nonattainment for ozone NAAQS of 0.07 ppm (70 ppb)

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

Air pollution has very high costs on public health and the American economy. It has been estimated that approximately 200,000 premature deaths occur in the U.S. each year, due to combustion-related air pollution primarily associated with transportation sources.⁸ Conversely, reducing fine PM pollution (through control measures) has been shown to improve human life expectancy and public health.⁹ A 2011 academic study¹⁰ found that \$182 billion in “total gross external damages” were associated with excessive ambient levels of the six criteria air pollutants in 2002. This is roughly two percent of the current U.S. gross domestic product. Included in the cost calculation are “adverse consequences for human health, decreased timber and agriculture yields, reduced visibility, accelerated depreciation of materials, and reductions in recreation services.” Notably, the greatest health burden of air pollution falls on children, the elderly, and people of all ages who have lung diseases such as asthma. Moreover, the highest levels of air pollution exposure tend to occur in areas where socioeconomically disadvantaged people live, work and go to school.

Globally, the World Health Organization (WHO) estimates that air pollution caused 3.7 million premature deaths in 2012. WHO has labeled urban air pollution to be “the largest single environmental health risk we face today,” noting that many of the world’s largest cities are headed towards public health emergencies that will entail “horrible future costs to society.”¹¹

Not included in the above estimates are the economic costs of global climate change induced by human-related greenhouse gas (GHG) emissions. Additional discussion about this is provided below.

1.3. Climate Change and Greenhouse Gases

Climate change refers to the relatively recent and ongoing rise in global average temperatures near the earth’s surface. It is caused mostly by an increase in the concentration of GHGs in the atmosphere. Over the past century, human activities have released large amounts of carbon dioxide (CO₂) and other GHGs into the atmosphere. This is largely responsible for a well-documented steady rise in average global temperatures “since the beginning of the industrial revolution.”¹² The result over several decades has been major changes and extremes in temperatures, weather patterns, precipitation levels, cyclones and hurricanes, and other climate effects. (For specific examples of “regional climate extremes” across the U.S., see http://www.ncdc.noaa.gov/extremes/cei/regional_overview). To avoid even-more-extreme weather events and disastrous rises in oceans levels, there is strong consensus in the global scientific

⁸Caiazza, Ashok, Waiz, Yim and Barrett, “Air Pollution and Early Deaths in the United States,” *Atmospheric Environment*, Volume 79, November 2013, accessed online at <http://www.sciencedirect.com/science/article/pii/S1352231013004548>.

⁹ Correia, Andrew W.; et al. “Effect of Air Pollution Control on Life Expectancy in the United States: An Analysis of 545 U.S. Counties for the Period from 2000 to 2007,” *Epidemiology*, January 2013, Vol. 24, Issue 1, 23-31.

¹⁰ Nicholas Z. Muller, Robert Mendelsohn, and William Nordhaus, Environmental Accounting for Air Pollution in the United States Economy, *American Economic Review* 101, August 2011, accessed online at: <http://pubs.aeaweb.org/doi/pdfplus/10.1257/aer.101.5.1649>

¹¹ Statement by Dr. Maria Neira, World Health Organization Director for Public Health, Environmental and Social Determinants of Health, *PHE e-News*, May 2015, <http://www.who.int/phe/news/may2015/en/>.

¹² National Aeronautics and Space Administration (NASA), “Earth Observatory,” <http://earthobservatory.nasa.gov/Features/WorldOfChange/decadaltemp.php>.

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

community that forceful, immediate and sustained action is needed to curtail GHG emissions from human activity.¹³

The majority of anthropogenic GHGs emissions are generated by burning fossil fuels to produce energy. In the U.S., electricity generation (primarily at centralized power plants) accounts for the largest share of emissions—32 percent of total GHG emissions since 1990—but transportation is a close second at 26 percent. Over the last 15 years, GHG emissions in the transportation sector increased in absolute terms more than any other sector (i.e. electricity generation, industry, agriculture, residential, or commercial).¹⁴

Currently, there are limited estimates for the future worldwide economic costs of climate change. California officials have recently estimated the potential scale of associated in-state economic and social costs. In sum, California estimates that the in-state costs resulting from rising sea levels, increased wildfire incidence, more frequent and larger-scale flooding, extreme weather events, and other climate-related catastrophes will reach hundreds of billions of dollars per year in the coming decades.¹⁵ Impacts and associated costs elsewhere in the U.S. (and worldwide) will vary due to many factors, but damages are also likely to be very large in magnitude.

As stated below by the U.S. EPA, key strategies to reduce GHG emissions in the transportation sector include the use of low-carbon fuels, deployment of new and improved vehicle technologies, and operating vehicles more efficiently. Combining these options can be an especially effective approach.

Low-carbon fuels, new and improved vehicle technologies, strategies to reduce the number of vehicle miles traveled, and operating vehicles more efficiently are all approaches to reducing greenhouse gases from transportation.

– U.S. EPA, “U.S. Transportation Sector GHG Emissions”

¹³ See for example NASA’s “Global Climate Change: Vital Signs of the Planet,” <http://climate.nasa.gov/evidence/>.

¹⁴ U.S. Environmental Protection Agency, “Climate Change: Basic Information,” <http://www3.epa.gov/climatechange/basics/>.

¹⁵ State of California, “California Climate Adaptation Strategy for Energy & Transportation”, undated, accessed online 1/13/16 at http://www.climatechange.ca.gov/adaptation/documents/Statewide_Adaptation_Strategy_-_Chapter_10_-_Transportation_and_Energy_Infrastructure.pdf.

2. The Major Role of “Heavy-Heavy-Duty” Vehicles and Trucks Overview of Heavy-Duty Trucking

Nationwide, on-road HDVs (medium- and heavy-duty trucks, plus buses) constitute only about five percent of the on-road vehicle population, yet they contribute approximately 50 percent of America’s smog-precursor emissions and 20 percent of our transportation-related 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.¹⁶

Approximately 12 million heavy-duty trucks (Class 3 through 8) are registered in the U.S. today; these are both single-unit and combination trucks that cover a wide range of applications and vocations.¹⁷ In total, U.S. trucking operations currently consume more than 50 billion gallons of petroleum fuel (diesel and gasoline) each year. About two thirds (29 billion diesel gallons per year) are consumed by the largest, most-powerful trucks that are categorized as “heavy-heavy-duty” vehicles (HHDVs, see box). Fuel consumption by this sector (relative to 2013) is expected to increase by about 20 percent by 2040, even though fuel efficiency for new HHDVs is expected to significantly improve during this period.¹⁸

Class 8 Heavy-Heavy-Duty Vehicles (HHDVs)

Class 8 HHDVs have a gross vehicle weight rating (GVWR) greater than 33,000 pounds; this category includes dump trucks, cement trucks, refuse haulers, transit buses, cab-over-engine tractors, and heavy-heavy-duty conventional tractors that are used in line-haul trucking.

Heavy-heavy-duty trucks (HHDTs) are highly impactful types of HHDVs. The special roles that HHDTs play in America’s economic, energy and environmental dynamics are further highlighted below.

2.2. Focus on HHDTs in High-Fuel-Use Goods Movement Applications

2.2.1. Fuel Use and Emissions

Class 8 HHDTs are *essential* to America’s goods movement economy; these large combination trucks move nearly 70 percent of all domestic freight.¹⁹ Approximately 2.6 million HHDTs are registered in the

¹⁶ U.S. EPA, “EPA and NHTSA Propose Greenhouse Gas and Fuel Efficiency Standards for Medium- and Heavy-Duty Trucks: by the Numbers,” Regulatory Announcement, June 2015, <http://www3.epa.gov/otaq/climate/documents/420f15903.pdf>

¹⁷ There are eight truck classes, categorized by the gross vehicle weight rating assigned to the vehicle when manufactured. For a good description (with diagrams) of the different truck types typically included in each class, see http://cta.ornl.gov/vtmarketreport/pdf/chapter3_heavy_trucks.pdf.

¹⁸ U.S. Energy Information Administration, “Annual Energy Outlook 2015 with Projections to 2040,” April 2015, [http://www.eia.gov/forecasts/aeo/pdf/0383\(2015\).pdf](http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf).

¹⁹ American Trucking Association, “New Report Predicts Continued Growth in Freight Trucking,” press release, July 27, 2015.

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

U.S. today; new unit sales topped 220,000 in 2014.²⁰ They collectively consume about 17 percent of the total petroleum fuel used in America's transportation sector. On average, each HHDT consumes more than 12,000 diesel gallons per year. Long-haul Class 8 tractors typically have much higher fuel consumption; they travel an average 105,000 miles annually, consuming about 20,000 diesel gallons.²¹ At the high end, a new long-haul truck can travel as much as 270,000 miles in a single year, while burning 45,000 gallons of diesel. In America (as well as worldwide), HHDT populations and fuel use are growing rapidly, as are the associated emissions of criteria pollutants and GHGs.²²

As could be expected, high fuel use by HHDTs results in proportionally high emissions of NO_x, PM, various TACs, and GHGs including CO₂. Because America's HHDT population is projected to continue increasing, this is expected to be our country's fastest-growing segment for GHGs and other harmful emissions,²³ even though the fuel efficiency of new HHDTs will continue to improve under federal requirements (described further). More than any other sector, it is imperative that air quality and transportation officials take rapid action to reverse these trends, and reduce the negative societal impacts of HHDTs. However, this must be done without disrupting or unnecessarily compromising the essential services they provide.

2.2.2. Alternative Fuels Conducive to HHDT Applications

The on-road heavy-duty transportation market is generally subdivided into a number of fleet types, including goods movement trucking, transit, refuse, municipal, and utility fleets. While each fleet is unique, these general vocational groupings tend to have similar operational characteristics that influence the economics and logistics of deploying either conventional or alternative fuel vehicles.

The on-road goods movement sector is dominated by diesel-fueled HHDTs. This sector can be separated into "private fleets" and "for-hire carriers." These two types of trucking fleets transport nearly three fourths of all U.S. freight (by value). Private fleets move freight and goods of the fleet owner, rather than those of other companies or organizations. Such operators typically include grocery stores, beverage companies, and construction companies. By contrast, for-hire carriers use HHDTs to transport goods for other entities. Large national fleets like ConWay, CR England, JB Hunt, and Swift are well-known examples of for-hire carriers. They carry about twice as much freight (by value) as private fleets.²⁴

The operations of private and for-hire carrier fleets are complex and can vary by fleet, region and task. Private fleets are generally more likely to be engaged in regional goods movement with operations

²⁰ Fleetowner.com, "Basic Numbers 2015, http://fleetowner.com/site-files/fleetowner.com/files/uploads/2015/07/Basic%20numbers%202015_1.jpg

²¹ American Trucking Association, "Professional Truck Drivers," fact sheet, http://www.trucking.org/ata%20docs/what%20we%20do/image%20and%20outreach%20programs/misc%20documents/pro%20Truck%20Drivers_final.pdf.

²² U.S. EPA, "EPA and NHTSA Propose Greenhouse Gas and Fuel Efficiency Standards for Medium- and Heavy-Duty Trucks: by the Numbers," Regulatory Announcement, June 2015, <http://www3.epa.gov/otaq/climate/documents/420f15903.pdf>

²³ U.S. EPA and National Highway Traffic Safety Administration, "Final Rulemaking to Establish Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles," <http://www3.epa.gov/otaq/climate/documents/420r11901.pdf>.

²⁴ Fleetowner.com, "Basic Numbers 2015, http://fleetowner.com/site-files/fleetowner.com/files/uploads/2015/07/Basic%20numbers%202015_1.jpg.

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

designed to address specific service territories and routes. This submarket typically deploys return-to-base trucks falling within a wide range of weight classes and types, from Class 5 and 6 package delivery vans to Class 8 semi-tractors. Baseline diesel engines are typically in the 7 to 13 liter class (230-400 HP, 800+ lb-ft of torque). Daily driving range tends to be in the short-to-mid category, from 50 to several hundred miles per day.

This return-to-base characteristic makes regional goods movement trucking (dominated by private fleets) generally conducive to using alternative fuel vehicles (AFVs), including battery-electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), fuel cell electric vehicles (FCVs), and natural gas vehicles (NGVs). First, shorter range requirements can generally be met by alternative fuels, despite their relatively low energy density compared to diesel. Second, return-to-base operations often provide opportunities for fleets to install infrastructure designed to fuel (or recharge) AFVs overnight. Third, regional short-haul delivery trucks frequently operate in low speed modes with extensive braking and idle time. Trucks with electric drive systems that include regenerative braking can be very efficient in these operational modes.

For-hire fleets are more likely to be engaged in interstate trade along major transportation corridors. Due to the nature of their operation, for-hire trucking is generally not conducive to return-to-base fueling, and it represents special challenges for switching over to an alternative fuel technology. These carrier fleets must have constant and ready access to commercial fueling stations, wherever they travel. This requirement is readily met by America's vast network of diesel stations specifically designed for access by large numbers of HHDTs.

The majority of heavy-duty trucks engaged in this interstate goods movement submarket are Class 8 semi-tractors purchased new from a major truck manufacturer. These tractors have substantial daily range requirements of 500 to 1,000 miles, and use engines in the 12 to 15 liter class (400+ HP, 1,500+ lb-ft torque). Thus, they need to carry large volumes of fuel. Class 8 tractors are typically sold into secondary markets after 500,000 to 750,000 miles have been accumulated (about five years). These HHDTs have an average life of about 15 years²⁵, so they are typically operated for many more years in a secondary market that features shorter daily hauls.

The important point here is that natural gas and alternative diesel fuels (biodiesel or renewable diesel) are the only alternative fuels that have seen any meaningful penetration into the challenging interstate trucking sector. (See Section 14 – Appendix 4 for more details about renewable diesel as a heavy-duty alternative fuel, and how it differs from biodiesel.) Natural gas has also served well for truck fleets that operate with extensive return-to-base, short-range trips, but this sector has a wider range of options. This includes use of medium-heavy-duty battery-electric trucks, as further discussed in this report.

²⁵ Fleet Owner, "IHS: Both fleet age and truck demand on the rise, November 2014, <http://fleetowner.com/truck-stats/ihs-both-fleet-age-and-truck-demand-rise>.

2.3. Closer Look: HHDTs in California Goods Movement

California’s vast transportation sector consumes nearly 3.5 billion gallons of diesel fuel per year. Nearly two thirds of the total (2.2 billion gallons per year) is consumed by heavy-duty trucks, including truck tractors for goods movement and refuse trucks. In particular, Class 8 truck tractors dominate the state’s diesel consumption, while performing their essential role to power California’s world-leading on-road goods movement system.

Nowhere is this more evident than in California’s 10,743 square mile SCAB, which includes Los Angeles and America’s largest seaport complex (the Ports of Los Angeles and Long Beach). Forty percent of U.S. containerized cargo is imported here, for subsequent transport throughout the country by truck or rail.

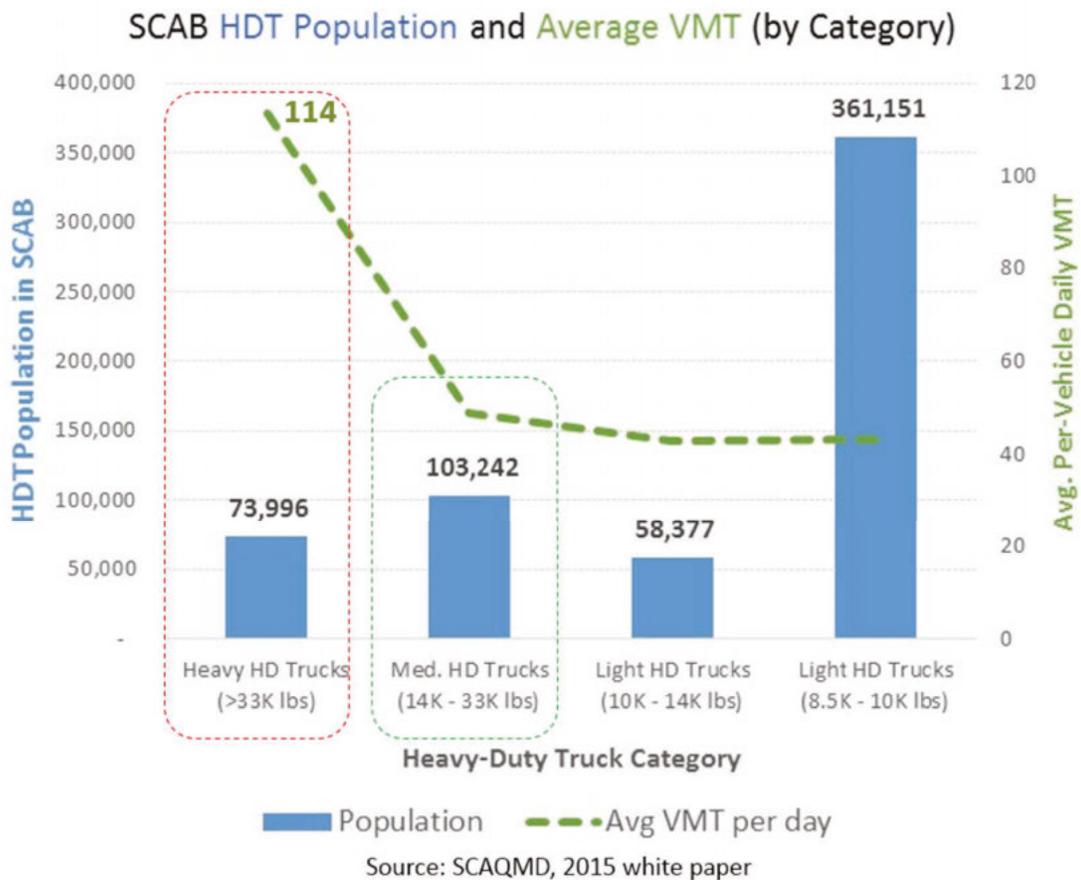


Figure 4. Heavy-duty truck (HDT) population and average miles traveled (VMT) in SCAB

An estimated 74,000 heavy-heavy-duty tractors (Class 8b HHDTs) regularly operate in the SCAB, each traveling more than 110 miles per day on average²⁶ (see red dotted-line box in Figure 4). Note that

²⁶ South Coast Air Quality Management District, “Final Goods Movement White Paper, October 2015, accessed online at: <http://www.aqmd.gov/docs/default-source/Agendas/aqmp/white-paper-working-groups/wp-goodsmvmt-final.pdf?sfvrsn=2>.

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

medium-heavy-duty trucks average about 40 miles of travel per day, which has been readily achieved by commercially available battery-electric vehicles of this size using a single charge.

One hundred miles to the north, California's San Joaquin Valley Air Basin (SJVAB) contains two of America's busiest HHDT corridors (Interstate 5 and State Route 99). Each year, HHDTs consume roughly one half-billion diesel gallons along these two corridors within the SJVAB.²⁷ As noted below, HHDTs making interregional trips dominate diesel use along these two corridors. Miles traveled by heavy-duty trucks in this region are projected to increase by 60 percent over the next 20 years.²⁸

It's not surprising that California's SCAB and SJVAB have America's worst air quality. Two criteria air pollutants—ozone and fine PM (PM_{2.5})—are of greatest concern to regulators. In the SCAB, HHDTs are the single largest source of ozone-forming NO_x emissions. They represent just 12.5 percent of the total on-road truck population, but emit 54 percent of the NO_x and 65 percent of the PM_{2.5}.²⁹

In the nearby SJVAB, HHDTs also are the single largest NO_x source, emitting almost 50 percent of the inventory. State Route 99 is considered to be the "north-south backbone" of the San Joaquin Valley's prolific trucking corridor for goods movement. At several locations along Route 99, heavy-duty trucks make up as much as 25 to 30 percent of the daily traffic, compared to California's statewide average of about 9 percent. Reportedly, the majority of truck trips along the Route 99 corridor are "interregional" in nature.³⁰ Nearly 100 percent of the trucks that pass through this corridor are powered by diesel engines. About 75 percent are Class 8, 5-axle tractor-trailer combination trucks.³¹

The key to achieve NAAQS for ozone and PM_{2.5} in these two air basins is to aggressively control NO_x from HHDTs. In the SCAB, preliminary analysis suggests that attaining the ozone NAAQS will require total NO_x emissions to be reduced from the 265 tons per day (tpd) that are currently projected for 2023 (i.e., assuming full implementation of existing regulations) down to approximately 132 tpd. By 2031, total NO_x emissions must be reduced to approximately 93 tpd (see Figure 5). This represents a 50 percent NO_x reduction beyond existing regulations by 2023, and an additional 15 percent NO_x reduction beyond 2023 levels by 2031.³² The nearby SJVAB must also achieve very large NO_x reductions over the next 10 to 20 years. In both cases, heavy-duty diesel trucks contribute the largest NO_x tonnage.

²⁷ Gladstein, Neandross & Associates, estimated using EMFAC and California state GHG inventory data.

²⁸ California Department of Transportation, Caltrans District 6 and 10 Business Development Team, "Updated Business Plan Volume 1 – Decision Makers Guide to Improving the Route 99 Corridor," February 2013, http://www.dot.ca.gov/dist6/planning/sr99bus/updated_bp_vol1_feb2013.pdf

²⁹ South Coast Air Quality Management District, "Goods Movement," 2016 AQMP White Paper, October 2015, <http://www.aqmd.gov/docs/default-source/Agendas/aqmp/white-paper-working-groups/wp-goodsmvmt-final.pdf?sfvrsn=2>

³⁰ Seyed Sadredin, Executive Director, San Joaquin Valley Air Quality Management District, Testimony to the U.S. House of Representatives, October 22, 2015, <https://www.valleyair.org/content/documents/Clean-Air-Act/Seyed-Sadredin-Testimony-10-22-15.pdf>.

³¹ Tulare County Association of Governments, "SR 99/SR 198 Gateways: Truck Origin and Destination Study, January 2015, prepared by Fehr Peers, <http://www.tularecog.org/wp-content/uploads/2015/07/SR99-SR198-Gateways-Survey-Results-2015.pdf>.

³² South Coast Air Quality Management District, figure and information provided in personal communication from staff, March 2016.

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

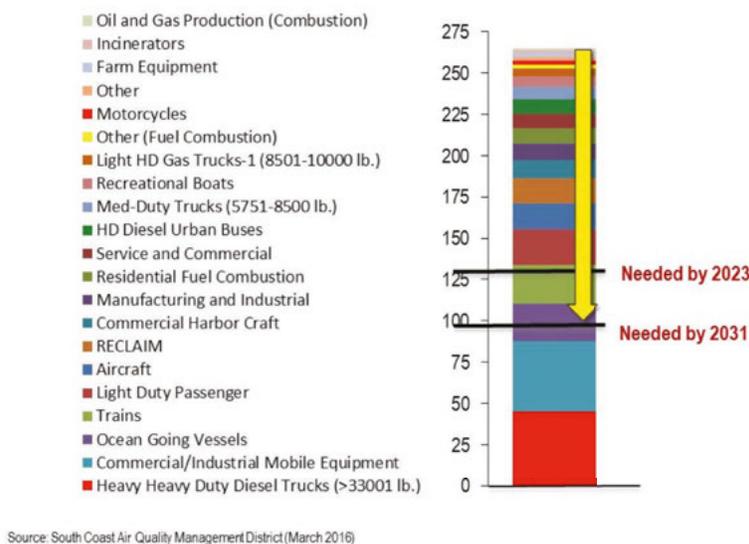


Figure 5. NOx reductions (tons per day) needed in SCAB to meet ozone NAAQS

In conjunction with the California Air Resources Board (CARB), local air quality officials at the South Coast Air Quality Management District (SCAQMD), and the San Joaquin Valley Air Pollution Control District (SJVAPCD) have developed urgent plans to dramatically reduce NOx and PM emissions from HHDTs in their air basins. Equally important, they seek to aggressively reduce HHDT emissions of carcinogenic DPM. SCAQMD’s most-recent Multiple Air Toxics Exposure Study (MATES IV) found DPM to be “the major contributor to air toxics risk, accounting on average for about 68 percent of the total” airborne cancer risk in the SCAB.³³ The SJVAB is home to America’s top four “most polluted metropolitan areas for year-round particle pollution;” an estimated 3.4 million people reside in these areas.³⁴ Much of this particle pollution is associated with intense diesel engine activity in the area by HHDTs engaged in goods movement.

Across the nation, many other large urban areas face similar challenges to reduce ozone-precursor and particle emissions from HHDTs (refer back to Figure 3 for the map showing cities across the U.S. in nonattainment for the federal ozone NAAQS). For example, the Dallas-Fort Worth and greater Houston areas have been designated by EPA as ozone nonattainment areas,³⁵ and the American Lung Association has ranked Phoenix as the top non-California metropolitan area for “people at risk” due to ozone pollution.”³⁶

³³ South Coast Air Quality Management District, “Multiple Air Toxics Exposure Study in the South Coast Air Basin, Final Report, May 2015, <http://www.aqmd.gov/docs/default-source/air-quality/air-toxic-studies/mates-iv/mates-iv-final-draft-report-4-1-15.pdf?sfvrsn=7>

³⁴ American Lung Association, “State of the Air 2016,” http://www.stateoftheair.org/2015/assets/ALA_State_of_the_Air_2015.pdf.

³⁵The nonattainment status of cities and EPA’s designations for the severity can change. For full current listings of all U.S. nonattainment areas, see EPA’s website at <https://www3.epa.gov/airquality/greenbook/hnc.html>.

³⁶American Lung Association, “Most Polluted Cities,” update from “State of the Air 2016,” <http://www.lung.org/our-initiatives/healthy-air/sota/city-rankings/most-polluted-cities.html>.

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

The next section summarizes some of the key policy goals of federal, state and local organizations that are designed to reduce petroleum usage and harmful emissions from America's vast heavy-duty transportation sector. As will be evident, extensive crossover exists in the techniques, technologies, methods and approaches that are being planned and adopted to simultaneously address these closely related issues.

3. Policy Goals and Objectives for U.S. On-Road HDV Transportation

Over the last two decades, America has made major advancements to reduce criteria pollutants, GHGs and TACs from on-road HDVs. Important reductions have been realized within some of the most-challenging HHDV applications, and significant volumes of diesel have been displaced with cleaner alternative fuels. *Deployment of approximately 65,000 heavy-duty NGVs has significantly contributed to all this progress.* Still, it is clear that 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. Air quality in nearly all major metropolitan areas of the U.S remains harmful to human health. Evidence continues to mount that the world has reached—and very possibly surpassed—the time for urgent action to reduce emissions of CO₂ and other GHGs, as needed to stabilize global climate change.

The most-urgent objective for air quality regulators is to systematically achieve major NO_x (and VOC) reductions to meet the ozone NAAQS. In particular, the more-stringent, ozone standard of 70 ppb adopted by EPA in 2015³⁷ will require highly-aggressive efforts to reduce transportation-related NO_x emissions, especially in California's worst nonattainment areas. In many places such as California's SCAB and SJVAB, HDVs powered by zero-emission and near-zero emission technologies will be required. As EPA has noted, "comprehensive efforts at the local, state and national level will be needed" to accomplish this transformation. These efforts will need to complement programs to reduce GHG emissions.³⁸

3.1. Petroleum Displacement and Increased Energy Diversity

3.1.1. Federal Initiatives and Policies

Transportation accounts for two thirds of U.S. expenditures on foreign oil, which amount to nearly \$1 billion *each day*. The U.S. Department of Energy considers it "vital" to decrease our nation's use of imported petroleum, and has identified a goal to reduce "net oil imports" by 50 percent by 2020. In addition to increased domestic production, the two key ways to accomplish this in the transportation sector are to 1) increase the fuel efficiency of America's fleet, and 2) expand use of non-petroleum alternative fuels. Overall, the U.S. government seeks to reduce transportation petroleum by 2.5 billion gallons per year in 2025.³⁹ Notably, one result of the scale back in domestic oil production since 2014

³⁷ EPA has formally adopted the 70 ppb ozone NAAQS. However, it must now review all of the county-level air quality data and officially designate any counties that are not in attainment for the new standard. Thus, discussion today of non-attainment counties is preliminary, and the list likely change to some degree after EPA conducts this analysis.

³⁸ U.S. Environmental Protection Agency, "Working to Reduce Ozone in California," October 1, 2015, accessed online at <http://www3.epa.gov/ozonepollution/pdfs/20151001californiafs.pdf>.

³⁹ U.S. Department of Energy, <http://www.energy.gov/eere/vehicles/vehicle-technologies-office-alternative-fuels-research-and-deployment>.

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

(largely due to very low crude prices) has been that U.S. imports of foreign oil again appear to be in a rising trend, after years of gradual decline.⁴⁰

The federal government implements various programs and policies to improve vehicle efficiency and encourage or mandate the use of alternative fuels (especially if produced from renewable sources). Activities to increase the use of alternative transportation fuels are carried out through various government agency collaborations and government-industry partnerships. For example:

- The federal Energy Policy Act (EPAct) requires that all “covered” vehicle fleets acquire AFVs when replacing fleet vehicles, or that they proportionally reduce the fleet’s petroleum use through other means
- The National Clean Fleets Partnership works to reduce petroleum use in large commercial fleets
- The Clean Cities - National Parks Initiative works to reduce petroleum use (and GHG emissions) in transportation at America’s National Parks
- The federal Renewable Fuel Standard (Energy Policy Act of 2005) and the Energy Independence and Security Act (2007) have established goals to require up to 36 billion gallons of renewable fuels annually by 2022.

One key federal program to reduce petroleum usage is squarely focused on improving the fuel economy of on-road HDVs. In August 2011, EPA and the Department of Transportation’s National Highway Traffic Safety Administration (NHTSA) announced a first-ever program to improve fuel efficiency of heavy-duty trucks and buses, while also reducing related GHG emissions. EPA and NHTSA each adopted complementary standards covering medium- and heavy-duty vehicle model years 2014 through 2018. These agencies are now in the process of promulgating a “Phase 2” round of similar standards covering model years 2019 to 2027. The emerging Phase 2 program, which will reportedly reduce petroleum use in America during this period by approximately 1.8 billion barrels of crude oil,⁴¹ is further discussed in the section on GHG emissions.

3.1.2. California’s Initiatives and Policies

Roughly half of the energy consumed in California is for transportation. More than 26 million cars and 1 million heavy-duty trucks are regularly operated within its boundaries. California’s annual transportation-related consumption is approximately 15.3 billion gasoline gallons and 3.5 billion diesel gallons; much of this is supplied via out-of-state energy sources, even though California is a major U.S. producer of crude oil.⁴²

⁴⁰ For a good discussion of this phenomenon, see The Wall Street Journal, “After Years of Decline, U.S. Oil Imports Rise,” October 26, 2015, <http://www.wsj.com/articles/after-years-of-decline-u-s-oil-imports-rise-1445851800>.

⁴¹ John Mikulin, U.S. EPA Specialist, Clean Energy and Climate Change, Air Division U.S. EPA Region 9, presentation at UC Davis Truck Technology Workshop, December 3, 2015, http://steps.ucdavis.edu/files/12-03-2015-Mikulin-US-EPA_UCD-MHDV-Workshop_12-3-15.pdf

⁴² California Energy Commission, “Fuels and Transportation Division,” <http://www.energy.ca.gov/transportation/>.

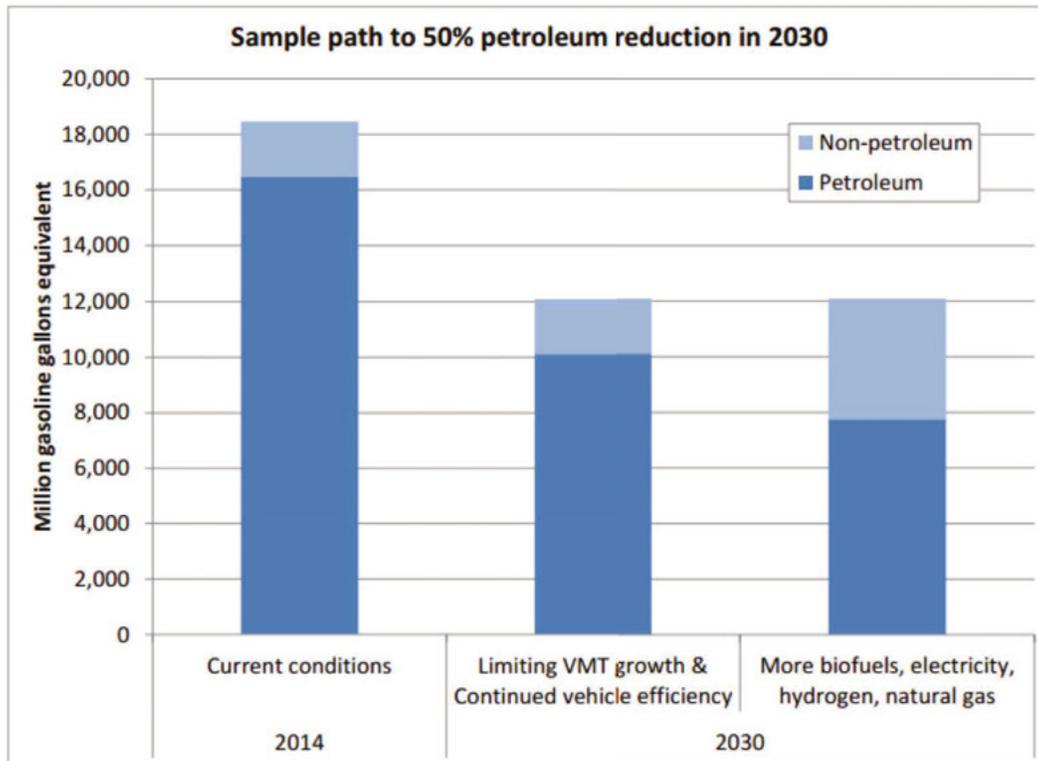


Figure 6. CARB's "sample path" to 50% petroleum reduction

The California Energy Commission (CEC) is primarily charged with reducing petroleum consumption in California, in conjunction with CARB. Under CEC and CARB oversight, the state has adopted aggressive goals that specifically target California's large, petroleum-intense transportation sector. One goal specifically targeted by Governor Jerry Brown is to reduce total petroleum use by 50 percent by 2030.⁴³ Figure 6 provides a "sample path" to meet this goal over the next 14 years, using a combination of limited growth for vehicle miles traveled (VMT); improved vehicle efficiency; and replacement of petroleum with non-petroleum fuels that include biofuels, electricity, hydrogen, and natural gas.

According to the state's estimates, achieving a 50 percent petroleum reduction in California could yield the following major benefits, much of which would be derived specifically from the transportation sector (**note:** costs were not identified).⁴⁴

Reduced pollution:

- About 50 percent less GHG emissions (including refineries)
- An 80 percent reduction in smog-forming pollution
- A 95 percent reduction in diesel particulate matter emissions

⁴³ See Governor Brown's Inaugural Address of January 5, 2015, <https://www.gov.ca.gov/news.php?id=18828>.

⁴⁴ Ryan McCarthy, Science and Technology Policy Advisor to the Chairman, presentation at the "Rethinking Transportation Conference in California, July 8, 2015, accessed online at <http://www.arb.ca.gov/cc/pillars/transportation/mccarthyppt.pdf>.

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

Stronger economy:

- Reduced fuel and petroleum dependence costs
- Diversified fuel supply

Numerous policies and efforts are underway or planned that are expected to achieve approximately 50 percent of California's petroleum-reduction goal. Policies involving on-road HDVs include:

- Heavy-duty engine and vehicle GHG standards
- Zero emission vehicle (ZEV) requirements for transit buses
- Market-based strategies such as Cap-and-Trade and the Low Carbon Fuel Standard
- California Transportation Plan
- Sustainable Freight Strategy
- State Implementation Plan and local Air Quality Management Plans
- Assembly Bill 32 Scoping Plan
- Alternative Diesel Fuels Program
- Mobile Source Strategy
- Senate Bill 535 (requirements for environmental justice and disadvantaged communities)

Specific California initiatives that target reducing petroleum use in the HDV sector include: 1) the Cap-and-Trade Program, 2) the Low Carbon Fuel Standard, and 3) the Alternative Diesel Fuels program. It is again noteworthy that—by design and due to inherent synergies—these initiatives will also help California address two other key transportation-related goals: improve ambient air quality and reduce GHG emissions. Below is a brief overview of the Alternative Diesel Fuels program. The Cap-and-Trade Program and the Low Carbon Fuel Standard are discussed in the section addressing GHG-reduction initiatives.

Alternative Diesel Fuels Program – In late 2015, CARB adopted a regulation governing alternative diesel fuels (ADF). The regulation puts in place a three-step process beginning in 2016 to create a path to bring cleaner diesel substitutes into the market. In 2014, “renewable diesel” was the most common ADF used in California. Most of this was supplied through overseas imports, although two California-based producers “are expected to come online as soon as 2016, producing a combined 17.5 million gallons per year.”⁴⁵ (As of the writing of this report, it is unclear if either producer has initiated RD production in California.) Renewable diesel (meeting ASTM International standard D975) is chemically identical to conventional diesel fuel. As such, it is considered a “drop-in” fuel for use in existing diesel engines and fuel infrastructure. As described later (Sections 4.3, 7.4.1 and especially Section 14), renewable diesel is a low-carbon-intensity transportation fuel that can readily displace conventional diesel fuel. Thus, it has potential to play a very significant role in transforming America's HHDT sector.

⁴⁵ California Energy Commission, “Draft Staff Report: 2016-2017 Investment Plan Update for the Alternative and Renewable Fuel and Vehicle Technology Program,” October 2015, accessed online at <http://www.energy.ca.gov/2015publications/CEC-600-2015-014/CEC-600-2015-014-SD.pdf>.

3.2. Improvement of Ambient Air Quality

3.2.1. Heavy-Duty Engine Emission Standards to Reduce NOx Emissions

For decades, EPA has used progressively more-stringent emissions standards applicable to new heavy-duty engines as the primary means to reduce NOx and PM emissions from HDVs. As Figure 7 shows, EPA has greatly reduced the allowable NOx and PM emissions from new heavy-duty engines since 1994. This currently culminates in the federal 2010 NOx and PM standards of 0.2 and 0.01 grams per brake-horsepower-hour (g/bhp-hr), respectively⁴⁶ (the three-dimensional green box in the figure).

Figure 7 also shows an essentially flat green box that correlates to NOx and PM emission levels of 0.02 and .01 g/bhp-hr, respectively. This reflects special engine certification levels that CARB has established under California's "Optional Low-NOx Standard" (OLNS). (CARB can adopt more-stringent emissions standards for engines and vehicles intended for sale in California; see the [call-out box](#)). In 2014, CARB adopted a three-tiered OLNS to incentivize manufacturers to voluntarily reduce NOx from their heavy-duty engines to 50, 75 and 90 percent below EPA's mandatory federal standard (green box). Specifically, the red box quantifies CARB's lowest-tier OLNS. With NOx at 0.02 g/bhp-hr, this is 90 percent lower than

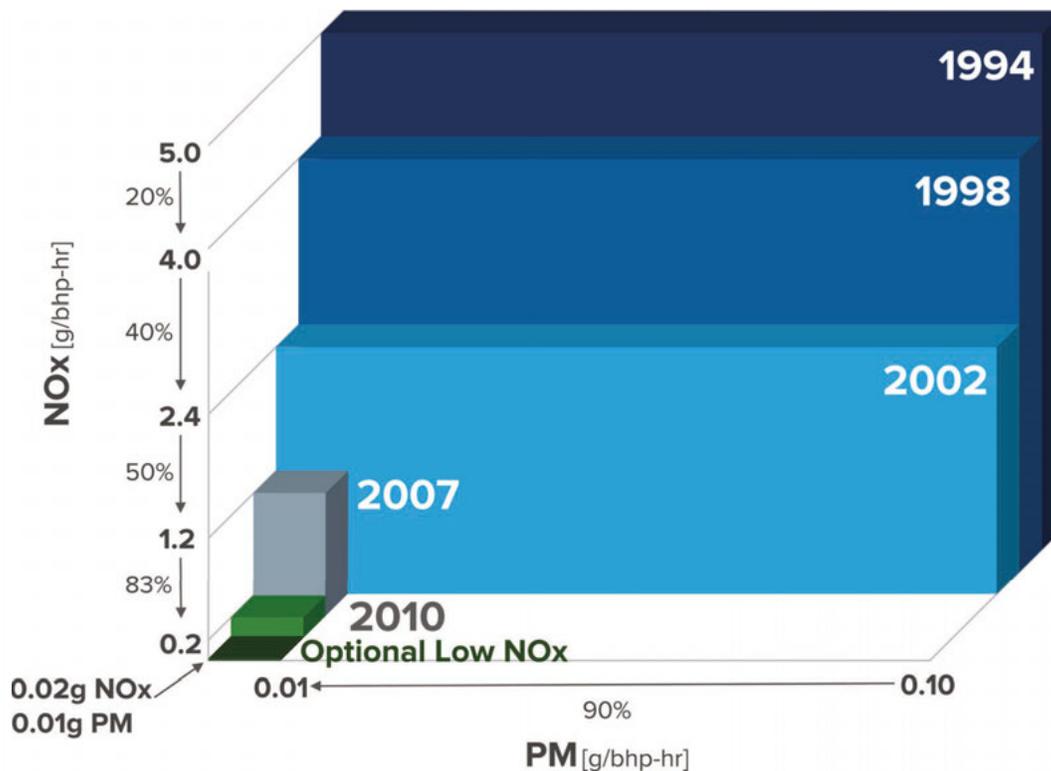


Figure 7. History of EPA and CARB heavy-duty engine standards for NOx and PM

⁴⁶66 Federal Register 5001 et seq (January 18, 2001) at page 5005. Accessible at <http://www.gpo.gov/fdsys/pkg/FR-2001-01-18/pdf/01-2.pdf>.

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

the mandatory federal heavy-duty engine standard of 0.2 g/bhp-hr.

In October 2015, the nationwide need to reduce NO_x emissions through *even-more-stringent* federal heavy-duty engine standards was significantly increased. EPA lowered the NAAQS for ground-level ozone from 75 to 70 parts per billion (ppb), to “improve public health protection, particularly for at-risk groups” such as children. EPA estimates that the public health benefits of dropping the ozone NAAQS to 70 ppb will range between \$2.9 and \$5.9 billion annually in 2025, compared to the estimated costs of \$1.4 billion.⁴⁷

California’s Clean Air Act (CAA) Waiver

Under the federal CAA, EPA sets emissions standards for mobile sources, including on-road heavy-duty engines. Due to California’s extraordinary air quality challenges, EPA has granted CARB a CAA “waiver” (42 U.S.C. 7543b) that allows it to adopt more-stringent standards within its jurisdiction, provided certain CAA statutes are met. Over nearly five decades, this has allowed CARB to repeatedly promulgate emissions standards that are more aggressive than those applicable to vehicles and engines sold in other states. However, EPA also allows states to “opt in” by adopting CARB’s emissions standards for new motor vehicles, provided they are identical to those for which EPA has granted CARB a waiver.

This more-stringent NAAQS is expected to cause many more counties across America to be designated as ozone nonattainment areas, once the list is finalized in 2017. For example, under a 70 ppb ozone NAAQS, several rural counties in California will likely fall out of attainment, adding to the state’s existing 16 ozone-nonattainment areas.^{48,49} For California’s existing areas of extreme ozone nonattainment (the SCAB and SJVAB), attaining a 70 ppb NAAQS will require even-more-aggressive, longer-term efforts to reduce air pollutant emissions. Comprehensive efforts at the local, state and national level will be needed to develop and deploy ultra-clean transportation technologies and fuels. Such efforts must be complementary with efforts to meet NAAQS for other criterial pollutants, such as PM_{2.5}.

This challenge to attain NAAQS becomes even more daunting when also considering California’s GHG-reduction goals. While often synergistic, technologies and processes to reduce GHGs from HDVs can conflict with those designed to reduce NO_x.⁵⁰ CARB is leading efforts to resolve these “NO_x-GHG tradeoffs” and find ways to meet all NAAQS within federal deadlines, while also steadily reducing GHG emissions. These plans are embodied in CARB’s draft “Mobile Source Strategy”⁵¹ document (October 2015), which is designed to simultaneously restore healthful air quality for millions of Californians,

⁴⁷ See Federal Register, Vol. 80, No. 206 (October 26, 2015), at <http://www.gpo.gov/fdsys/pkg/FR-2015-10-26/pdf/2015-26594.pdf>.

⁴⁸ California Air Resources Board, “California Supports U.S. EPA Action to Strengthen National Ozone Standard,” news release, October 1, 2015.

⁴⁹ For an interactive map of EPA’s projected ozone levels in 2025, when the new ozone NAAQS will be in effect, see http://ozoneairqualitystandards.epa.gov/OAR_OAQPS/OzoneSliderApp/index.html#.

⁵⁰ For a good discussion about how NO_x-GHG tradeoffs affect tough product development decisions faced by heavy-duty engine and vehicle manufactures, see “What’s in Store for Emissions and NO_x Control?” at <http://www.ccjdigital.com/whats-in-store-for-emissions-and-nox-control/>.

⁵¹ California Air Resources Board, “Mobile Source Strategy: Discussion Draft,” October 2015, http://www.arb.ca.gov/planning/sip/2016sip/2016mobsrc_dd.pdf.

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

reduce the State's GHG emissions to slow global warming, and reduce dependence on petroleum (see Section 4.6 for further discussion).

3.2.2. Reduction of Health Risks from Diesel Exhaust

DPM is the most impactful TAC emitted by heavy-duty diesel vehicles. It is a special kind of fine PM formed in the exhaust of diesel-fueled compression-ignition engines. DPM can agglomerate and adsorb other species to form structures of complex physical and chemical properties, many of which can be harmful to human health. Nationally, EPA indicates that "considerable evidence" makes diesel exhaust "a likely carcinogen" due primarily to its DPM content.⁵² In California, CARB has defined DPM as "a known carcinogen," citing more than 30 human epidemiological studies that "strongly suggest a causal relationship between occupational diesel exhaust exposure and lung cancer."⁵³

Other TACs found in the exhaust of diesel engines include potential cancer-causing substances such as arsenic, benzene, formaldehyde, nickel, and polycyclic aromatic hydrocarbons. EPA, CARB and OEEHA all list a wide array of substances emitted from diesel engines that are either "hazardous air pollutants" (HAPs) or TACs.⁵⁴

Numerous studies have found that emissions of DPM and other TACs from diesel engines generally concentrate in close proximity to freeways and very busy roadways, where large numbers of HDVs are operated. DPM levels up to 25 times greater than in the general ambient air have been measured.⁵⁵ SCAQMD's most-recent Multiple Air Toxics Exposure Study (MATES IV) found DPM from diesel exhaust to be the major contributor to air toxics risk in the SCAB.⁵⁶ This toxic risk is closely associated with intense activity by heavy-duty diesel trucks along goods movement corridors in the greater Los Angeles area. This can be clearly seen in SCAQMD's MATES IV map (Figure 8), showing peak areas of air toxic risk in dark shades that coincide with major freeways, the two ports of Los Angeles and Long Beach, and freight rail corridors.

⁵² U.S. Environmental Protection Agency, "Diesel Particulate Matter," <http://www3.epa.gov/region1/eco/airtox/diesel.html>

⁵³ California Air Resources Board, "The Report on Diesel Exhaust," <http://www.arb.ca.gov/toxics/dieseltac/de-fnds.htm>

⁵⁴ California Air Resources Board, "Fact Sheet on Toxic Air Contaminant Emissions from Diesel-Fueled Engines, accessed online 12-23-15 at <http://www.arb.ca.gov/toxics/dieseltac/factsht1.pdf>.

⁵⁵ California Office of Environmental Health Hazards Assessment, "Adoption of Air Toxics Hot Spots Program Guidance Manual for Preparation of Health Risk Assessments," March 6, 2015, accessed online at http://oehha.ca.gov/air/hot_spots/hotspots2015.html.

⁵⁶ South Coast Air Quality Management District, "Multiple Air Toxics Exposure Study in the South Coast Air Basin, Final Report, May 2015, <http://www.aqmd.gov/docs/default-source/air-quality/air-toxic-studies/mates-iv/mates-iv-final-draft-report-4-1-15.pdf?sfvrsn=7>

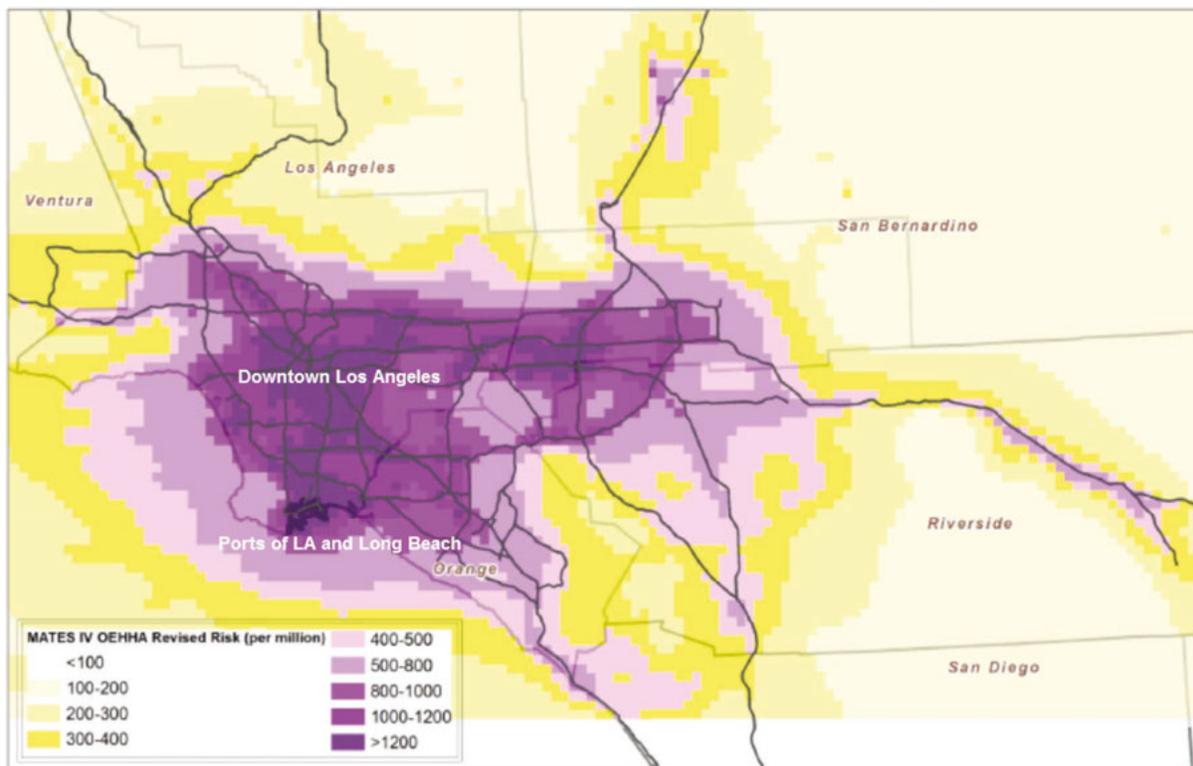


Figure 8. SCAQMD MATES IV map: cancer risk from air toxics in greater Los Angeles

People who regularly spend time in these TAC “hot spot” areas can have very significant health impacts caused by the air-borne pollutants. Deleterious effects on children are especially noteworthy, as TAC pollution “is associated with acute health effects, exacerbating asthma and negatively impacting the ability of children to learn.”⁵⁷ OEHA estimates that more than 150 schools in California are located within 500 feet of extremely high traffic roadways such as good movement corridors. These schools tend to be in “environmental justice” areas where disproportionate numbers of economically disadvantaged pupils are “at increased risk of developing bronchitis” and other respiratory illnesses due to the elevated levels DPM and other TACs associated with traffic.⁵⁸ The air toxic hotspots illustrated by the MATES IV map correlate closely with environmental justice areas identified by SCAQMD. This again emphasizes that socioeconomically disadvantaged communities tend to be disproportionately exposed to high levels of cancer risk. Similar correlations of diesel engine activity, high cancer risk, and environmental justice areas can be found across the United States.

As with the NOx-reduction approach, EPA and CARB have primarily controlled emissions of PM (including DPM) from heavy-duty engines through promulgation of increasingly stringent emissions standards applicable to new engine sales. To meet the current standard of 0.01 g/bhp-hr, 2007 model year and newer on-road heavy-duty engines are essentially required to be factory-equipped with diesel

⁵⁷ California OEHA, “Adoption of Air Toxics Hot Spots Program Guidance Manual for Preparation of Health Risk Assessments,” March 6, 2015, accessed online at http://oehha.ca.gov/air/hot_spots/hotspots2015.html.

⁵⁸Ibid.

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

particulate filters (DPFs). One year prior, EPA mandated all U.S. on-road diesel fuel to a sulfur content of less than 15 ppm. This requirement in 2006 for “ultra-low sulfur diesel” (ULSD) enabled wide-scale use of DPFs for on-road HDVs, allowing their engines to reduce PM by 90 percent and meet the 0.01 g/bhp-hr standard.

Together, DPFs and ULSD are highly effective at reducing PM emissions from the exhaust of diesel-fueled HDVs. However, the overall health risks do not necessarily get significantly reduced on newer diesel HDVs equipped with DPFs and other advanced emission controls. OEHHA researchers indicate that, for risk assessment purposes, the available data do not indicate that diesel exhaust from new technology diesel engines “should be considered to be fundamentally different” compared to exhaust from older diesel engines.⁵⁹ Moreover, about two-thirds of DPM emissions have historically come from off-road applications. EPA and CARB are just beginning to implement emerging requirements to reduce PM emissions from large off-road diesel engines by burning low-sulfur diesel fuel and incorporating technologies like DPFs.

EPA and CARB have enacted “diesel risk reduction” strategies that go well beyond stringent engine certification standards. These programs focus largely on reducing DPM and TACs from older, in-use diesel HDVs that pre-date the 2007 model year. Generally, the approach involves one or more of the “5 R” strategies applicable to in-use HDVs: replace, retrofit, repower, repair, and refuel. Importantly, using a combination of the “refuel” and “replace” (or “repower”) options—specifically, replacing diesel HDVs with those powered by low-emission or near-zero-emission heavy-duty natural gas engines—can provide a broadly applicable, immediate way to reduce these communities’ exposure to diesel exhaust from HDVs.

3.2.3. Accelerated Deployment of Zero- and Near-Zero-Emission HDTs

The multitude of harmful air quality and public health impacts from the U.S. transportation sector make America’s fleet of HDVs—especially HHDTs used in goods movement—a top priority of air quality regulators for expedited transition to very low emitting fuels and technologies. As previously noted, the most-dire cases are found in California. To achieve the necessary NO_x reductions for timely ozone and PM_{2.5} attainment, the SCAB and SJVAB must expeditiously phase-in HDVs that either 1) emit no regulated pollutants—per CARB’s definition of a “zero emission vehicle” (ZEV); or 2) emit near-zero NO_x levels. Other highly impacted areas of the country (e.g., Houston and Phoenix) have similar needs and goals.

The State Implementation Plan (SIP) for any nonattainment region must identify specific control measures and policies to demonstrate how NAAQS will be attained. As part of California’s SIP, SCAQMD is now preparing its 2016 Air Quality Management Plan (AQMD), which identifies incentives for “early deployment of zero and near-zero-emission technologies” as an important strategy. SCAQMD has noted

⁵⁹ California Office of Environmental Health Hazard Assessment (OEHHA), “A Risk Assessment Evaluation of New Technology Diesel Engine Exhaust Composition,” poster presentation by JD Budroe, AG Salmon and MA Marty; 2012, http://oehha.ca.gov/public_info/pdf/SOT2012dieselRA.pdf.

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

that this includes “investments in technologies that meet multiple objectives - air quality, climate, toxics, and energy efficiency. Specifically (emphasis added):

“The 2016 AQMP will strongly rely on a transition to zero- and near-zero emission technologies in the mobile source sector including automobiles, transit buses, medium- and heavy-duty trucks, and off-road applications to meet the air quality standards. The plan will focus on existing commercialized technologies and energy sources and newer technologies that are nearing commercialization based on demonstration programs and limited test markets, including their supporting infrastructure.”⁶⁰

Air quality regulators have not yet formally defined the term “near-zero-emission vehicle” (NZEV). Generally, it is equated with the NO_x emissions of a comparable battery-electric vehicle when accounting for proportional emissions associated with base-load electricity generation. Emissions of NO_x from electricity generation vary from state-to-state, depending on the specific “mix” of energy sources used to make electricity. SCAQMD has developed a working definition for heavy-duty NZEVs as being those powered by heavy-duty engines that achieve at least a 90 percent NO_x reduction, relative to the current federal heavy-duty on-road engine standard of 0.2 grams per brake horsepower-hour (g/bhp-hr). This 90 percent reduction level (0.02 g/bhp-hr NO_x) is equivalent to the lowest tier of the “Optional Low-NO_x Standards” that California adopted in 2014 for heavy-duty on-road engines. Sections 4.3 and 6.4 provide further discussion on this important topic.

In the HDV sector, urban transit buses have long been a focal point for early deployment of emerging low-emissions technologies and alternative fuels. This continues today with federal, state and local efforts that seek to rapidly transition transit buses to ZEV and NZEV technologies. Currently, there are no federal initiatives that *mandate* production, purchase or use of transit buses that emit at ZEV or NZEV levels. However, many existing and emerging federal programs are designed to help develop, commercialize and deploy cleaner transit bus technologies.

At the state level, CARB has adopted a regulation for California transit agencies that includes a long-term requirement for larger agencies to purchase “zero emission” buses. This requirement has been delayed twice “due to technology readiness concerns” and the ongoing need to continue assessing the commercial maturity of battery-electric and/or fuel cell buses. Most recently (November 2015), CARB noted that “promising zero emission bus technology” (i.e., battery electric and hydrogen fuel cell) has reached “the early commercialization phase,” while also acknowledging that near-zero-emission natural gas buses are soon to be fully commercialized. CARB is now working with stakeholders to develop an Advanced Clean Transit proposal that will incorporate all of these “advanced clean technologies.” However, CARB’s long-term goal is to transition all public transit buses to zero-emission technologies.⁶¹

⁶⁰ South Coast Air Quality Management District, “Blueprint for Clean Air,” 2016 AQMP White Paper, October 2015, <http://www.aqmd.gov/docs/default-source/Agendas/aqmp/white-paper-working-groups/wp-blueprint-final.pdf?sfvrsn=2>.

⁶¹ California Air Resources Board, “Updated Agenda for the Advanced Clean Transit Technology Symposium, email from listserv, February 5, 2016.

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

The natural gas industry and certain stakeholders are working with CARB to demonstrate that near-zero-emission heavy-duty natural gas engines fueled by RNG also provide a sustainable pathway to meet the State's needs for NOx and GHG emissions reductions from the public transportation sector. As detailed further in this report, transit buses with the CWI ISL G NZ engine fueled by RNG will be deployed in commercial service before the end of 2016.

3.3. Reduction of Greenhouse Gases / Climate Pollutants

3.3.1. Federal Efforts, Policies and Initiatives

Nationally, 26 percent of GHG emissions are generated by America's transportation sector. On-road HDVs (trucks and buses) are responsible for approximately 20 percent of these transportation-related GHG emissions. By 2020, the federal government's goal is to reduce overall GHG emissions by 17 percent, with a long-term goal of an 80 percent reduction by 2050 (relative to 2010 levels).⁶²

EPA and other federal agencies are leading national efforts to address climate change. These efforts fall into the general categories of 1) collecting GHG emissions data and identifying opportunities to reduce emissions; 2) implementing policies and regulations to affect GHG reductions; 3) evaluating the costs and benefits of new policy options; 4) working to advance the science of climate research, 5) providing technical assistance and analytic tools to states, regions and communities; and 6) partnering internationally to engage other governments on how to ensure that world-wide GHG reductions are achieved.⁶³

Below are summaries for several relevant federal efforts that fall within these categories.

White House Climate Action Plan – In March 2014, the White House released its “Climate Action Plan: Strategy to Reduce Methane Emissions.” This document describes the Obama Administration's “targeted strategy” to build on existing methane reduction measures and take new steps to further reduce emissions. The strategies that are most relevant to this white paper are focused on landfills, oil & gas operations, and agricultural operations.⁶⁴ As part of this Plan, EPA has proposed a suite of requirements focused on reducing GHG and VOC emissions from America's “rapidly growing” oil and gas industry. The proposals are intended to complement rules the agency issued in 2012 to reduce pollution from this industry.⁶⁵

Clean Power Plan for Existing Power Plants - On August 3, 2015, President Obama and EPA announced “Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units.” Commonly called “The Clean Power Plan (CPP), EPA considers this to be an “historic and important step

⁶² Dr. Sunita Satyapal, Director, U.S. DOE Fuel Cells Technology Office, presentation to the California Business Council, (citing http://hydrogen.energy.gov/pdfs/13005_well_to_wheels_ghg_oil_ldvs.pdf), November 2015.

⁶³ U.S. Environmental Protection Agency, “What EPA is Doing about Climate Change,” <http://www3.epa.gov/climatechange/EPAactivities.html>.

⁶⁴ White House, “Climate Action Plan: Strategy to Reduce Methane Emissions,” March 2014, https://www.whitehouse.gov/sites/default/files/strategy_to_reduce_methane_emissions_2014-03-28_final.pdf

⁶⁵ U.S. EPA, “Oil and Natural Gas Pollution Standards,” accessed online on October 7, 2015, <http://www3.epa.gov/airquality/oilandgas/>.

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

in reducing carbon pollution from power plants.” This plan, which became effective in December 2015, “continues progress already underway in the U.S. to reduce CO₂ emissions from the utility power sector.” It is “designed to strengthen the fast-growing trend toward cleaner and lower-polluting American energy” by adopting “strong but achievable standards for power plants.”⁶⁶ Implementation of the Clean Power Plan would reduce the carbon intensity of grid-supplied electricity. Since all transportation fuel pathways rely on grid electricity to some extent, this would help reduce GHG emissions from the transportation sector, in varying degrees by pathway. In addition, the Clean Power Plan would reduce NOx emissions from plants that generate power for heavy-duty BEVs. See Sections 6.8 and 11 for additional discussion on how a cleaner grid could impact GHG and NOx emissions from HDVs. However, as of February 2016, the U.S. Supreme Court ordered a temporary suspension for enforcement of the CPP, until further legal challenges to the plan are resolved. Therefore, the future impact of the CPP on reducing U.S. GHG emissions is currently uncertain.

New Source Performance Standards - In August 2015, EPA proposed “new source performance standards” to directly regulate methane emissions from the oil and gas sector. This proposed rule is one part of the Obama administration’s larger effort to reach a goal set in January 2015 to achieve a 40 to 45 percent reduction in methane emissions from the oil and gas sector by 2025 (relative to 2012 levels). EPA estimates that the proposed standards on new and modified sources would prevent up to 400,000 short tons of methane from being leaked by 2025, the equivalent of up to 9 million metric tons of CO₂.

EPA-NHTSA Phase 2 HDV Fuel Efficiency Standards - In August 2011, EPA joined with the Department of Transportation’s National Highway Traffic Safety Administration (NHTSA) to adopt a landmark program to reduce GHG emissions and improve fuel efficiency of heavy-duty trucks and buses. EPA and NHTSA each adopted complementary “Phase 1” standards covering MDV and HDV model years 2014 to 2018. Together, EPA’s CO₂ emission requirements and NHTSA’s fuel efficiency requirements form a comprehensive Heavy-Duty National Program. Under this program, vehicle manufacturers must meet increasingly stringent fuel economy and GHG emissions standards for three categories of on-road HDVs above 8,500 GVWR. These include Class 7 and 8 tractor trucks as well as a wide array of other HDV types (such as delivery, refuse, tow trucks, transit, shuttle, school buses, and emergency vehicles).

These standards provide flexibility, allowing for emissions and/or fuel consumption credits to be averaged, banked, or traded. Although the agencies recognize that NGVs and other alternative fuels can provide significant CO₂ and petroleum reduction benefits, they did not include any special credits or benefits for NGVs under these EPA and NHTSA rules. Instead, the agencies will measure and certify tailpipe CO₂ emissions for the EPA program and convert those to fuel consumption assumptions for the NHTSA program.

Recently, EPA and NHTSA proposed Phase 2 standards that would require further GHG reductions and fuel economy improvements from HDVs for model years 2019 through 2027. The proposed regulations

⁶⁶ U.S. Environmental Protection Agency, “Clean Power Plan for Existing Power Plants,” Rule Summary, <http://www.epa.gov/cleanpowerplan/clean-power-plan-existing-power-plants#CPP-final>.

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

under draft are expected to require up to 20 percent GHG reductions (1 billion metric tons of CO₂ equivalent) and fuel economy improvements from heavy-duty trucks by 2027. An alternative proposal could accelerate the implementation to 2024 and is being strongly advocated for by environmental groups and several state air quality agencies. The regulation also requests comment on a potential future emissions standard for heavy-duty engines that would require lower NO_x emissions, introducing further challenges in managing inherent tradeoffs between reducing NO_x emissions and improving fuel economy (i.e., reducing CO₂ emissions).

EPA and NHTSA assume that some degree of drivetrain “hybridization” will be adopted for HDVs to comply with the proposed rules. This would primarily entail engine start/stop technologies and electrified power take-off systems, rather than full incorporation of electric drive. Natural gas engines are well poised to meet the 2027 standards today without hybridization, due to the rule’s use of tailpipe CO₂ emissions rather than well-to-wheels (full-fuel-cycle) CO₂ emissions. However, diesel vehicles will need to employ a combination of technologies including engine efficiency improvements, vehicle weight reduction, and, in some cases, hybridization to achieve the standards.⁶⁷

Participation in the Paris Agreement – At the Paris Climate Conference (“COP21”) in December 2015, the U.S. and 194 other countries adopted “the first-ever universal, legally binding global climate deal.” This “Paris Agreement” establishes a long-term, durable global framework to reduce global GHG emissions. The objective is to sufficiently reduce world-wide GHG emissions to limit global warming to “well below” 2 degrees Celsius. Included are goals for low-carbon transportation including a “Global Green Freight Action Plan.” The Paris Accord agreement will be “deposited at the UN in New York and opened for signature” beginning in April, 2016.⁶⁸

3.3.2. California’s Efforts, Policies and Initiatives

California’s vast transportation sector accounts for 37 percent of the state’s GHG emissions. In 2006, the California Legislature passed a sweeping Global Warming Solutions Act (Assembly Bill 32, or AB 32). AB 32 initiated a comprehensive, multi-year program to reduce GHG emissions in California, including many elements targeted to the transportation sector. It requires CARB to develop and approve a Scoping Plan that describes California’s approach to aggressively reduce GHG emissions to 1990 levels by 2020 (approximately a 15 percent reduction). The State also has a longer-term goal to reduce GHG emissions by 80 percent by 2050 (per California Executive Order S-3-05).

AB 32 requires CARB to adopt regulations that can achieve “the maximum technologically feasible and cost-effective GHG emission reductions.” The Scoping Plan must be updated every five years to evaluate if California is on track to achieve its 2020 GHG-reduction goal. In May 2014, CARB approved the first update, noting that GHG reductions will be needed “from virtually all sectors of the economy and will be

⁶⁷ Some of this section about the EPA-NHTSA fuel economy / GHG standards is based on recent work prepared by GNA.

⁶⁸ The White House, “U.S. Leadership and the Historic Paris Agreement to Combat Climate Change,” press release, December 12, 2015, <https://www.whitehouse.gov/the-press-office/2015/12/12/us-leadership-and-historic-paris-agreement-combat-climate-change>

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

accomplished from a combination of policies, planning, direct regulations, market approaches, incentives and voluntary efforts.”⁶⁹

The integrated climate strategy⁷⁰ that California is now implementing under the umbrella of AB 32 entails the following primary objectives involving California’s large transportation sector:

- Reduce carbon intensity of all transportation fuels (10 percent overall reduction by 2020)
- Increase use of renewable electricity (which also impacts the carbon intensity of transportation fuels)
- Reduce vehicle petroleum use (50 percent by 2030)
- Reduce emissions of short-lived climate pollutants (including methane and black carbon from vehicles)

Key initiatives to carry out California’s goals for GHG reductions and climate change are summarized below.

Cap-and-Trade Program - California’s Cap-and-Trade Program is a key element of its statewide efforts to reduce GHG emissions and address climate change, as required under AB 32. It is a market-based (rather than “command-and-control”) program that seeks to reduce GHG emissions from about 450 relatively large “covered entities” that are responsible for approximately 85 percent of California’s GHG inventory. The program sets a statewide limit on these entities, and establishes a price signal needed to drive long-term investment in cleaner fuels and more efficient use of energy. Cap-and-Trade is designed to provide flexibility for covered entities to seek out and implement the lowest-cost options to reduce GHG emissions. A portion of the GHG emissions permits (allowances) established by the Cap-and-Trade Program are sold at quarterly auctions and reserve sales, and the proceeds are allocated to projects that support the goals of AB 32. The program began in 2013 by including electricity generators and large industrial facilities with annual emissions at or above 25,000 MTCO_{2e}. In 2015, Cap-and-Trade was expanded to extend compliance obligations to distributors of transportation fuels, natural gas and other fuels.

CARB set the initial 2012 “cap” under this program at about two percent below “business as usual” emissions levels that were forecasted for 2012. Each year from 2015 to 2020, the cap declines by three percent. The program is designed to provide covered entities with “the flexibility to seek out and implement the lowest cost options” to reduce GHG emissions. As noted above, this mechanism of Cap-and-Trade is intended to drive long-term investments in cleaner fuels and energy-efficient technologies that produce progressively lower GHG emissions. Simultaneously, Cap-and-Trade is designed to reduce emissions of criteria pollutants and TACs throughout California.⁷¹

⁶⁹ California Air Resources Board, “Assembly Bill 32 Overview,” <http://www.arb.ca.gov/cc/ab32/ab32.htm>.

⁷⁰ California Air Resources Board, “California Climate Change Strategy: An Integrated Plan for Addressing Climate Change,” presentation by Richard Corey at “Rethinking Transportation in California,” July 9, 2015, accessed online at <http://www.arb.ca.gov/cc/pillars/transportation/coreyppt.pdf>.

⁷¹ California Air Resources Board, “Overview of ARB Emissions Trading Program,” undated, accessed online on 11-03-15 at http://www.arb.ca.gov/cc/capandtrade/guidance/cap_trade_overview.pdf.

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

Note: California's Cap-and-Trade program provides a good example of the important nexus between efforts to reduce petroleum usage, address climate change and restore healthful air quality in America's urban areas.

A very important element of California's Cap-and-Trade program is that it supports investments in advanced low-carbon transportation technologies and fuels. Proceeds from Cap-and-Trade auctions go into California's Greenhouse Gas Reduction Fund (GGRF). State law sets the framework for investing these funds in projects that reduce GHG emissions while also achieving "co-benefits" such as reducing criteria pollutants and TACs. California Senate Bill (SB) 535 requires that 25 percent of GGRF proceeds be allocated to projects that provide a benefit to disadvantaged communities, with at least 10 percent of the funds going to projects located within those communities.⁷² California is currently in the process of implementing a "Second Investment Plan" for GGRF funds, which seeks to "maximize co-benefits to public health, the environment, and the economy." The California legislature and Governor Brown have appropriated more than a billion dollars under the Second Investment Plan, of which roughly \$300 million is intended to reduce GHG emissions in the HDV transportation sector. Two of the three core concepts for the Second Investment Plan are "sustainable communities & clean transportation" and "clean energy and energy efficiency."

Table 1 summarizes priority elements involving HDV technologies and fuels that are included within these core concepts, and the proposed fiscal appropriations under this phase of the investment plan⁷³. As indicated, \$350 million will be allocated towards the Sustainable Communities & Clean Transportation category, of which one priority element is to support deployments of zero- and near-zero emission on-road HDVs. However, the final breakout for appropriations by various fuel-technology pathways (heavy-duty BEVs, FCVs, NGVs) is largely undetermined.

Cap-and-Trade auction proceeds in the GGRF are largely dispersed through two initiatives managed by CARB, the Low Carbon Transportation Program and the Air Quality Investment Program (AQIP). Investments from these two programs are designed to accelerate California's transition to low carbon freight and passenger transportation—with an emphasis on investments that benefit disadvantaged communities. CARB develops a funding plan for these monies, in conjunction with other relevant state organizations such as CEC and the state's higher education system. For on-road HDVs, key types of projects that can be funded under Cap-and-Trade auction proceeds include advanced technology demonstration projects for freight equipment and other heavy-duty engines and equipment.⁷⁴

⁷² California Environmental Protection Agency, "Greenhouse Gas-Reduction Investments to Benefit Disadvantaged Communities," <http://www.calepa.ca.gov/EnvJustice/GHGInvest/>.

⁷³ California Air Resources Board, "Cap-and-Trade Auction Proceeds: Draft Second Investment Plan, Fiscal Years 2016-17 and through 2018-19," presentation at public workshop, November 3, 2015, http://www.arb.ca.gov/cc/capandtrade/auctionproceeds/draft_second_investment_plan_workshop_presentation.pdf.

⁷³ Ibid.

⁷⁴ California Air Resources Board, "Low Carbon Transportation and Air Quality Improvement Program (AQIP)," <http://www.arb.ca.gov/msprog/aqip/aqip.htm>.

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

Table 1. Core concepts and priority elements (HDV-related) for GGRF 2nd Investment Plan

Core Concept / \$ Appropriations	Appropriation (Department)	Priority Elements Related to HDV Sectors and Fuels
Sustainable Communities & Clean Transportation	\$350 million (California Air Resources Board)	<ul style="list-style-type: none"> • In-state production of low carbon fuels • Zero and near-zero emission trucks, freight, and non-freight equipment • Freight efficiency • Support sustainable communities strategies
Clean Energy & Energy Efficiency	\$60 million (University of California / California State University System)	<ul style="list-style-type: none"> • Anaerobic digestion and composting • Waste-to-fuel (dairies, biomass and landfills)

Source: CARB, “Draft Investment Goals and Concepts, workshop handout, November 2015, http://www.arb.ca.gov/cc/capandtrade/auctionproceeds/draft_second_investment_plan_workshop_handout.pdf

Local air quality officials in California’s SCAB and SJVAB and other stakeholders have indicated that Cap-and-Trade (i.e., GGRF) allocations are disproportionately low for immediate and sustained deployment of HHDVs powered by near-zero-NOx engines. For example, SJVAPCD officials emphasized that the SJV is “heavily impacted” by emissions from HHDVs moving goods along I-5 and SR 99. Consequently, timely attainment of NAAQS for both ozone and PM_{2.5} will not be achieved without greater funding allocations for “new near-zero-emission technologies in the freight sector” (i.e., CWI’s emerging line-up of heavy-duty “NZ” natural gas engines).⁷⁵

Two major trucking industry groups, the American Trucking Associations and the California Trucking Association, have advocated for California to allocate at least 20 percent of GGRF monies “towards a wide range of lower-emission vehicles with both greenhouse gas and NOx co-benefits, including those utilizing internal combustion engines like lower-emission natural gas vehicles.”⁷⁶

Low Carbon Fuel Standard (LCFS) - In 2007, California adopted landmark legislation establishing the first U.S. program that mandates a systematic reduction in the “carbon intensity” (CI) of transportation fuels. The LCFS is a pillar supporting California’s effort to reduce GHG emissions in accordance with AB 32’s 2020 target, and beyond. The regulation is also intended to spur innovation in transportation fuels and to reduce California’s dependence on petroleum.

California’s LCFS focuses on the full fuel cycle, or “well-to-wheels” (WTW) GHG emissions of transportation fuels. CARB developed the LCFS to achieve a 10 percent reduction in WTW GHG emissions from the transportation fuel mix by 2020. Reductions are based on the relative CI values for

⁷⁵ San Joaquin Valley Air Pollution Control District, “Comments on Cap and Trade Auction Proceeds Second Investment Plan, comments submitted to CARB by Executive Director Seyed Sadredin, November 12, 2015.

⁷⁶ American Trucking Associations and California Trucking Association, “Comments on the California Air Resources Board’s Draft Technology Assessment: Low Emission Natural Gas and Other Alternative Fuel Heavy-Duty Engines,” joint letter to CARB, January 13, 2016.

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

baseline transportation fuels (diesel and gasoline) and lower-CI “pathways,” such as heavy-duty NGVs using fossil or renewable CNG. A CI score for each pathway is established in grams of “CO₂-equivalent” per mega joule (g/CO₂e/MJ). Producers and sellers of these alternative fuels can generate LCFS credits based on the difference in the CI of the alternative fuel and the conventional fuel it displaces (i.e., diesel for HDVs). Credits can then be purchased by petroleum fuel producers to comply with the regulation’s required 10 percent CI reduction of baseline diesel or gasoline.

In September, 2015, CARB reauthorized the LCFS program and updated its GHG emissions models. Applying the updated model, CARB provided preliminary revised CI scores of major existing and potential HDV fuel pathways, compared to the baseline current-technology diesel pathway. Various transportation fuel pathways have CI scores well below that of the diesel baseline. These include renewable natural gas and renewable diesel (combusted in internal combustion engine vehicles), hydrogen (used in fuel cell vehicles), and California grid electricity (to recharge battery-electric vehicles). Fossil CNG and LNG currently achieve CI scores that are approximately 15 and 8 percent, respectively, below the diesel baseline. Further discussion is provided in Section 6.8 about the relative importance and roles of these pathways in meeting California’s LCFS goals, as well as their relevance to the bigger picture of potential to aggressively address global climate change.

Short-Lived Climate Pollutants (SLCPs) - SLCPs are powerful climate forcers that remain in the atmosphere for a much shorter period of time than CO₂ and other longer-lived GHGs. They include black carbon, methane (CH₄), and fluorinated gases (F-gases) such as hydrofluorocarbons. According to CARB,

“SLCPs are estimated to be responsible for about 40 percent of current net climate forcing. While the climate impacts of CO₂ reductions take decades or more to materialize, cutting emissions of SLCPs can immediately slow global warming and reduce the impacts of climate change.”⁷⁷

Mitigating SLCP emissions is one of Governor Brown’s “five pillars” to reduce California’s GHG emissions by 40 percent below 1990 levels by 2030. California is taking specific action on several fronts to reduce SLCP emissions by 2030. Steps that have already been taken by the state to reduce SLCP emissions have been focused on three areas: 1) black carbon from transportation, 2) methane from oil and gas operations and landfill emissions, and 3) F-gas emissions from refrigerants, insulating foams, and aerosol propellants.

Most significantly, Senate Bill 605 requires CARB to develop a plan in 2015 to reduce SLCP emissions. This California SLCP plan is intended to inform, and be integrated into, the state’s overall efforts to meet 2030 goals for reducing emissions of GHGs, criteria pollutants, and toxic air pollutants. In April 2016, CARB released a new report entitled “Proposed Short-Lived Climate Pollutant Reduction Strategy.”⁷⁸ It discusses numerous options to accelerate SLCP emission reductions in California. These include incentives for early voluntary reduction actions and market-supporting activities, including those that support in-state biogas production.

⁷⁷ California Air Resources Board, “Draft Short-Lived Climate Pollutant Reduction Strategy,” September 2015, accessed online at <http://www.arb.ca.gov/cc/shortlived/2015draft.pdf>.

⁷⁸ California Air Resources Board, “Proposed Short-Lived Climate Pollutant Reduction Strategy,” April 2016, <http://www.arb.ca.gov/cc/shortlived/meetings/04112016/proposedstrategy.pdf>.

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

As Table 2 shows, by 2030 California is targeting reductions of 40 percent for methane and hydrofluorocarbons, and 50 percent for black carbon, relative to their respective 2013 inventories.

In the Proposed SLCP Strategy, CARB outlines reduction actions that “provide a wide array of climate, health, and economic benefits throughout the State.” For example:

The State's organic waste should be put to beneficial use, such as for soil amendments/compost,

Table 2. SLCP emissions and proposed targets for reductions by 2030

California SLCP Emissions and Proposed Target Emission Levels (MMTCO ₂ e)*				
Type of SLCP	2013 Inventory	2030 BAU**	2030 Proposed Strategy	% Change from 2013 Inventory
Black Carbon (non forest) ³	38	26	19	-50%
Methane	118	117	71	-40%
Hydrofluorocarbons (HFCs)	40	65	24	-40%
*Using 20-year GWPs from the 4th Assessment report of the IPCC for methane and HFCs, and 5th Assessment report for black carbon (the first report to define a GWP for black carbon).				
**Business as usual (BAU) forecasted inventory includes reductions from implementation of current regulations.				

electrical generation, transportation fuel, and pipeline-injected renewable natural gas. Practical solutions must be developed and implemented to overcome barriers to waste gas utilization for pipeline injection and grid interconnection. Additional data on SLCP sources must be collected in order to improve California's SLCP emission inventory and better understand potential mitigation measures. Finally, the State should provide incentives to accelerate market transitions to cleaner technologies that foster significant system-wide solutions to cut emissions of SLCPs. Many of the sources and sectors responsible for SLCP emissions are concentrated in communities with high levels of pollution or unemployment, which could especially benefit from targeted investments to improve public health and boost economic growth.

Control of Direct-Vehicle GHG Emissions – If natural gas is to meet its full potential as a low-GHG transportation fuel, direct (downstream) GHG emissions (primarily CO₂ and methane) must be reduced to very low levels. Consequently, CARB intends to “strengthen natural gas engine and vehicle requirements to maximize the fuel’s low-NO_x and GHG-reduction benefits and improve engine efficiency.”⁷⁹ To help ensure that these reduction potentials are realized, CARB intends to adopt separate standards for natural gas engines and vehicles. Potential control measures to minimize direct-vehicle GHG emissions from heavy-duty NGVs include requirements for closed crankcase ventilation systems, a

⁷⁹ California Air Resources Board, comment letter on Phase 2 Notice of Proposed Rulemaking, from Chairman Mary Nichols to EPA Administrator Gina McCarthy and NHTSA Administrator Mark R. Rosekind, October 1, 2015.

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

limiting of fuel “boil-off” from LNG vehicles, and requirements to reduce tailpipe methane and nitrous oxide (N₂O) emissions.⁸⁰

In addition, CARB supports phasing-in inclusion of upstream emissions in the certification process for heavy-duty NGVs.⁸¹ The International Council on Clean Transportation (ICCT) recommends a similar approach for certifying these vehicles, in its July 2015 “Assessment of Heavy-Duty Natural Gas Vehicle Emissions: Implications and Policy Recommendations.”⁸²

3.3.3. Other State and Regional GHG-Reduction Initiatives

Numerous other states and regions in the U.S. are also planning or implementing efforts to mitigate climate change by reducing GHG emissions. Examples include the following:

- New York City is “committed to combating” the threat of climate change by reducing GHG emissions generated within the city. The city is developing an “80 by 50” program to reduce GHG emissions 80 percent by 2050 (relative to the 2005 baseline). Mitigation measures for transportation-related GHG emissions include implementing “cleaner vehicles and low-carbon transportation mode shifts.”⁸³
- New York City, Boston and Washington D.C. have been recognized as U.S. cities showing international leadership in tackling climate change across key sectors. These “C40 Cities Awards 2015” were held in Paris during the COP21 climate negotiations.
- More than 100 U.S. cities have committed to the international Compact of Mayors program, which was launched at the 2014 United Nations Climate Summit. This is the world’s largest coalition of city leaders addressing climate change by pledging to reduce GHG emissions, track progress and prepare for the impacts of climate change. It establishes a common worldwide platform to “capture the impact of cities’ collective actions through standardized measurement of emissions and climate risk, and consistent, public reporting of their efforts.”⁸⁴
- Oregon is taking action to reduce GHG emissions by inventorying sources, mandating GHG reporting, and adopting a Clean Fuels Program focused on reduced GHG emissions. This program includes Oregon’s version of a Low Carbon Fuel Standard, which seeks to reduce the carbon intensity of transportation fuels used in the state by 10 percent by 2025; it is essentially modeled on California’s LCFS.⁸⁵

⁸⁰ California Air Resources Board, comment letter on Phase 2 Notice of Proposed Rulemaking, from Chairman Mary Nichols to EPA Administrator Gina McCarthy and NHTSA Administrator Mark R. Rosekind, October 1, 2015.

⁸¹ Ibid.

⁸² International Council on Clean Transportation, Assessment of Heavy-Duty Natural Gas Vehicle Emissions: Implications and Policy Recommendations,” July 2015, <http://www.theicct.org/assessment-heavy-duty-natural-gas-vehicle-emissions-implications-and-policy-recommendations>.

⁸³ City of New York, “New York City’s greenhouse gas emissions will be 80 percent lower by 2050 than in 2005,” <http://www1.nyc.gov/html/onenyc/visions/sustainability/goal-1.html>.

⁸⁴ The Compact of Mayors, “Cities Committed to the Compact of Mayors,” <http://www.compactofmayors.org/history/>.

⁸⁵ State of Oregon, Department of Environmental Quality, “Oregon Clean Fuels Program,” <http://www.deq.state.or.us/aq/cleanFuel/qa.htm>.

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

- Massachusetts and 10 other Atlantic Coast states have initiated development of a coordinated low carbon fuel standard.⁸⁶ The Northeast States for Coordinated Air Use Management (NESCAUM) supports these states in their individual and regional efforts to reduce GHG emissions, improve energy efficiency, improve ambient air quality and implement renewable energy technologies. However, these efforts in the Northeast appear to currently be inactive.
- Seventeen states (California, Connecticut, Delaware, Hawaii, Iowa, Massachusetts, Michigan, Minnesota, Nevada, New York, New Hampshire, Oregon, Pennsylvania, Rhode Island, Vermont, Virginia and Washington) have joined to develop and expand the use of clean energy sources to fight climate change. These states plan to work together “to expand the use of renewable energy, diversify energy sources, modernize energy infrastructure, craft transformational energy policy and to encourage the use of clean transportation options.”⁸⁷

3.4. Increased Use of Renewable Fuels and Energy

A wide array of programs and policies focus on some form of renewable fuels or energy to help mitigate climate change and advance clean energy initiatives. In addition to reducing GHG emissions, these policies can:

- Increase energy security and reliability
- Reduce air pollution
- Promote economic development
- Improve public health and quality of life⁸⁸

Some key examples of specific programs and policies are briefly described below.

3.4.1. Federal Renewable Fuel Standard (RFS 2)

The federal Renewable Fuel Standard (RFS) program was first created as part of the Energy Policy Act of 2005. This was extended in 2007 and became known as RFS2. Under RFS2, EPA joins with two other major federal agencies (the Department of Agriculture and the Department of Energy) to administer a program requiring specific volumes of renewable fuel to replace traditional petroleum-based transportation fuels and heating oils. Currently, the program calls for 36 billion gallons of renewable fuels by 2022. Of that volume, a minimum of 21 billion gallons are required to be advanced biofuels derived from renewable biomass and providing at least a 50 percent lifecycle GHG reduction compared to petroleum fuels.⁸⁹

⁸⁶ Environmental Leader, “Northeast States Agree to Low Carbon Fuel Standard,” citing the Associated Press, January 7, 2009, <http://www.environmentalleader.com/2009/01/07/northeast-states-agree-to-low-carbon-fuel-standard/>.

⁸⁷ Timesunion, “Cuomo Signs 17-State Energy Accord, February 16, 2016, <http://blog.timesunion.com/capitol/archives/246191/cuomo-signs-17-state-energy-accord/>.

⁸⁸ U.S. Environmental Protection Agency, “State and Local Climate and Energy Program - Basic Information,” <http://www3.epa.gov/statelocalclimate/basic-info/index.html>.

⁸⁹ U.S. Environmental Protection Agency, “Renewable Fuel Standard,” <http://www.epa.gov/renewable-fuel-standard-program>.

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

In 2014, EPA recognized RNG from landfills, digesters, and wastewater treatment plants as cellulosic biofuels (a subset of advanced biofuels). Through the credit-generating process known as Renewable Identification Numbers (RIN), RNG can generate significant economic value for fuel producers through sales of RIN credits to traditional petroleum suppliers. Further, electricity produced from RNG can also be used to generate cellulosic biofuel RIN credits. However, to generate such credits, a fuel producer must show that the fuel was used in an application that would normally consume petroleum fuels. For transportation applications, this means that the fleet is a critical element of the credit-generation process and that economic value can be derived for fleets and midstream fuel suppliers if the fleet operates NGVs (or plug-in hybrid vehicles). RIN credit values for Cellulosic and Advanced Biofuels, known as D3 and D5 RINs, respectively, fluctuate based on market conditions.⁹⁰

Notably, the future of the federal RFS is uncertain. Both political parties have criticized EPA's implementation of the program, and some lawmakers seek to repeal it. However, congressional action is not expected imminently, as certain issues are in federal court due to industry lawsuits.⁹¹

3.4.2. California Renewable Portfolios Standard (RPS)

Like the federal government under RFS2, California seeks to aggressively switch over to renewable fuels, especially for its electricity-generation and transportation sectors. Key elements relative to meeting transportation-related goals for renewables include the Cap-and-Trade program and the LCFS, described previously. In addition, California has established a Renewables Portfolio Standard (RPS) Program that is specific to the state's electricity-generation mix. The overarching RPS goal is to systematically increase the use of renewable energy as a percentage in generation of the state's electricity mix consumption over the next 35 years. Originally established by legislation enacted in 2002, the RPS has been amended multiple times. As of January 2016, the law requires electric utilities to derive 50 percent of their retail electricity sales from eligible renewable energy sources by 2030, with established interim targets.⁹²

California's unique RPS will help keep the state's electricity grid mix among the nation's cleanest for many years to come. This is relevant because all HDV fuel-technology pathways that significantly use electricity will have reductions in full-fuel-cycle GHG emissions. In addition, "upstream emissions" of NOx (and other regulated pollutants) from electricity generation will be reduced. See Section 6.4 for important additional discussion.

3.4.3. Other States and Regions

Many other states and regions across the U.S. are involved with initiatives to increase the use of renewable power and fuels. In general, states are adopting policies to support greater investment in associated technologies and fuels. Examples include RPS-type policies, interconnection standards, and

⁹⁰ *Ibid.*

⁹¹ *Environment & Energy Daily*, "Renewable fuel standard up for another lashing," March 14, 2016.

⁹² California Energy Commission, "California Renewable Energy Overview and Programs," accessed online at <http://www.energy.ca.gov/renewables/>.

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

funding or incentive policies. Good examples are provided by EPA at its “Renewable Energy” webpage, which is accessible at the following link:

<http://www3.epa.gov/statelocalclimate/state/topics/renewable.html>.

3.5. Transportation Planning and Economic Development

3.5.1. Federal Efforts and Initiatives

The U.S. government uses transportation planning as a “cooperative, performance-driven process to determine America’s “long and short-range transportation improvement priorities.” In U.S. cities with a population greater than 50,000, authorities use metropolitan transportation plans to identify and guide essential transportation system investments. Each plan must address freight and goods movement planning. Input from a variety of public and private stakeholders—including state departments of transportation, metropolitan planning organizations (MPOs), freight stakeholders, and the general public—must be considered to successfully integrate freight planning into these existing transportation planning processes. MPOs are federally mandated (and funded) transportation policy bodies consisting of representatives from local and state transportation authorities. Today, there more than 300 MPOs in the U.S.; the number of MPOs for each state ranges from one (Alaska) to more than 25 (Florida).

Federal law requires each metropolitan transportation plan to develop long- and short-range strategies towards integrated, efficient intermodal transport of people and goods. These plans are updated every five years in air quality attainment areas, every four years in nonattainment or maintenance areas, or more frequently in all areas as State and local officials deem necessary.⁹³ The federal government—primarily through the Federal Highway Administration (FHWA)—provides oversight to ensure that transportation planning projects reflect community needs and take into account human health and environmental impacts. Before any federally funded transportation projects can move forward to construction, FHWA must address and comply with broad-based environmental laws, including those addressing air quality.

One of the most-important elements of transportation planning is the “conformity” requirement under the Clean Air Act (CAA). Through the transportation conformity process, the CAA requires that federal funding and approval goes to transportation activities that are consistent with air quality goals. Specifically, metropolitan transportation plans, metropolitan transportation improvement programs, and related federal projects must conform to the purpose of the “State Implementation Plan” (SIP). Any state that includes one or more area designated to be in nonattainment of NAAQS must prepare a SIP. Under conformity, transportation-related projects and expansions using federal funds cannot “cause or contribute to any new violations” of the NAAQS; increase the frequency or severity of NAAQS violations; or delay timely attainment of the NAAQS or any required interim milestone.” This conformity process applies to transportation plans, transportation improvement programs, and projects funded or

⁹³ U.S. Department of Transportation, Federal Highway Administration, “Overview of Transportation Planning,” http://www.fhwa.dot.gov/planning/publications/briefing_book/part01.cfm.

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

approved by the Federal Highway Administration (FHWA) or the Federal Transit Administration (FTA) in NAAQS nonattainment areas.⁹⁴

The new federal “Fixing America's Surface Transportation Act” (“FAST Act”) makes changes and reforms to federal transportation programs that affect the conformity process. These changes includes ways to streamline the approval processes for new transportation projects, establish and fund new on-highway freight projects, and strengthen the list of factors that states and MPOs must consider in their transportation planning processes. It also requires the U.S. DOT to designate alternative fuel corridors along major national highways.⁹⁵

Conformity and other CAA requirements can force officials in nonattainment areas to make tough decisions about new development that will generate transportation-related emissions. The preferred approach is to rely on emerging low-emission fuels and technologies to “offset” potential new emissions. Lacking this option, it may be necessary for state and local transportation officials to implement draconian measures that limit growth and/or VMT in the area.⁹⁶ EPA’s recent adoption of a more-stringent new ozone NAAQS at 70 ppb makes this challenge even more daunting. California again presents the most extreme cases. If air quality and transportation officials are unable to demonstrate NAAQS attainment in the SCAB and/or the SJVAB, they face “economically onerous”⁹⁷ “costly sanctions” imposed by the federal government, potentially with “dire consequences” that include “severe economic hardship.”⁹⁸

At the same time, the federal government must take into account *economic development* in developing transportation plans and policies for specific geographic areas. Federal statute states that "transportation should play a significant role in promoting economic growth, improving the environment, and sustaining quality of life." The specific economic goals that transportation policies and projects can support are generally determined by local officials and priorities. They are often very specific to needs identified by local decision makers, such as to increase overall employment in a local area, increase employment in a specific industry or economic sector, or increase employment within a specific area (e.g., in an identified "enterprise zone").⁹⁹

3.5.2. California’s Sustainable Freight Action Plan

California’s on-road freight transport system is the state’s major economic engine. Moving billions of dollars in freight each year has tremendous benefits for California, but it also accounts for major

⁹⁴ U.S. Department of Transportation, Federal Highway Administration, “Air Quality Transportation Conformity,” http://www.fhwa.dot.gov/environment/air_quality/conformity/con_broc.cfm.

⁹⁵ Federal Highway Administration, “Air Quality and Climate Change Highlights, December 2015 – January 2016,” http://www.fhwa.dot.gov/environment/air_quality/conformity/highlights/high0116.cfm.

⁹⁶ Ibid.

⁹⁷ South Coast Air Quality Management District, “2016 Air Quality Management Plan,” fact sheet dated January 28, 2016, emailed to GNA by staff.

⁹⁸ Seyed Sadredin, Executive Director, San Joaquin Valley Air Quality Management District, Testimony to the U.S. House of Representatives, October 22, 2015, <https://www.valleyair.org/content/documents/Clean-Air-Act/Seyed-Sadredin-Testimony-10-22-15.pdf>.

⁹⁹ U.S. Department of Transportation, Federal Highway Administration, “Transportation Conformity,” http://www.fhwa.dot.gov/environment/air_quality/conformity/.

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

emissions of NO_x, toxic DPM and GHGs. Consequently, one of the state's top objectives is to immediately begin transitioning to "a less-polluting, more efficient, modern freight transport system," in a process expected to take "several decades" to complete. State officials consider this transition essential to achieve California's public health mandates, climate goals, and economic needs. As previously noted, this requires systematic transition towards a system powered "with zero emissions everywhere feasible, and near-zero emissions with renewable fuels everywhere else."¹⁰⁰

"Vision" for 2050 Sustainable Freight System in California

Freight in California is transported by zero emission equipment everywhere feasible, and near-zero emission equipment powered by clean low-carbon renewable fuels everywhere else.

**—State of California multi-agency presentation,
"California Sustainable Freight Action Plan - Public**

California Executive Order B-32-15 (Governor Jerry Brown) requires key state agencies to jointly "develop an integrated action plan by July 2016 that establishes clear targets to improve freight efficiency, transition to zero-emission technologies, and increase competitiveness of California's freight system." This California Sustainable Freight Action Plan is to be "informed by existing state agency strategies," while also incorporating "broad stakeholder input."¹⁰¹ The overarching goal is essentially to substitute petroleum and other fossil fuels with advanced, clean energy technology as the primary means to move goods in California. According to CARB, this Action Plan will include specific recommendations, actions, investments, and milestones to build "a sustainable freight transportation system." This will "demonstrate California's private and public leadership in advancing statewide and national freight priorities, objectives, and goals."¹⁰²

As shown in Figure 9, five different existing state reports are serving as the foundation for the California Sustainable Freight Action Plan. These reports are:

- Safeguarding California: Reducing Climate Risk
- California Freight Mobility Plan
- 2014 Integrated Energy Policy Report Update
- Heavy-Duty Technology and Fuels Assessment Overview (draft)
- Sustainable Freight Pathways to Zero and Near-Zero Emissions – Discussion Document

¹⁰⁰ California Air Resources Board, "Sustainable Freight: Pathways to Zero and Near-Zero Emissions, Discussion Document, April 2015.

¹⁰¹ Office of Governor Edmund G. Brown, Jr., "Executive Order B-32-15," July 7, 2015, accessed online at: <https://www.gov.ca.gov/news.php?id=19046>

¹⁰² Ibid.

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

Each of these reports includes focus on ways to mitigate harmful impacts of diesel engines that currently power California's vast goods movement sector.¹⁰³ To ensure progress, California Executive Order B-32-15 requires CARB and other state agencies to initiate work on "corridor-level freight pilot projects" throughout the state. The pilot projects are required to integrate advanced technologies, alternative fuels, freight and fuel infrastructure, and local economic development opportunities. CARB, Caltrans and other state agencies are in the process of holding stakeholder workshops about potential pilot projects, which must have potential to "transform" California's freight transport system.¹⁰⁴

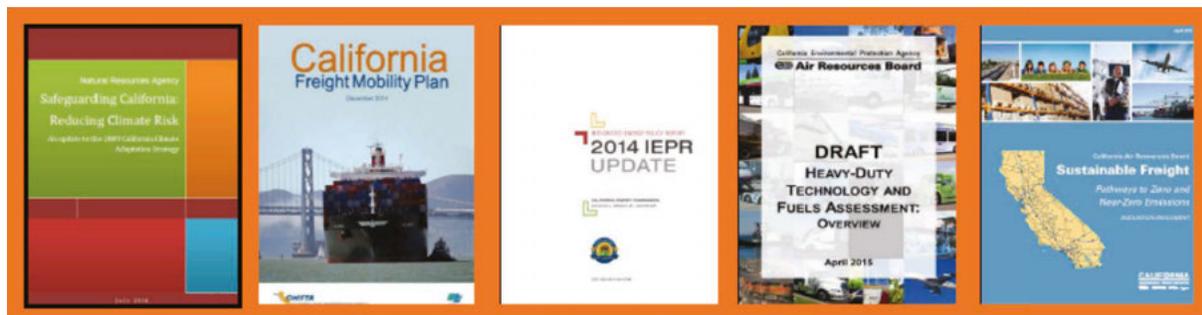


Figure 9. Reports serving as the foundation for California's Sustainable Freight Action Plan

Much of the state's Sustainable Freight Action Plan specifically focuses on Southern California's major goods movement system. One CARB target is to "foster future economic growth within the freight and goods movement industry by promoting flexibility, efficiency, investment, and best business practices through State policies and programs."¹⁰⁵ A 2013 study¹⁰⁶ for the region prepared on behalf of the Southern California Association of Governments (SCAG) stressed similar goals, stating that (emphasis added):

The final policy consideration in selecting financing strategies for goods movement improvements is cost responsibility. . . the public sector invests in freight transportation to:

- *Enable economic growth by increasing productivity, trade, and access to resources, markets, and labor.*
- *Ensure network continuity and connectivity across geographic regions and political jurisdictions.*

¹⁰³ State of California multiagency (CalEPA, Caltrans, CARB, CEC, and others) webinar; slide presentation entitled "California Sustainable Freight Action Plan," October 1, 2015.

¹⁰⁴ California Air Resources Board, "CA Sustainable Freight Action Plan: Pilot Projects," staff presentation (undated), accessed online on November 4, 2015.

¹⁰⁵ State of California multiagency (CalEPA, Caltrans, CARB, CEC, and others), public workshop presentation entitled "California Sustainable Freight Action Plan," January – February 2016, http://www.arb.ca.gov/gmp/sfti/CSFAPWorkshopPresentation_DRAFTFORPUBLICCOMMENT_01252016.pdf

¹⁰⁶ Southern California Association of Governments, "On the Move: Southern California Delivers the Goods," prepared by Cambridge Systematics, February 2013, accessed online at <http://www.freightworks.org/DocumentLibrary/CRGMPIS%20-%20Final%20Report.pdf>.

3.6. Achievement of Environmental Sustainability Goals by HDV End Users

Many major private and government organizations in the U.S. have adopted goals for environmental sustainability. These largely focus on how to reduce the air quality and GHG footprints associated with their HDVs used to transport goods and/or people. For example, large multinational corporations such as Frito Lay, PepsiCo, United Parcel Services (UPS), Proctor & Gamble, Unilever, Anheuser-Busch, Coca-Cola, Owen Corning, Lowe's, IKEA, Honda, Fiat Chrysler, and numerous others are rapidly moving towards low-carbon transportation fuels and near-zero or zero-emission technologies for their HDV fleets. Major cities like Los Angeles and New York have been strongly pursuing programs to test and deploy large numbers of clean HDV technologies. Section 5.5 provides specific cases of where heavy-duty NGVs have become foundations of major environmental sustainability programs.

3.7. Summary of Key Policy Goals and Timelines

Across America, restoring healthful air quality requires transformational change for our heavy-duty transportation sector. It's not just in California; nearly half of Americans live in areas with unhealthy ambient levels of ozone, other criteria pollutants and TACs. In the areas with the worst ozone problems, rapid turnover of the "legacy" HDV fleet to the newest, cleanest diesel models will not provide enough NO_x reductions to achieve the ozone NAAQS in 2023 and beyond. To meet such challenging deadlines and targets, HDVs must be systematically deployed that either emit 1) no regulated pollutants (directly, per CARB's definition of a "zero emission vehicle," or ZEV); or 2) near-zero levels of regulated pollutants.

As stressed by CARB (emphasis added),

"Controlling emissions from heavy-duty trucks is the key to reducing criteria pollutants and meeting GHG targets. The key to reducing emissions is introducing technology early to allow the market to develop."¹⁰⁷

CARB has adopted very aggressive policies to simultaneously achieve NAAQS in California's many nonattainment areas and achieve major GHG reductions. The timeline shown in Figure 10 summarizes California's key deadlines to meet climate change goals (top line) and attain NAAQS by reducing ozone-precursor and PM emissions. **Note:** in this timeline produced by CARB, the "preliminary NO_x target" of 65 to 70 percent needed to attain ozone standards by 2031 represents the NO_x reductions needed beyond all regulations that have already been adopted.

¹⁰⁷ California Air Resources Board, "Heavy-Duty Trucks: ARB's Goals and Technology Insights," staff presentation, April 22, 2015.

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

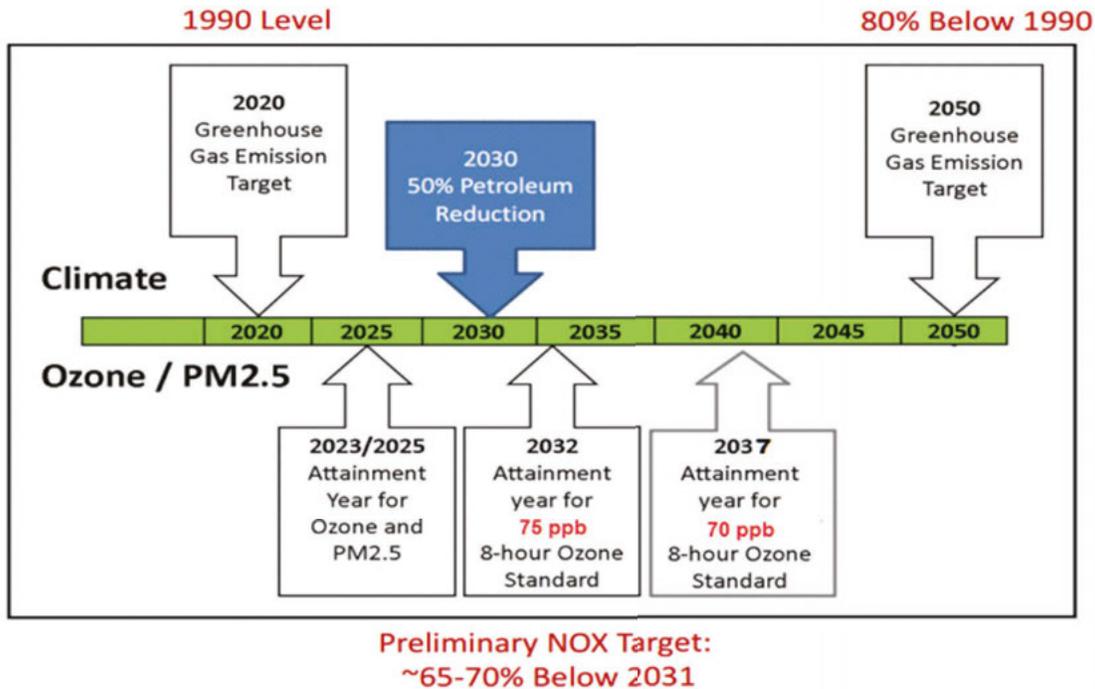


Figure 10. California's timeline to achieve NAAQS (bottom) and GHG targets (top).

CARB is also coordinating with agencies such as the CEC to help address petroleum-reduction policies and goals. Other states are also announcing aggressive strategies to reduce GHG emissions, which must be implemented while simultaneously demonstrating how to achieve NAAQS attainment; examples include New York, Washington, and Oregon.

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

Table 3 provides a broad summary of key federal, state and local policy issues that are relevant to the need for advanced, clean HDV technology (especially HHDTs).

Table 3. Summary of key policy initiatives relevant to clean HDV technology

Major Policy / Goal	Jurisdiction / Agency	Major Need(s) / Objective(s)	Timeline to Achieve
Attainment of Ozone NAAQS (75 and 70 ppb)	Federal, State and Local: EPA, CARB, Air Districts	Reduce ozone precursor NOx emissions > 90% below 2010 baseline	2023 / 2032 for extreme cases
Petroleum Reduction / Displacement	Federal: EPA, NHTSA, DOE	Reduce petroleum usage by 2.5 billion gallons per year	2025
Phase 2 GHG Reduction	Federal: EPA, NHTSA	Reduce GHGs from HDVs by 20%	2027
New Source Rule for Methane	Federal: EPA	40% to 45% reduction in methane emissions (from 2012)	2025
Federal Renewable Fuel Standard	Federal: EPA	36 billion gallons of renewable fuel	2022
AB 32, Executive Orders S-3-05 and B-30-15	California: all applicable state agencies	Reduce GHG emissions to 1990 levels by 2020, 40% by 2030 and 80% below 1990 levels by 2050	2020/ 2030 / 2050
Petroleum Reduction (goal only, to date)	California: CEC, CARB	Reduce petroleum use in heavy-duty trucks by up to 50%	2030
Sustainable Freight Action Plan (Executive Order B-32-15)	California: numerous state agencies	Improve freight efficiency, transition to ZEV technologies, and increase CA freight system competitiveness	2016: complete plan 2050: achieve end goals
Renewable Portfolio Standard	California: CPUC, CEC	33% renewables for energy generation, up to 50%	2020 / 2030
Short-Lived Climate Pollutant (SLCP) Strategy	California: CARB	Reduce SLCP emissions (black carbon, methane, F-gases)	TBD
Diesel Risk Reduction Plan	California: CARB	Reduce diesel PM emissions by 85% (from 2000)	2020
Advanced Clean Transit Rule	California: CARB	Transition to 100% ZE transit bus fleet, require NZE technology/fuel in transition	2040
Truck and Bus Regulation	California: CARB	Replace nearly all in-use trucks and buses to comply with 2010 or equivalent emissions	2023
Low Carbon Fuel Standard	California: CARB Oregon: Department of Environmental Quality	Reduce carbon intensity of transportation fuels by 10%	2020
Environmental Justice /Disadvantaged Communities (e.g., CA SB 535)	California: multiple agencies	Spend minimum percentages of funds for low-emission HDVs on projects that directly or indirectly benefit disadvantaged communities	Ongoing

Regulators have identified four *leading* near-zero and zero-emission technologies for on-road HDVs as having the best potential to help America achieve these time-sensitive, challenging goals and objectives. Each pathway assumes increasing use of renewable sources as a major strategy to reduce GHG emissions.

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

These fuel-technology pathways are:

1. Low-NOx diesel internal combustion engine (possible hybridization with electric drive)
2. Low-NOx natural gas internal combustion engine (possible hybridization with electric drive)
3. Electric drive with advanced storage batteries
4. Electric drive with hydrogen fuel cells

The next section further describes these four leading approaches to zero- and near-zero-emission HDVs, and the importance of their respective “addressable” markets to achieve key pollutant reductions.

4. Leading Approaches for Zero- and Near-Zero Emission HDVs

4.1. Overview of Key Fuel and Technology Pathways

For the immediate and foreseeable future, four HDV fuel-technology combinations appear to offer the best potential to help transform America’s on-road heavy-duty transportation sector. Each of these four technology / fuel pathways is briefly characterized in Table 4 by the prime mover technology, fuel/energy source, proven emissions profile (for direct HDV emissions), and estimated timeline for commercialization to begin volume deployments. This reflects a snapshot in time; it does not assume potential (but unforeseen) technology breakthroughs or market interventions.

Table 4. HDV fuel / technology pathways with best potential to meet NOx and GHG targets

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

Each of these four fuel-technology pathways offers unique promise and potential to help transform America’s on-road HDV fleet. CARB has clearly recognized that the key for successfully reducing large amounts of NOx and GHG emissions *is early wide-scale deployment* of zero- and near-zero-emissions HHDVs. The actual role that each of these four fuel-technology pathways will ultimately play largely depends on how soon and to what degree they can be commercially deployed, especially in HHDV applications. As further documented, only one approach and pathway has the proven ability to provide

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

major NO_x and GHG reductions in high-impact HHDT sectors over the next 15 to 20 years. This is early deployment of commercially available heavy-duty natural gas NZEVs using progressively higher blends of RNG.

4.2. Heavy-Duty “Zero-Emission Vehicle” (ZEV) Technology

Heavy-duty battery-electric vehicles (BEVs) and fuel cell vehicles (FCVs) are promising “zero-emission vehicle” (ZEV¹⁰⁸) technologies in the early stages of development and demonstration. Both types of heavy-duty ZEVs continue to gradually improve on cost and performance. For the long-term solution to transform our HDV transportation sector, air quality regulators highly favor transition to these two ZEV technologies, *to the greatest and fastest extent practicable*. Potential exists for BEVs and FCVs to become workhorses of America’s goods and people transportation systems, at some point in the future. However, wide-scale commercialization in the HDV sector—especially for the most-impactful HHDT applications—appears to be one to two decades away (see below).

4.2.1. The Attraction—and Uncertainty—of ZEV Technologies

Air quality regulators often favor ZEVs largely because they lack any on-board source of fuel combustion. Thus, ZEVs inherently continue to directly emit no regulated pollutants throughout their useful lives. Even the cleanest heavy-duty internal combustion engine (ICE) vehicles have potential to undergo emissions degradation as years of arduous, high-mileage service are accrued.¹⁰⁹ Especially given this fact, it can be more effective for regulators to mitigate emission levels from relatively small numbers of large “stationary sources” (e.g., electric power plants), rather than attempting to control hundreds of thousands of in-use HDV “mobile sources” as they age and deteriorate. Essentially, these are the key points of the following statement by CARB:

“BEVs by definition have no tailpipe emission and therefore completely eliminate the emission of criteria pollutants at the source. In other words, BEV tailpipe emissions are 100 percent lower than tailpipe emissions from today’s conventionally fueled vehicles. Even in the future, when diesel or natural gas vehicles may be much cleaner than today’s vehicles (certified to a 0.02 gram per brake horsepower hour (g/bhp-hr) NO_x standard, for example), BEVs still will provide additional tailpipe emission benefits, which may be crucial for attaining ambient air quality standards.”¹¹⁰

¹⁰⁸ “ZEV” is used here as defined by the California Air Resources Board, i.e., they do not directly emit criteria pollutants (or CO₂). Like all vehicle types, ZEVs do generate such emissions on a “full-fuel-cycle” basis.

¹⁰⁹ It is noteworthy that ZEVs can become less efficient in converting energy to move goods or people, and this degradation has its own cost in terms of increased emissions on a full-fuel-cycle basis and/or battery replacement requirements.

¹¹⁰ California Air Resources Board, “Draft Technology Assessment: Medium- and Heavy-Duty Battery Electric Trucks and Buses,” September 2015.

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

It's clear that California seeks to transition the state's large population of on-road HDVs over to ZEV technology in vocations where it is feasible (e.g., near-dock drayage trucking), as soon as possible. To facilitate this transition, CARB and other state agencies intend to use a combination of financial incentives and regulatory approaches. However, there is a major problem with overreliance on ZEV technology to achieve major near-term emission reductions from key HDV sectors. Such technologies do not yet exist for critical high-fuel-use HDV applications such as Class 7 and 8 goods movement trucking. In fact, the timeframe for commercial deployment of battery-electric and fuel cell HDVs in Class 7 and 8 trucking applications is a virtual "wildcard." Expert opinion within the trucking industry¹¹¹ and among key government agencies (for example, see CARB quote below) indicates ZEV technologies are decades away from meeting cost, performance and fueling infrastructure goals for long-haul trucking applications. However, ZEV technologies can work well in short-range, local-haul HDV applications such as near-dock drayage service. Important efforts are well underway to commercialize heavy-duty battery-electric, plug-in hybrid electric, fuel cell, and other architectures that can deliver full or partial zero-emission operation.¹¹²

Existing major barriers (primarily battery cost and power density) limit the expanded applicability of BEVs in medium-duty and heavy-duty on-road applications.

Expanding BEV technology into most applications in the heavy-duty truck segment will require further developments in battery technology and lower vehicle component costs overall. It is not expected that BEVs can penetrate into the long-haul trucking vocation in the next several decades, where significant high speed steady-state operations dominate the vehicles duty cycle, without significant advances in battery energy density and BEV recharging technologies.

California Air Resources Board, "Draft Technology Assessment: Medium- and Heavy-Duty Battery Electric Trucks and Buses," October 2015.

The following subsections summarize the findings of CARB and other organizations regarding this critical issue of commercial maturity, applicability and scalability for the two leading types of heavy-duty ZEV pathways, BEVs and FCVs. The focus is on high-impact, high-fuel use HHDT applications.

¹¹¹ GNA interviewed high-level executives from five major North American truck OEMs; all indicated there is "no foreseeable timeframe" for commercially viable battery or fuel cell HDTs. ARB, EPA, DOE and DOT have all indicated such vehicles are 20 (or more) years away from volume sales and deployment.

¹¹² For a good discussion of the potential options and architectures, see Calstart's report "I-710 Project Zero-Emission Truck Commercialization Study Final Report, November 2013, http://www.calstart.org/Libraries/I-710_Project/I-710_Project_Zero-Emission_Truck_Commercialization_Study_Final_Report.sflb.ashx.

4.2.2. Technology Assessment Summary: Heavy-Duty BEVs

Table 5. Summary: CARB’s key technology assessment findings on heavy-duty battery-electric vehicles

Heavy-Duty Battery-Electric Vehicles: Key CARB Statements / Findings ¹¹³
<ul style="list-style-type: none">• BEVs are beginning to penetrate medium- and heavy-duty vehicle markets; electric transit buses are increasingly available from a variety of manufacturers.• Some battery-electric school buses and shuttle buses are commercially available, as are other medium-duty BEVs (primarily delivery vehicles).• Battery-electric Class 8 heavy-duty trucks remain a significant challenge.• Current California-based medium- and heavy-duty on-road BEVs are predominantly trucks and buses that operate on urban or suburban routes that have a high frequency of stops and starts, high idle times, lower average speeds and daily ranges of generally 100 miles or less.• Battery electric buses are making inroads into transit fleets, and represent the largest number of medium- and heavy-duty BEVs globally.• Three manufacturers currently sell battery-electric buses in the U.S., employing different battery charging strategies, quick in-route charging and slow overnight charging, to compete in the transit market.• Existing major barriers (primarily battery cost and power density) limit the expanded applicability of BEVs in medium-duty and heavy-duty on-road applications.• Hundreds of medium-duty BEVs are operating on California's roads in early commercialization stages; they are being utilized in an optimal urban delivery duty cycle, and have state incentives to promote adoption.• It is expected that medium-duty BEVs will make widespread penetration into the market place in 5 to 10 years.• Medium-duty battery-electric trucks require less power and typically drive fewer miles than heavy-duty BEVs; MDTs with “optimal duty cycle” such as delivery and food distribution are ideal candidates for electrification.• Heavy-duty BEVs are now in the demonstration phase or “varying stages of manufacture” (by small-volume manufacturers). Increased production volumes (of heavy-duty hybrid vehicles) may reduce common BEV/Hybrid component costs, further reducing the incremental cost of BEVs when compared to conventional diesel trucks.• Heavy-duty truck operation can be a very demanding weight class for on-road trucks. Efforts to electrify vehicles in this category have begun with vocations that meet the optimal duty-cycle. There are not any commercially available heavy-duty BEVs outside the transit bus segment at this time, but there are several on-going demonstrations of BEVs in the heavy-duty vehicle sector with drayage trucks and refuse hauler projects underway, as previously mentioned.• Expanding BEV technology into most applications in the heavy-duty truck segment will require further developments in battery technology and lower vehicle component costs overall. It is not expected that BEVs can penetrate into the long-haul trucking vocation in the next several decades, where significant high speed steady-state operations dominate the vehicles duty cycle, without significant advances in battery energy density and BEV recharging technologies.• Batteries for medium- and heavy-duty trucks and buses are currently in the \$400 to \$600 per kWh range¹¹⁴, consistent with the projections by Deutsche Bank. At \$600/kWh, a 350 kWh system such as might be used in a Class 8 drayage truck would be expected to cost \$210,000.• While there is an increased cost to purchase BEVs compared to conventionally fueled vehicles in the foreseeable future, BEVs have reduced operating and maintenance (O&M) costs. Thus, savings may be realized by employing BEV technologies in place of conventional fueled vehicle technologies.

¹¹³ CARB, “Draft Technology Assessment: Medium- and Heavy-Duty Battery Electric Trucks and Buses,” October 2015, http://www.arb.ca.gov/msprog/tech/techreport/bev_tech_report.pdf.

¹¹⁴ Notably, the U.S. DOE seeks to reduce battery costs for light-duty BEVs down to \$125/kWh by 2022. Some accounts indicate that Tesla, with increasing volume production, is already below \$250/kWh; it’s unclear how much of the full battery system this entails.

4.2.3. Technology Assessment Summary: Heavy-Duty FCVs

Table 6. Summary: CARB’s key technology assessment findings on heavy-duty FCVs

Heavy-Duty Fuel Cell Vehicles: Key CARB Statements / Findings ¹¹⁵
<ul style="list-style-type: none">• Overall, medium- and heavy-duty FCVs are primarily in demonstration stages.• Fuel cell buses are now in early commercialization, with two manufacturers are offering models for sale in North America; these buses have similar bus availability, performance, and durability to conventional transit buses.• Demonstrations for other medium- and heavy-duty FCV applications are in early stages.• Early market for heavy-duty FCVs is expected to be in applications where the vehicles can be centrally fueled, operated, and maintained.• Fuel cells are the most promising advanced technology to enable long haul trucks, a major contributor to California’s criteria and greenhouse gas emissions, to reach zero- or near-zero emission goals.• FCVs are expected to have substantially lower overall well-to-wheel carbon dioxide equivalent emissions than vehicles powered by diesel- or natural gas fueled engines.• Use of FCVs will provide significant reductions in petroleum consumption, because electric powertrains are much more efficient than internal combustion powertrains, and hydrogen is made from non-petroleum feedstocks.• California hydrogen will be required to have 33 percent renewable energy content, which will further reduce FCV petroleum use and well-to-wheel emissions.• FCVs can also help balance the grid and reduce dependence on fossil fuels by utilizing hydrogen produced by renewable energy during off-peak hours.• The main constraints” for expanded FCV use are vehicle cost, cost of and access to hydrogen fuel, and potentially, the need for more frequent vehicle fueling.• By the end of 2016, 51 hydrogen stations are expected to be operational to fuel approximately 13,500 light-duty FCVs; almost all these hydrogen stations will not be compatible with medium- or heavy-duty vehicles. (Note: these stations are being built to meet demand from light-duty FCVs; medium- and heavy-duty FCVs have uncertain deployment timeframes, and building hydrogen stations to accommodate them will cost more.)• The next focus should be on fuel cell electric trucks that are centrally fueled and have the potential to become commercial in the near future such as delivery vehicles, refuse trucks, and drayage trucks.

4.2.4. Addressable Market for NOx Reductions from Heavy-Duty ZEVs

This longer-term, uncertain time frame for commercialization of heavy-duty ZEVs raises a key question: What is the addressable percent of the HDV market for ZEV technologies, especially in high-impact HHDT applications? By what time frame can those ZEV technologies be deployed in sufficient numbers to effect major NOx and GHG reductions?

In certain MHDV and bus applications, there is potential within the next decade to deploy increased numbers of heavy-duty ZEVs to “address” (reduce) meaningful amounts of NOx and GHG emissions. Based on current heavy-duty ZEV technology, these are medium-fuel-use, return-to-base applications

¹¹⁵ CARB, “Draft Technology Assessment: Medium- and Heavy-Duty Fuel Cell Electric Vehicles,” November 2015, http://www.arb.ca.gov/msprog/tech/techreport/fc_tech_report.pdf.

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

having daily range requirements less than about 100 miles. This has been noted in CARB’s recent Technology Assessment series, and in various similar assessments by other key government agencies.

GNA further characterized this in a recent study¹¹⁶ by analyzing all 384 heavy-duty BEVs awarded under California’s HVIP¹¹⁷ incentive program, from program inception in 2009 through August 2015. As Figure 11 shows, all 384 awards that involved heavy-duty BEVs have been for Class 1 through 6 delivery trucks or (Class 8a) transit buses, with driving ranges (as estimated by their manufacturers) at 100 or fewer miles.

To date, none of these 384 HVIP BEV awards have involved HHDTs, such as refuse or large goods movement trucks. As CARB and EPA have acknowledged, commercially viable ZEV technology does not yet exist in these challenging sectors. The dichotomy is that these unfilled HHDT applications are the high-impact sectors in which air quality regulators most need to “address” and rapidly reduce NOx (and GHG) emissions.

To quantify the technically addressable emissions reductions that can be achieved in the SCAB by deploying current-technology heavy-duty BEVs, GNA incorporated this HVIP award and range

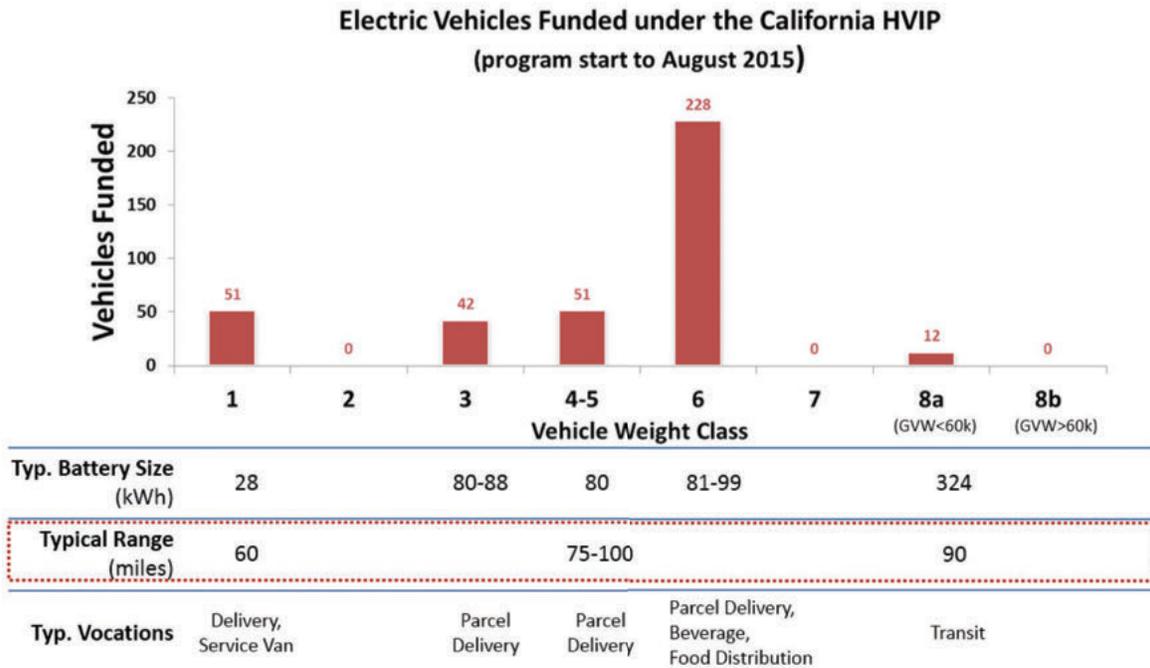


Figure 11. Award trends (CA HVIP) for heavy-duty BEVs by weight, range and vocation

¹¹⁶ Gladstein, Neandross & Associates, “Zero-Emissions Truck Assessment,” final report for the South Coast Air Quality Management District, September 2015.

¹¹⁷ California’s Hybrid Truck and Zero-Emission Truck and Bus Voucher Incentive Program (HVIP) aids the introduction of hybrid and electric trucks and buses by reducing their purchase price in California. HVIP works through a series of authorized dealers through which all fleets may purchase vehicles. Up to \$110,000 can be provided by the state to help fleets buy down the costs of zero-emission trucks or buses that meeting program requirements. See <https://www.californiahvip.org/>.

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

information into California's emissions models, and other relevant HDV datasets. GNA found that an estimated 19 percent of the SCAB NO_x inventory and 18 percent of the GHG inventory associated with those HDV types are technically addressable for reductions using on-road battery-electric technology. This represents a best-case scenario for heavy-duty BEV penetration (e.g., cost was not considered), based on current battery-electric technology in the marketplace. It is important to note, however, that unforeseen technology breakthroughs could increase the percentages of NO_x and GHG emissions that are technically addressable with heavy-duty BEVs.¹¹⁸

CARB has essentially reached the same conclusion regarding addressable market for heavy-duty ZEVs to achieve NO_x reductions. In its draft Mobile Source Assessment—which is intended to serve as a blueprint for California's next State Implementation Plan (SIP) to demonstrate how to attain the ozone and PM_{2.5} NAAQS—CARB assesses NO_x reductions that can be achieved with heavy-duty zero-emission trucks (battery and fuel cell) versus NZEV trucks (those that use 0.02 g/bhp-hr NO_x engines). It is concluded 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_x trucks.”¹¹⁹

The CEC, in charge of California's transportation energy usage, has also noted the need for low-NO_x HDVs to achieve major criteria pollutant reductions over the next 15+ years, due to lack of feasibility for heavy-duty ZEVs:

*California faces challenging requirements for reducing criteria air pollutants by 2023 and 2032. Further development of low-NO_x engines, both for NGVs and conventional vehicles, is needed to help achieve these goals for vehicle applications where introducing zero-emission technologies is not feasible.*¹²⁰

California's SCAB and SJVAB—the two air basins with the greatest challenges to achieve NAAQS attainment—best exemplify the urgency of this situation. As previously described, both air basins require very large NO_x reductions from heavy-duty trucks. Heavy-duty ZEVs can help provide near-term NO_x reductions in short-range applications. However, for the most-impactful trucking applications (regional and long-haul Class 8 trucks), these two areas cannot wait for commercialization of ZEV technologies. This has been clearly recognized by the air quality management districts in those two jurisdictions.

For example, SJVAPCD has indicated that a long-term Mobile Source Strategy that heavily relies on BEVs “may fall short in identifying and prioritizing strategies needed” to attain the ozone NAAQS in the SJVAB. SJVAPCD noted that CARB's MSS and the Sustainable Freight Strategy do not sufficiently emphasize the importance of achieving *near-term criteria pollutant reductions* as needed to meet the *legally*

¹¹⁸ Gladstein, Neandross & Associates, “Zero-Emissions Truck Assessment,” final report for the South Coast Air Quality Management District, September 2015.

¹¹⁹ California Air Resources Board, “Mobile Source Strategy: Discussion Draft,” October 2015, http://www.arb.ca.gov/planning/sip/2016sip/2016mobsrc_dd.pdf.

¹²⁰ California Energy Commission, AB 1257 Natural Gas Act Report: Strategies to Maximize the Benefits Obtained from Natural Gas as an Energy Source, Draft Staff Report, September 16, 2015.

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

enforceable 2023 ozone NAAQS attainment deadline, versus meeting longer-term GHG emission reduction goals established for the state's 2050 climate change objectives. SJVAPCD noted the following specific concerns about the Sustainable Freight Plan¹²¹:

- The “exclusive focus on electrification and renewable sources may fail to provide meaningful (near-term NOx) reductions.”
- The state’s “focus on electrification” in the heavy-duty trucking sector provides “solutions for shorter-range applications” that are “less suitable” for use in the Central (San Joaquin) Valley trucking corridors.
- Hydrogen fuel cell HDVs must be considered as being a “longer-term solution,” due to technology gaps, limited fueling infrastructure and high costs.

The South Coast Air Quality Management District (SCAQMD), which is drafting the SCAB’s 2016 AQMP, continues to strongly rely on both heavy-duty ZEV and NZEV technologies. SCAQMD’s draft 2016 AQMP takes a realistic approach towards how to achieve significant, expeditious NOx reductions in the most-challenging HDV sectors. For example, policy objectives¹²² that SCAQMD is using to guide development of the new AQMP include:

- Eliminate reliance on future technologies to the maximum extent possible by providing specific pathways to attainment with specific control measures
- Invest in strategies and technologies that meet multiple HDV transportation objectives (air quality, climate change, air toxic exposure, and energy)
- Use enhanced socioeconomic analysis to help select the most efficient and cost-effective path to achieve multi-pollutant and multi-deadline targets
- Seek significant funding for incentives to implement early deployment and commercialization of known zero- and near-zero-emission technologies

In sum, for high-fuel-use, high-impact HHDT applications, HDV OEMs¹²³, transportation experts and government regulators generally agree¹²⁴ that heavy-duty BEVs and FCVs will not achieve sufficient technological or commercial maturity to provide large NOx- and GHG-reduction benefits during the critical timeframe between 2016 and 2030. In the absence of unforeseen technological breakthroughs, consensus indicates that it will be beyond 2030 before commercialized heavy-duty BEVs and FCVs are able to start penetrating into America’s most-impactful HHDT markets.

¹²¹ San Joaquin Valley Air Pollution Control District, “Review and Approve Action Plan for Promoting the Use of Natural Gas Technology for Goods Movement in the San Joaquin Valley,” staff presentation during “Governing Board Study Session,” May 6-7, 2015, accessed online on November 2, 2015.

¹²² South Coast Air Quality Management District, “2016 Air Quality Management Plan,” fact sheet dated January 28, 2016, emailed to GNA by staff.

¹²³ GNA interviewed high-level executives from five major North American truck OEMs; all indicated there is “no foreseeable timeframe” for commercially viable battery or fuel cell HDTs.

¹²⁴ For example, see EPA / NHTSA Phase 2 rulemaking, CARB’s “Draft Technology Assessment: Medium- and Heavy-Duty Battery Electric Trucks and Buses,” and SJVAPCD’s “Action Plan for Promoting the Use of Natural Gas Technology for Goods Movement in the San Joaquin Valley.”

4.3. Heavy-Duty “Near-Zero-Emission Vehicle” (NZEV) Technology

4.3.1. California’s Optional Low-NO_x Emissions Standard

This longer-term, uncertain timeline for heavy-duty ZEV technology has influenced California’s recent adoption of its optional low-NO_x emissions standards for on-road heavy-duty engines. In developing these standards, CARB set three NO_x emission tiers relative to the current “mandatory” federal / California NO_x standard of 0.2 g/bhp-hr. These are 1) 50 percent below (0.10 g/bhp-hr), 2) 75 percent below (0.05 g/bhp-hr), and 3) 90 percent below (0.02 g/bhp-hr). According to CARB, this was specifically done “to encourage engine manufacturers to introduce new technologies” that “showcase” pathways to rapidly achieve major NO_x reductions. Since HDVs using cleaner fuels and technologies entail higher capital costs (primarily due to low-volume amortization of development costs), the optional low-NO_x standards were intended to help “prioritize funding in incentive programs” such as California’s Carl Moyer Program.¹²⁵

4.3.2. Technology Assessment Summary: Low-NO_x Heavy-Duty Engines

CARB has concluded that “combustion technology will continue to dominate” California’s on-road HDV sector “over the next 15 years.” This is essentially the converse of its finding that commercial heavy-duty ZEV technologies are at least 15 years away. However, CARB notes that next-generation HDVs powered by advanced ICE technology will need to be at least “90 percent cleaner than today’s current standards.” This means they must meet (or beat) the lowest tier of CARB’s optional low-NO_x standards. In tandem, CARB indicates that 50 percent or more of the fuels combusted in those low-NO_x heavy-duty engines will need to be “clean and renewable.” CARB’s intends to “implement statewide strategies that employ lower NO_x combustion engines coupled with the use of renewable fuels,” to “attain near-term air quality and climate goals.”¹²⁶

As with the ZEV technologies, CARB has performed recent technology assessments on the two heavy-duty ICE pathways it deems most capable of meeting the bottom-tier optional low-NO_x engine standard. The following tables summarize key statements and findings about Diesel (Table 7) and Natural Gas (Table 8). Implicit in both cases is that CARB seeks to transition any low-NO_x engine technologies from burning “fossil” diesel or natural gas, over to renewable versions of these fuels. This is needed to complement major NO_x reductions with maximized GHG reductions.

¹²⁵ California Air Resources Board, “Optional Reduced NO_x Emission Standards for On-Road Heavy-Duty Engines,” accessed online November 11, 2015 at <http://www.arb.ca.gov/msprog/onroad/optionnox/optionnox.htm>.

¹²⁶ CARB, Mobile Source Strategy, October 2015.

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

Table 7. Summary: CARB’s key Technology Assessment findings on low-NOx diesel engines

Low-NOx Heavy-Duty Diesel Engines: Key CARB Statements / Findings¹²⁷
<ul style="list-style-type: none">• A heavy-duty diesel engine “package” that “provides maximum benefits of both NOX and GHG emissions is currently not yet determined”• Technology development is progressing, with “promising signs these objectives will be realized”• Ongoing development and demonstration programs (e.g., the CARB-sponsored Low NOX program at Southwest Research Institute) “are expected to identify technology packages that will provide significant further reductions of both NOX and GHG emissions by the end of 2016”• “Further NOX reductions to lower levels of approximately 90 percent below current standards will be possible through a combination of newer diesel engine designs, advanced diesel aftertreatment technologies, improved SCR catalysts with advanced substrates, and improved controls”

Table 8 Summary: CARB’s key Technology Assessment findings on low-NOx NG engines

Low-NOx Heavy-Duty Natural Gas Engines: Key CARB Statements / Findings¹²⁸
<ul style="list-style-type: none">• Cummins Westport’s 8.9 liter spark-ignited natural gas engine certified to a 0.02 g/bhp-hr optional NOX standard will be commercially available in 2016 for applications in transit buses, refuse trucks, and tractors• CARB staff “expects other engine sizes meeting one of the optional NOx standards (0.02, 0.05, 0.1 g/bhp-hr) to become available within the next year or two” (Note: this came to fruition with CWI’s announced intent to certify its 6.7 and 11.9 liter natural gas engines to CARB’s optional low-NOx standards, by 2018)• “These advanced natural gas vehicles are expected to deliver near term opportunities to reduce NOX emissions, and with the use of renewable natural gas, could also deliver deep GHG emission reductions”• NOX certification levels for the latest (already commercialized) natural gas engines “are 25 percent to 75 percent below the 2010 NOX certification standard, depending on engine size, while NOX certification levels for the latest diesel engines are 10 percent to 60 percent below the standard”• Furthermore, recent in-use emissions test data from natural gas, diesel, and diesel hybrid engines certified to the 2010 NOX emission standard show that natural gas engines do not appear to suffer the control challenge experienced by diesel engines in low temperature, low speed, and low load operations.• Based on current certification levels and lower in-use emissions at low temperature operations, and the success achieved for similar light-duty SI engines, CARB believes “natural gas engines are likely to be certified to today’s optional low-NOX emission standards sooner than will diesel engines”• “A shift to natural gas-powered heavy duty trucks alone will not be sufficient to meet California’s air quality challenges in the long term”

As briefly summarized in these two tables, only one engine fuel / technology pathway—exemplified by the CWI 8.9 ISL G NZ heavy-duty natural gas engine—has achieved CARB’s goal of commercialized internal combustion engines that are at least 90 percent lower on NOx emissions than the current heavy-duty engine standard. When fueled by increasing blends of RNG, this fuel-technology pathway can initiate a transformation of America’s heavy-duty transportation sector. This major achievement and

¹²⁷ CARB, “Draft Technology Assessment: Lower NOx Heavy-Duty Diesel Engines,” September 2015, http://www.arb.ca.gov/msprog/tech/techreport/diesel_tech_report.pdf.

¹²⁸ CARB, “Draft Technology Assessment: Low Emission Natural Gas and Other Alternative Fuel Heavy-Duty Engines,” September 2015, http://www.arb.ca.gov/msprog/tech/techreport/ng_tech_report.pdf.

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

its implications towards transforming America's heavy-duty transportation sector are discussed extensively in the sections that follow.

CARB provided two important policy statements about its plans to achieve air quality goals in California's transportation sector, based on findings from these low-NO_x HDV technology assessments. First, CARB announced that it "intends to begin development of mandatory low-NO_x standards . . . applicable to all California certified heavy-duty vehicles." Second, because out-of-state-registered HDVs contribute significantly to California's emissions inventory, CARB concluded that it must "petition EPA to require lower NO_x standards for all HDVs nationally."¹²⁹

4.4. Emergence of Commercially Viable Heavy-Duty Natural Gas NZEVs

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 bottom-tier optional low-NO_x emissions standard*. This "next-generation" heavy-duty natural gas engine is now becoming commercially available. With no further modifications, it can operate on growing volumes of renewable natural gas (RNG), either when blended with fossil gas or using 100 percent RNG. This engine offers broad, near-term applicability in several HDV sectors that power our freight and public transportation systems (transit buses, refuse haulers, and short-haul delivery trucks). Within two years, at least one additional engine platform using this same ultra-low-NO_x technology (the CWI 11.9 liter ISX12 G NZ) is expected to follow. This will expand on-road applications of near-zero emissions HDVs into HHDTs used in high-fuel-use goods movement applications, including for-hire trucking.

Clearly, a game-changing proposition has emerged for transformation of America's diesel-dominated freight movement system. Section 5 provides an overview of the current status of heavy-duty NGV technology and deployments. Section 6 provides a detailed assessment of the emerging "near-zero-emission" heavy-duty engine technology represented by CWI's initial entry, the ISL G NZ engine. Section 7 provides additional details about the opportunities and challenges for RNG to become a major transportation fuel in America, including discussion about feedstock, production, supply and cost.

4.5. Potential for Commercialization of Heavy-Duty Diesel NZEVs

Heavy-duty diesel engines are formidable power-plants, and the "workhorses" for America's on-road freight movement system. State-of-the-art diesel HDVs offer low cost, long driving range, fast refueling time, good fuel efficiency (i.e., relatively low tailpipe emissions of CO₂), and ubiquitous access to low-cost fuel. To date, no on-road heavy-duty diesel engine has been certified to a NO_x level below the existing standard of 0.2 g/bhp-hr. However, efforts are underway in the U.S. by manufacturers and air regulators to improve diesel engine NO_x emissions down to levels significantly below the current standard. CARB estimates that the 75 percent reduction tier (0.05 g/bhp-hr) of California's optional low-NO_x standard will be achieved in heavy-duty diesel engines within a few years. CARB does not estimate

¹²⁹ CARB, "Draft Technology Assessment: Low Emission Natural Gas and Other Alternative Fuel Heavy-Duty Engines," September 2015, http://www.arb.ca.gov/msprog/tech/techreport/ng_tech_report.pdf.

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

when diesel engines will be able to achieve the lowest low-NO_x tier of 0.02 g/bhp-hr. It is implied that this will occur within approximately two to five years.¹³⁰

Reducing NO_x down to these very low levels, while also addressing new federal requirements for efficiency improvements and reduced GHG emissions¹³¹, presents engineering challenges for any type of heavy-duty engine. However, resolving “NO_x-GHG tradeoffs” can be significantly more difficult for heavy-duty diesel engines compared to natural gas versions. As stated by an executive engineer at Cummins Engine Company in mid-2015, “more work is needed to identify a robust solution” for achieving the targeted 90 percent NO_x reduction for diesel engines. So far, a “potential path” has been identified to achieve a 50 percent reduction, “with minimal CO₂ penalty.” By contrast, the heavy-duty natural gas engine pathway to a 90 percent NO_x reduction is less challenging, while entailing a lower “CO₂ penalty.”¹³² (A few months later, CWI proved this by certifying the ISL G NZ natural gas engine to 0.02 g/bhp-hr NO_x, while also meeting EPA’s GHG requirement.)

Heavy-duty natural gas engines appear to offer another important advantage over diesel engines: their ability to maintain low NO_x emissions during in-use operation. Based on a body of test data,¹³³ CARB has found that 2010-compliant heavy-duty diesel engines with advanced emissions controls can exhibit NO_x “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_x certification levels that still offer good margin to meet very challenging useful life emissions requirements.¹³⁴

Notwithstanding these challenges, advanced on-road diesel engines may soon achieve CARB’s interim optional low-NO_x levels (0.10 or 0.05 g/bh-hr). When using renewable diesel fuel, such engines can also provide compelling full-fuel-cycle GHG-reduction benefits. For example, renewable diesel from “tallow” feedstock has a carbon intensity rating that is approximately 72 percent below today’s conventional on-road diesel fuel.¹³⁵ Given that renewable diesel is handled, dispensed and used the same as conventional diesel fuel, this pathway has fewer fuel-related barriers compared to alternative pathways that include heavy-duty NGVs, BEVs and FCVs. Section 14 – Appendix 4 further describes renewable diesel and its potential role to help advanced diesel engines achieve progressively lower emissions of NO_x and GHGs.

¹³⁰ CARB, “Draft Technology Assessment: Lower NO_x Heavy-Duty Diesel Engines,” September 2015, http://www.arb.ca.gov/msprog/tech/techreport/diesel_tech_report.pdf.

¹³¹ Depending on vehicle weight class, by 2017 heavy-duty diesel engines are required to reduce GHG emissions by 5 to 9 percent relative to 2010 GHG emission levels.

¹³² Dr. Wayne Eckerle, Cummins Engine Company, “Engine Technologies for GHG and Low NO_x,” presentation at the ARB Symposium on California’s Development of its Phase 2 Greenhouse Gas Emission Standards for On-Road Heavy-Duty Vehicles, April 22, 2015, http://www.arb.ca.gov/msprog/onroad/caphase2ghg/presentations/2_7_wayne_e_cummins.pdf.

¹³³ For example, see In-Use Emissions Testing and Demonstration of Retrofit Technology for Control of On-Road Heavy-Duty Engines, accessible online at <http://www.arb.ca.gov/lists/com-attach/35-techfuel-report-ws-BmdcLciAjAHYIM7.pdf>.

¹³⁴ California Air Resources Board, “Draft Technology Assessment: Lower NO_x Heavy-Duty Engines,” September 2015, http://www.arb.ca.gov/msprog/tech/techreport/diesel_tech_report.pdf.

¹³⁵ California Air Resources Board, “LCFS Illustrative Fuel Pathway Carbon Intensity Using CA-GREET 2.0,” discussion document presented by staff at September 17, 2015 public hearing (illustrative only).

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

The subsection that follows describes CARB's assumed penetrations over the next 35 years in California for various heavy-duty NZEV and ZEV technologies, including internal combustion engines fueled by either renewable diesel or renewable natural gas.

4.6. California's Estimated Mix of Heavy-Duty NZEVs and ZEVs

In Southern California's SCAB, total NO_x emissions must be reduced by approximately 65 percent to attain the ozone NAAQS, while also achieving major GHG reductions. Despite the nation's overall most-stringent existing and planned NO_x-reduction requirements, it is projected that the SCAB will not achieve its 2023 and 2032 reduction goals. SCAQMD's draft 2016 AQMP and CARB's draft Mobile Source Strategy are both designed to outline very specific potential new control measures that will be able to demonstrate ozone attainment in the SCAB, while also delivering GHG reductions in line with California's aggressive 2030 and 2050 goals.

Given major uncertainty for wide-scale deployment of BEVs and FCVs in the most impactful heavy-heavy-duty on-road sectors, CARB's draft Mobile Source Strategy largely relies on NZEV technologies to power the majority of the state's HHDTs by 2030. It states that low-NO_x trucks are "the most viable approach" to meet California's mid- and longer-term air quality goals. It is noted that "large-scale deployment" of low-NO_x, very-low-PM goods movement trucks over the next 15 years "will provide the largest health benefit of any single new strategy" under consideration by California. Specifically, CARB assumes California will need to deploy "approximately 400,000" near-zero-emission HHDTs by 2030. To simultaneously meet GHG and petroleum-use-reduction targets, "approximately 55 percent of the truck fuel demand" will need to be met with renewable fuel.¹³⁶

Figure 12 provides specific penetration assumptions for deployment of low-NO_x HDVs (both **natural gas** and **diesel**) in California's draft Mobile Source Strategy. These curves were found by extracting information embedded in CARB's Vision Model. By 2030, the Vision model assumes approximately 560,000 in-use HDVs (of all types, including HHDTs) will be equipped with low-NO_x engines. By 2050, nearly 2 million HDVs will be powered by low-NO_x engines. To accomplish this, CARB assumes there will need to be a mandatory phased-in requirement for low-NO_x heavy-duty engines in all 50 states.¹³⁷ Beginning in the 2024 model year, new engines will be required to emit at or below the lowest tier (0.02 g/bhp-hr) of California's *currently* optional low-NO_x standard.

The SCAQMD Governing Board has strongly backed the need for a national standard at 0.02 g/bhp-hr, noting that "the majority of the NO_x emissions from heavy-duty trucks in California come from trucks that are registered out-of-state." The Board voted in March 2016 to petition EPA to take adopt such a national standard as soon as possible, thereby "leveling the playing field between trucks purchased in California and those purchased out of state."¹³⁸

¹³⁶ California Air Resources Board, "Draft Mobile Source Strategy," October 2015.

¹³⁷ This again highlights that out-of-state trucks contribute very significantly to California's NO_x inventory.

¹³⁸ South Coast Air Quality Management District, "Authorize Staff to Petition U.S. EPA to Adopt Lower On-Road Heavy-Duty Engine Exhaust Emission Standard for NO_x," Governing Board Item #16, March 4, 2016.

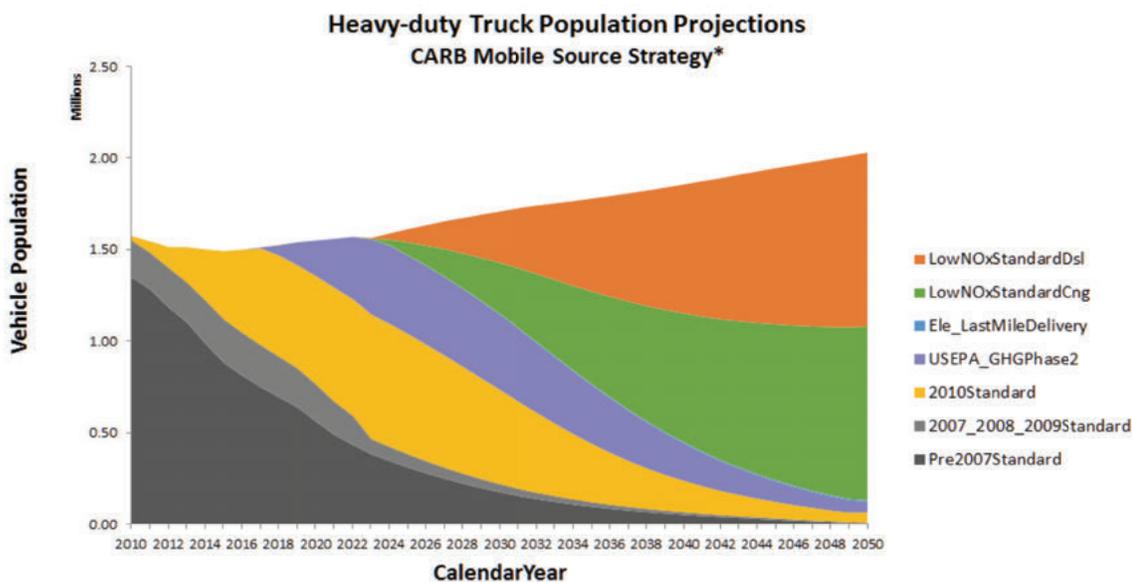


Figure 12. CARB projections for California’s mix of HHDT populations over next 35 years

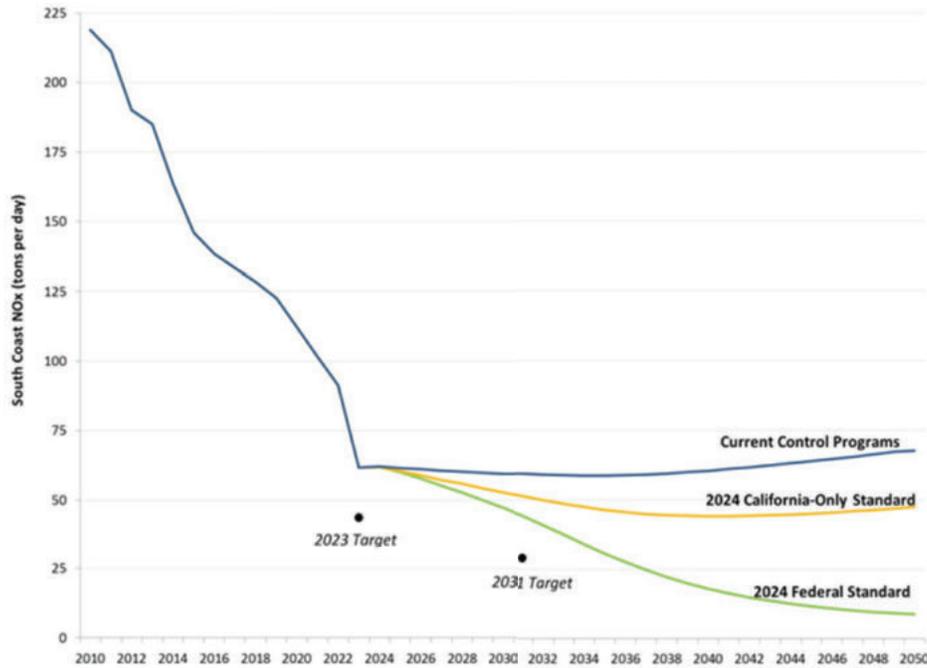
Even under this scenario with a national standard for low-NOx heavy-duty engines—but *they are not significantly deployed until 2024*—the SCAB fails to achieve NOx reductions targeted for the heavy-duty on road sector in 2023 and 2031. This is illustrated in Figure 13.

In this scenario, the key point is that California’s model assumes that heavy-duty NZEVs will not be deployed until approximately eight years after natural gas NZEV technology becomes commercially available (April 2016). This is contrary to CARB’s acknowledgement that California must deploy heavy-duty low-NOx engine technologies as soon as they become commercially available. Early deployment is essential for areas like the SCAB and SJVAB to achieve NAAQS attainment. However, it is also key to combine this supply side approach with effective mechanisms to create demand for heavy-duty NZEVs. These generally consist of incentives (“carrots”) and regulations (“sticks”) designed to accelerate fleet turnover.

In sum, beginning in mid-2016 with commercial role out of CWI’s ISL G NZ engine, there appears to be clear and realistic potential *well before 2024* to deploy meaningful numbers of HDVs powered with near-zero-NOx natural gas engines. The addressable NOx reductions from such deployments are likely to significantly expand by 2018, with the anticipated certification and commercialization of an “NZ” version of CWI’s 12-liter heavy-duty natural gas engine (see Section 6.1). In addition, CWI is expected to certify its 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. Collectively, these three heavy-duty natural gas

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

engines have potential to begin delivering up to 90 percent NOx reductions in virtually every on-road HDV application by 2018.



*The scenarios illustrated in this figure reflect natural turnover rates.

Figure 13. Impact of California-only vs 50-state low-NOx standard on SCAB NOx targets

4.7. The Need for All Heavy-Duty ZEV and NZEV Pathways

It is clear that America must continue to push for the cleanest on-road HDV fuel and technology pathways. It will be essential to avoid overreliance on technologies that are not yet commercialized, or “picking winners” in very unsure markets. All four heavy-duty ZEV and NZEV fuel-technology pathways that were highlighted (refer back to Table 4) are likely to be needed, if America is to meet daunting energy and environmental challenges, while continuing to transport freight efficiently and competitively. See the box below for examples of corroborating statements.

Corroborating Statements on the Need for All Clean HDV Pathways

“The greatest reduction in (full fuel cycle) emission factors can be achieved through the use of zero emission technologies operated on renewable electricity or hydrogen, and through the use of near-zero emission technologies operated on renewable fuels such as renewable natural gas or renewable diesel.”

-CARB “Draft Heavy-Duty Technology and Fuels Assessment: Overview,” April 2015

“In Southern California, clean, zero- and near-zero emission vehicle technologies are critical to meeting clean air standards. Cummins Westport’s new (ISL-G NZ natural gas) engine provides an important tool toward reaching that goal.”

-SCAQMD Executive Officer Dr. Barry Wallerstein, October 2015.

“It will likely take a combination of vehicle types and fuel types to achieve a low-carbon future for trucking, with electricity, hydrogen fuel cells and biofuels all likely playing a role. And since the exact role or potential role of each is unclear, it seems wise to pursue all these technologies and strategies in combination, possibly for another 10 years or more, at least until a dominant pathway, or perhaps an equilibrium combination (which may vary by truck type and use), emerges.”

University of California – Davis, “Strategies for Transitioning to Low-Carbon Emission Trucks in the United States,” June 2015.

To meet multiple challenging air quality and energy policy goals, regulators are relying on ZEV technology for light-heavy and medium-heavy duty applications to play significant roles. For example, CARB notes such zero-emissions trucks “will be an important part of California’s strategy to meet its long-term environmental goals.” The draft Mobile Source Strategy focuses on deploying heavy-duty ZEVs in applications that “are currently well-suited for broad market development, such as transit buses, airport shuttles, and last mile delivery.”¹³⁹ In fact, CARB has drafted the concept of a “Last Mile Delivery Regulation” that would require the purchase of zero emission trucks for class 3-6 last-mile delivery trucks in California. On a preliminary basis, this measure might include sales requirements for BEVs that “begin in 2021 at approximately 200 units per year” and progress up to 900 per year in 2032, resulting in approximately 3,100 heavy-duty BEVs statewide by 2030. This would represent an estimated 0.2 percent of California’s 1.7 million on-road HDVs in 2030.¹⁴⁰ At these projected levels and timeline for market penetration, deployment of heavy-duty BEVs will have very minimal impact on meeting the broad array of California’s critical air quality, energy and climate change policy goals discussed in Section 3 of this report. This will also be the case on a national scale.

Larger and more-immediate results must be achieved. This can only be realized via expeditious wide-scale market penetration of ultra-clean technologies and fuels that are commercially proven and available in the immediate term. Therefore, the remainder of this white paper focuses on the compelling value proposition that advanced near-zero-emission natural gas HDVs provide across America to meet very challenging energy, air quality and economic goals.

¹³⁹ “Last-mile delivery” in this context refers to the last leg in the supply chain where trucks deliver goods to the ultimate consumer. Last-mile delivery presents challenges to trucking companies engaged in such service, but it generally entails relatively short trips that could be met by Class 3 through 6 BEVs.

¹⁴⁰ California Air Resources Board, “Draft Mobile Source Strategy,” October 2015.

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

In depth analyses of dedicated battery electric, hybrid, and/or fuel cell powered zero emission truck technologies are not provided in this report. This is due to the high degree of uncertainty about timelines, costs, technology readiness, operational feasibility, North American OEM product availability, and other significant unknowns impacting the commercial availability of such technologies across a wide range of HDV applications. CARB’s draft “Heavy-Duty Technology and Fuels Assessment Overview” and “Sustainable Freight Pathways to Zero and Near-Zero Emissions” provide insight and information into the current and anticipated future status of zero tailpipe emission technologies that can be deployed within the heavy-duty transportation sector.

4.8. Key Determinants and Factors for Large-Scale Market Penetration

There are a multitude of critically important market conditions that must align for successful deployment of any new HDV platform in real-world commercial operations. One model used by major truck OEMs refers to different “technology readiness levels” (TRLs) for commercializing heavy-duty trucks. As an OEM progresses through all these stages, the necessary investments can grow

Table 9. Technology Readiness Levels (TRLs) for Commercializing HHDTs (Volvo)

TRL No.	TRL Description	Magnitude of Necessary Investments
1	Basic Principle	
2	Concept Formulation	
3	Component Evaluation	
4		
5	System Integration / Demonstration	
6		
7		
8	Truck Verification	
9	Commercial Truck Model Launch	

Source: adapted from Volvo Group presentation “Investment Considerations: Medium & Heavy-Duty Truck Technologies in California,” presented by Dawn Fenton, Director, Sustainability & Public Affairs, December 3, 2015, <http://steps.ucdavis.edu/files/12-03-2015-Fenton-CEC-12-3-15-FINAL.pdf>.

exponentially, and full commercialization can take many years (see Table 9 example).

Notably, when OEMs commercialize emerging fuel-technology pathways, this process can require extra resource commitments during the last stages of commercialization (i.e., TRLs 8 through 9 in the table), for special training, customer support and field service.

A review of the process to commercialize heavy-duty NGVs over the last two decades provides an informative case study. During the early days of heavy-duty NGV commercialization in the 1990s, a small number of companies developed and deployed heavy-duty NGV. This was primarily done through conversions, upfits and retrofits; OEM products and support were limited, if available at all. Reliability of these early heavy-duty NGVs did not fully meet the expectations of commercial fleet operators. Even as

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

mainstream HDV OEMs began to enter the market, failures were widespread; at times, it was challenging for fleets to meet daily rollout requirements. Early adopter fleets such as UPS (medium- and heavy-duty trucks), Waste Management (refuse trucks), and Los Angeles County Metro (transit buses) can testify about the struggles of deploying first-generation technologies, and the perseverance required by them and all stakeholders to achieve today's commercially robust heavy-duty NGVs. Section 5.3 provides additional details about the commercial maturity that the heavy-duty NGV industry has achieved.

This experience showed that many factors must be in place for full commercialization and wide-scale market penetration of any HDV technology. Start-up companies can play an important role to develop new technologies and set up initial support systems. However, it is the mainstream heavy-duty OEMs that must ultimately adopt, embrace and invest in these technologies. And, as noted in Table 9, the process for full commercialization can take many years, with the necessary investments by OEMs growing exponentially along the way.

The current state of the market to develop heavy-duty BEVs and FCVs is analogous to the development of the heavy-duty NGV market in the mid-1990s. There are important efforts underway by OEMs, start-up companies and organizations to develop an array of zero-emission (or partial-range zero-emission) HDV technologies. The range of fuel-technology architectures includes 100 percent battery-electric drive; battery-electric drive with range extension technology (e.g., a very clean engine, or a fuel cell), fuel cell and battery-electric hybrids, and catenary-electric hybrids. As various government programs, policies and efforts are focused on the continued development of such technologies, they are gradually growing in their potential for meaningful commercial deployments. As documented in this report, initial volume deployments for good movement applications are likely to be limited to technically feasible vocations involving short-haul delivery service.

Much like the early days of the NGV market, it will require gradual growth over many years for OEMs to fully develop robust, commercially viable heavy-duty BEVs or FCVs for goods movement applications. This must include all the OEM and after-market support infrastructures—and fueling stations—that are needed to facilitate mainstream deployments of such HDVs. This timeline is generally consistent with the projections made by various agencies, as noted elsewhere in this report.

5. Current Status of Heavy-Duty NGV Technology and Deployments

Very large investments over 20+ years by heavy-duty engine and vehicle manufacturers—combined with significant government incentives to help buy down higher capital costs—have enabled heavy-duty NGVs to emerge as a proven 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. This has resulted in high demand for these products from heavy-duty fleet owners. Today, an estimated 65,000 heavy-duty NGVs are displacing diesel fuel on America’s roadways.¹⁴¹ 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.

The following subsections provide additional details about the current status of heavy-duty NGV technology and deployments.

5.1. Overview of NGV Populations and Key End-Use Sectors

The worldwide fleet of NGVs consists of roughly 15.2 million vehicles (almost exclusively CNG), of which North America is home to only about one percent.¹⁴² The majority of North American NGVs are concentrated in the United States. While the U.S. is a relatively minor user of NGVs compared to top international users (e.g., Iran, Argentina, Brazil, India and Italy), America has been experiencing consistent growth for consumption of natural gas as motor vehicle fuel. From 1997 to 2011, the U.S. Energy Information Administration (EIA) estimates that the volume of natural gas consumed for transportation grew at an average annual rate of nearly 20 percent. That growth continues today; EIA estimates that 2014 consumption reached nearly 37 Billion Cubic Feet (the equivalent of about 275 million DGE). It appears that EIA estimates are significantly low, however. Based on informed estimates for the volumes of CNG and LNG that major companies currently provide in the U.S. for NGVs, the total national throughput is estimated to be as high as 400 million DGE per year.¹⁴³

An estimated 153,000 on-road NGVs are currently operated in the U.S., of which about 43 percent are medium- or heavy-duty vehicles. Approximately 18,000 NGVs were produced and sold in 2014; two thirds were MDVs and HDVs (see Figure 14). Total NGV production and sales in the U.S. decreased slightly in 2014 compared to 2013, but increases were realized in high-fuel-use MDV and HDV sectors (i.e., displacement of diesel, not gasoline). Various trends suggest that MDV and HDVs will comprise an increasing share of America’s NGV population. Refuse and transit are seen as key sectors that will

¹⁴¹ NGVAmerica, “For Fleets,” <http://www.ngvamerica.org/vehicles/for-fleets/>.

¹⁴² U.S. DOE, Alternative Fuels Data Center, “Natural Gas Vehicles,” accessed online on 10-29-15 at http://www.afdc.energy.gov/vehicles/natural_gas.html.

¹⁴³ Personal communication from Clean Energy to GNA, March 2016.

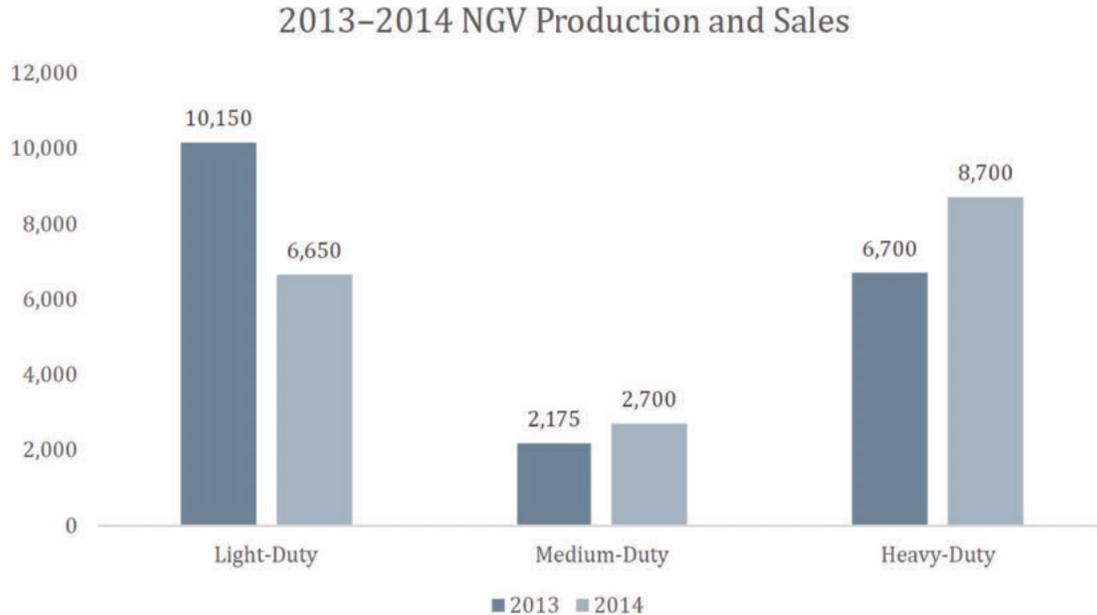


Figure 14. 2013-2014 NGV Production and Sales (NGVAmerica, 2015)

continue to support NGVs sales, but goods movement trucking applications are also expected to drive significant growth.¹⁴⁴

5.2. Fuel Volumes Used in Transportation

The volume of natural gas used by U.S. NGVs has more than doubled since 2000.¹⁴⁵ Figure 15 breaks out natural gas consumption by all types of NGVs in the U.S. over the last five years (total U.S., and top user areas including Washington D.C.). In 2014, an estimated 35,820 million cubic feet (MMCF) of natural gas were consumed nationwide by motor vehicles. This equates to an annual “displacement” of approximately *one quarter of a billion petroleum gallons* (gasoline and diesel). Nearly half of this—approximately 46 percent (the equivalent of 126 million diesel gallons)—was dispensed in California.¹⁴⁶ This demonstrates the importance of California’s NGV-related programs and policies in the overall North American market.

¹⁴⁴ NGVAmerica, “2014 NGV Production and Sales Report”, 2015

¹⁴⁵ U.S. Energy Information Administration, “Nonpetroleum share of transportation energy at highest level since 1954,” May 18, 2015, accessed online at <http://www.eia.gov/todayinenergy/detail.cfm?id=21272>.

¹⁴⁶ Notably, U.S. EIA’s estimates for vehicular use of natural gas in California tend to be on the low end. The California Energy Commission’s “DMV-based” estimate is that California-based NGVs consumed 146 million DGE in 2014.

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

In addition, it is important to note that growing volumes of the CNG and LNG used to fuel America's NGVs are coming from renewable feedstocks (see Section 6.5). This significant and growing use of RNG in the North American market has been possible because it is a drop-in fuel that can immediately be 1) dispensed at hundreds of already established natural gas fueling stations, and 2) consumed by an estimated 65,000 heavy-duty NGVs on American roads today. Unlike alternative fuels such as biodiesel, there is no "blend wall" for using RNG in heavy-duty natural gas engines. This means end user fleets can seamlessly move towards higher-level blends of RNG as the fuel becomes more available. Thus, there is strong synergy at work; this existing and growing inventory of NGVs and fueling stations makes it possible to systematically and steadily increase use of extremely low-carbon-intensity RNG across America (see Section 6.5).

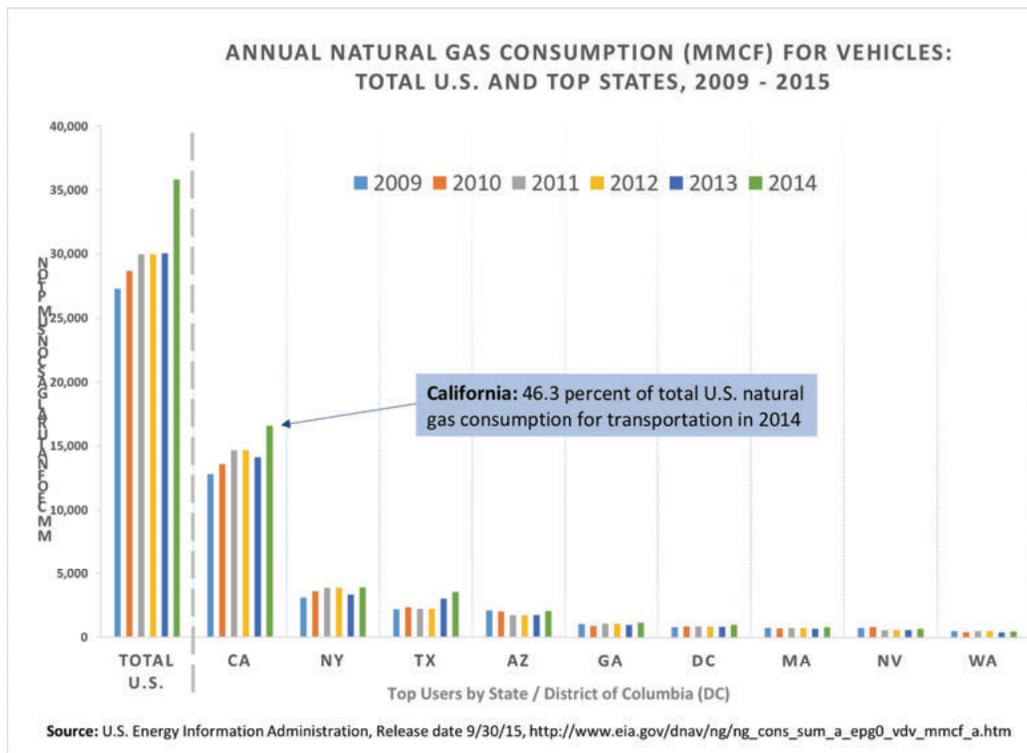


Figure 15. Trends in consumption of natural gas for transportation (U.S. and top areas)

The following subsections describe specific vehicle applications and technologies that are responsible for this growing usage of fossil and renewable natural gas, in the form of CNG or LNG.

5.3. Commercial Maturity and Availability

5.3.1. Overview

Heavy-duty NGVs use commercially mature technology. This is clearly reflected by the wide array of commercial platforms that numerous manufacturers and aftermarket companies offer today. These HDVs use market-proven, technically mature natural gas combustion and fuel storage technologies. Primarily due to their relatively expensive onboard fuel systems, heavy-duty NGVs entail higher capital costs compared to conventional (diesel) HDVs. Specialized fuel tanks are needed to safely carry sufficient volumes of fuel, either as a compressed gas (i.e., CNG) or cryogenic liquid (i.e., LNG).

CNG and LNG tanks store less energy (fewer DGEs) per volume and mass than diesel fuel tanks. Today, affordable CNG and LNG fuel tank packages are routinely customized for specific applications and range requirements. This provides sufficient vehicle range for heavy-duty NGVs to work quite well, especially in “return-to-base” types of operation. Although capital costs are significantly higher, an attractive fuel price spread versus diesel (up until 2014) has generally provided compelling payback for end users that switch their fleets over to natural gas fuel. These favorable economics—in addition to very significant air quality benefits—have been strong drivers for growing deployments of heavy-duty NGVs in the U.S. across a diverse range of applications that include transit buses, work trucks, solid waste collection vehicles, short-haul trucking, and even long-haul trucking. More discussion on heavy-duty NGV economics is provided in Section 5.4.

5.3.2. Heavy-Duty Engine and Vehicle Offerings

Today, one particular heavy-duty engine manufacturer, Cummins Westport Inc. (CWI), leads the way to develop and market heavy-duty natural gas engines suitable for HDV applications. CWI is a 50:50 joint venture between Cummins Inc. and Westport. From 2007 to 2013, suppliers of NGVs in the Class 6 through Class 8 weight groups largely relied on CWI’s 8.9L ISL G spark-ignited, “dedicated” natural gas engine. This 9-liter engine is most suitable for Class 6 applications (e.g., beverage trucks), up to “light” Class 8 applications (under 60,000 lbs gross combined weight, or GCW). This includes transit buses, refuse trucks and near-dock drayage trucks. While the ISL G has been deployed in heavier applications, performance and durability have not been well suited for most applications over 60,000 lbs.

In late 2013, CWI introduced its ISX12 G natural gas engine designed for larger HDV applications, including regional trucking at a full 80,000 lbs GCW. This product release was much anticipated by the trucking industry. The ISX12 G is rated up to 400 hp and 1,450 lb-ft torque, which is well suited for most regional and line-haul trucking applications. Like the smaller ISL G, the ISX12 G operates on 100 percent natural gas (fossil or renewable) stored on the tractor as either CNG or LNG. The ISX12 G and all CWI dedicated natural gas engines are manufactured by Cummins, then made available as a factory-direct option from leading truck manufacturers that include Freightliner, Peterbilt, Kenworth, Volvo, and Mack.

Today, most heavy-duty natural gas trucks sold in North America utilize these two CWI spark-ignited engines (the ISL G and ISX12 G). As shown in Table 10, all six major heavy-duty truck OEMs currently

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

offer at least one natural gas-equipped model. Five of the six OEMs offer multiple models using both CWI engine platforms. Freightliner and the PACCAR group (Kenworth and Peterbilt) offer the most models, including over-the-road tractors and vocational trucks. The commercially available HDVs powered by these two CWI natural gas engines cover a wide array of on-road HDV applications, from long-haul Class 8 trucks to medium-duty street sweepers. In addition, the GM 6.0-liter and Ford 6.7-liter natural gas engines are commercially available options to power medium-duty applications such as step vans, shuttle buses, tow trucks and beverage trucks.

Table 10. Commercially available heavy-duty natural gas truck models, by OEM

Heavy-Duty Truck OEM	Existing Models using CWI ISL G 8.9L	Existing Models using CWI ISX12 G 11.9 L
Freightliner	Cascadia 113	M2 112, 114 SD
Kenworth	T660, T680, T800SH, T880S, W900S	T440, T470, W900S
Peterbilt	579, 567, 384, 365, 320	384, 365, 320
Volvo Trucks	VNL	VNM
Mack	Pinnacle	LR, TerraPro
International	TranStar	(None)

5.3.3. Gaps and Expected New Commercial Offerings

Currently, a “power gap” exists at the upper end of engines offered for heavy-duty natural gas trucks. CWI’s 11.9-liter (ISX12 G) is very capable of moving full Class 8 loads (@ 80,000 lbs GCW) in many situations. However, for fleets that haul these heavy loads in mountainous terrain, there is still a need for a natural gas engine in the 13 to 15 liter class that can match the performance provided by large on-road diesel engines (e.g., 450 HP and 1550 lb-ft of peak torque). Consequently, some of the largest over-the-road trucks commonly used for long-haul applications (e.g., the Peterbilt 389) are not currently offered with natural gas engines.

To potentially fill this power gap, Cummins (outside of CWI, i.e., independent of Westport) has been developing a spark-ignited stoichiometric 15-liter heavy-duty natural gas engine that will target Class 8 heavy-duty long-haul trucks. With financial support from the South Coast AQMD, the California Energy Commission, and Southern California Gas Company, Cummins has established “the fundamental technology configuration” for the new 15-liter natural gas engine for demonstration. The basic design uses multi-point injection, a modified head, modified intake and exhaust manifolds, cooled EGR, charge air cooling, turbo-charger, and three-way catalyst. Originally, Cummins anticipated having this 15-liter heavy-duty natural gas engine ready for on-road testing and demonstration in late 2016, with the timeframe for commercialization at 2019 to 2020.¹⁴⁷ However; in mid-2015 Cummins expressed preference to re-focus this heavy-duty natural gas engine development work on a near-zero-NOx 12-

¹⁴⁷ Richard Carlson, South Coast Air Quality Management District, “Update on the 0.02g NOx Engine Development,” presentation to the California Natural Gas Partnership Steering Committee Meeting, April 21, 2015, taken from the official meeting minutes.

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

liter engine that would target refuse transfer and drayage trucking operations. Thus, further work on the 15-liter product was suspended until further notice. See Section 6.1 for additional details about the 12-liter configuration.

At the lower end of the HDV spectrum, CWI's spark-ignited 6.7-liter CNG engine is expected to soon become commercially available, to expand or open new market opportunities. This engine is based on the Cummins ISB 6.7 that is a successor to the B 5.9 engine found in a wide variety of vehicles including Dodge/Ram diesel trucks.¹⁴⁸ It will provide a very low-emitting option for on-road applications such as school buses. CWI has announced its intentions to commercialize a lower-NOx version of this 6.7-liter CNG engine, with commercialization expected within one year (see Section 6.1).

5.3.4. Growing Partnerships Among Key NGV Industry Players

Increasing involvement of OEMs regarding how heavy-duty NGVs are being built, sold, warranted and serviced provides a clear sign that these vehicles are approaching diesel-like commercial maturity. Major fuel providers are also entering into strategic partnerships. Below are a few of the numerous important alliances recently established to improve the commercial maturity of heavy-duty NGVs and increase their deployment.

- Freightliner has signed a seven-year agreement with Agility Fuel Systems—a leading designer and producer of natural gas fuel storage and delivery systems for HDVs—making Agility the sole provider of natural gas fuel systems for Freightliner NGVs.



Figure 16. Agility's CNG fuel system installed on FCA Transport truck

- Cummins Inc. and Agility have also entered into a strategic partnership. The overarching goal of this partnership is to “deliver a diesel-like experience” to end users, making heavy-duty NGVs “as easy to operate and service as diesel vehicles.” The partnership includes technology development and integration of software and hardware between the natural gas engine (Cummins) and the onboard fuel storage and delivery system (Agility). This will significantly improve performance and uptime of heavy-duty NGVs, which has already become very good. Additionally, Agility and Cummins will integrate their sales, aftermarket support and distribution networks. This will enable North American customers to get their heavy-duty NGVs serviced at authorized Cummins distributor and OEM truck dealer locations,

¹⁴⁸California Energy Commission, “2015 Natural Gas Vehicle Research Roadmap – Draft Review Copy,” prepared by the National Renewable Energy Laboratory, accessed online at <http://www.afdc.energy.gov/pdfs/draft-natural-gas-vehicle-research-roadmap.pdf>

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

where they can also obtain replacement parts. Cummins and Agility plan to use this partnership to accelerate adoption in North America of heavy-duty trucks fueled by natural gas.¹⁴⁹

- Clean Energy has also joined with Agility, to initiate a joint natural gas fuel system sales program designed to help reduce the incremental cost of heavy-duty natural gas trucks. Under the program, Agility and Clean Energy will work with trucking customers and offer fuel systems installed at a substantially reduced cost when there is a natural gas fueling agreement.¹⁵⁰
- Quantum Technologies, another leader in on-board natural gas storage systems, has joined with Gain Fuels to package and offer CNG trucks through existing dealership relationships at pricing options “designed to accelerate the pay-back period for fleets and truck operators desiring to switch from diesel to CNG.”¹⁵¹

5.4. Overview of Life-Cycle Economics

The total cost of ownership for any fleet type includes the costs of buying, operating, and maintaining each vehicle over its full useful life (for on-road HDVs, this is roughly 15 years). Additionally, lifecycle economics should incorporate costs of building, operating and maintaining facilities to refuel and maintain the fleet.

HDV economics tend to be unique for each fleet type, location, fuel and mix of technologies. Currently, there are many unknowns about advanced near-zero and zero-emission HDVs, which makes it challenging to accurately predict their real-world capital expenses (CAP EX) and operational expenses (OP EX). Examples of poorly defined cost parameters include initial capital costs as a function of production and sales volumes; availability of incentives that can offset those costs; fuel and maintenance costs; and secondary costs such as replacing battery packs or specialized fuel tanks. These parameters will largely define comparative lifecycle costs for tomorrow’s heavy-duty goods movement sector. Since many are poorly defined (or unknown), it is challenging to accurately estimate how fast prospective buyers will achieve “payback” on investments.

Section 6.9 uses cost- and performance-related assumptions for three types of heavy-duty ZEVs and NZEVs to compare their costs for deployment and cost effectiveness for achieving emissions reductions. However, an analysis of comparative full lifecycle costs for various types of low- and zero-emission HDVs is beyond the scope of this report. For examples of comprehensive third-party assessments and comparisons, see various recent works by CARB¹⁵² and the National Renewable Energy Laboratory posted at <http://www.nrel.gov/transportation/>. Also see the University of California-Davis Institute of Transportation Studies 2013 report entitled “Analysis of Class 8 Hybrid-Electric Truck Technologies Using

¹⁴⁹ Agility Fuel Systems and Cummins Inc., personal communications to GNA (January 2016) and twin press releases of May 5, 2015 <http://cumminsengines.com/agility-fuel-systems-and-cummins-announce>.

¹⁵⁰ Clean Energy Fuels, Agility Fuel Systems and Clean Energy Announce Joint CNG System Sales Program, press release, February 6, 2015, <https://www.cleanenergyfuels.com/press-room/agility-fuel-systems-clean-energy-announce-joint-cng-fuel-system-sales-program/>.

¹⁵¹ Quantum Technologies, press release, May 6, 2015, <http://www.qtww.com/press/quantum-and-gain-fuels-form-industry-alliance-for-no-money-down-program-for-cng-trucks/>

¹⁵² For example, see CARB’s Technology Assessment series at <http://www.arb.ca.gov/msprog/tech/tech.htm>, and its “Draft Discussion Topics on Costs” (Transit Agency Working Group), <http://www.arb.ca.gov/msprog/bus/wg201601cost.pdf>.

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

Diesel, LNG, Electricity, and Hydrogen, as the fuel for Various Applications,” which is downloadable from the UC-D ITS website.

5.5. Growing Use of Heavy-Duty NGVs to Meet Corporate Sustainability Goals

Life-cycle economics are not likely to drive potential end users toward adoption of heavy-duty NGVs as long as the price of diesel remains exceedingly low (near \$2 per gallon). However, growing confidence in the major environmental benefits of commercially proven heavy-duty NGVs is actively serving as impetus for fleets to make the transition. This is exemplified by the many major American corporations now investing in heavy-duty natural gas trucks as foundations of their sustainability policies. Even with the national average price of diesel at about \$2 per gallon, many large American corporations and cities are transitioning their HDV fleets over to NGVs. They are doing this specifically to reduce air quality and climate-change impacts of their operations. Several key examples are described below.

United Parcel Services - UPS continues to “transform” its worldwide package delivery fleet towards heavy-duty NGVs and other AFV technologies. Under its corporate sustainability initiative, UPS intends to drive its fleet of lower-emitting HDVs “one billion miles” by the end of 2017. For UPS, natural gas has emerged as a viable alternative fuel that meets diverse needs, “especially the demands of the heavy-duty, over-the-road trucks that connect our regional bases.”

“Using RNG could be the solution to our engineering challenge” to use highly abundant, sustainable renewable sources of low-carbon fuels.

— **Steve Leffin, Director, UPS Global Sustainability**

These Class 8 trucks travel an average of 400 to 600 miles per day, and require diesel-equivalent horsepower and torque. According to UPS, heavy-duty NGVs (fueled by both LNG and CNG) “have proven to be the best alternatives to diesel for these trucks, meeting their required range and performance criteria, while burning cleaner than diesel or gasoline.” UPS also reports that CNG performs well in its smaller package-delivery trucks that drive mostly on local routes that average more than 100 miles daily. As of the end of 2014, UPS had deployed more than 1,000 CNG medium-heavy-duty package trucks and 1,297 heavy-heavy-duty tractors operating on LNG or CNG. In March 2016, UPS announced it will add another 380 CNG tractors to its U.S. fleet.¹⁵³



Figure 17. UPS driver filling a CNG package delivery truck.

To support this growing, world-leading fleet of heavy-duty NGVs, UPS has already built 23 LNG and CNG fueling operations across

¹⁵³ United Parcel Services, press release of March 15, 2016, <https://www.pressroom.ups.com/pressroom/ContentDetailsViewer.page?ConceptType=PressReleases&id=1458045961286-597>

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

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. UPS is already using "Redeem" biomethane (RNG) in California, under an agreement with Clean Energy. 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.¹⁵⁴

Ryder Systems – Ryder is a truck leasing and logistics company. It has long been a leader to deploy heavy-duty NGVs for commercial transportation applications. Reportedly, Ryder has amassed "more than 40 million miles of experience" operating heavy-duty NGVs. In late 2015, as part of its corporate sustainability plans, Ryder announced an agreement with Clean Energy to switch all natural gas dispensed at two fueling stations in Southern California over to 100 percent Redeem RNG.¹⁵⁵



Figure 18. Ryder LNG truck at fueling station

Unilever – This large multinational company makes more than 400 brands of products, and transports them nearly one billion miles per year. Unilever has made a corporate sustainability commitment to use lower-emission trucks for transporting its products to market, with a goal to "halve the greenhouse gas impacts of our products by 2020." Noting that goods movement trucking is extremely dependent on "fossil oil," Unilever claims to be "leading the transition from diesel to CNG in North America," and plans to have hundreds of heavy-duty goods movement trucks using CNG or LNG by 2018.¹⁵⁶

Lowe's – This home improvement company has been working with its carriers and environmental partners to reduce GHG emissions and fuel costs, "while promoting responsible transportation practices across the industry." In 2013, Lowe's launched its dedicated fleet of heavy-duty natural gas trucks at its distribution center in Texas. Lowe's, which has partnered with Clean Energy for CNG infrastructure, notes that this "dedicated fleet is among the first serving a major retail distribution center in North America to run solely on natural gas." The corporate goal is to transition Lowe's entire heavy-duty carrier fleet to natural gas by the end of 2017. NFI Industries, which is Lowe's longtime carrier partner, operates a national fleet exceeding 2,000 heavy-duty tractors.¹⁵⁷ NFI, which already operates heavy-duty NGVs in California, Texas and Pennsylvania, recently added 12 CNG tractors for its fleet in Central Florida; these are powered by CWI's 12-liter heavy-duty natural gas engine.¹⁵⁸

¹⁵⁴ United Parcel Services, "2014 Global Sustainability Report," <http://sustainability.ups.com/media/UPS-2014-Corporate-Sustainability-Report.pdf>.

¹⁵⁵ Transport Topics, "Ryder to Sell Clean Energy Fuel's Renewable Natural Gas, October 12, 2015, <http://www.ttnews.com/articles/basetemplate.aspx?storyid=40035>.

¹⁵⁶ Unilever, "Going to market – reducing transport emissions," <https://www.unilever.com/sustainable-living/the-sustainable-living-plan/reducing-environmental-impact/greenhouse-gases/going-to-market-reducing-transport-emissions/>.

¹⁵⁷ Lowe's, Social Responsibility: Transitioning to Natural Gas, <http://responsibility.lowes.com/2014/stories/transitioning-to-natural-gas/>.

¹⁵⁸ JOC.com, NFI boosts natural gas truck fleet, December 24, 2015, http://www.joc.com/international-logistics/logistics-providers/nfi-industries/nfi-boosts-natural-gas-truck-fleet_20151224.html.

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

Ruan Transportation Management Systems – This privately held transportation company maintains a fleet of approximately 100 CNG tractors, of which 42 trucks provide service for an Indiana dairy, Fair Oaks Farms. All of Ruan’s heavy-duty NGVs serving the dairy are fueled by RNG produced at the dairy. Biogas is created from animal waste in an onsite anaerobic digester, upgraded to biomethane, and piped to a station where it is compressed for fueling by the fleet. Ruan serves ten additional shippers using heavy-duty NGVs using fossil natural gas.¹⁵⁹

Frito-Lay – This food-and-beverage company (a division of PepsiCo) operates one of the largest private trucking fleets in the U.S. Frito-Lay has made major commitments to reduce the environmental footprint of its large on-road truck fleet. The company operates hundreds of heavy-duty CNG trucks in its distribution operations in California, Arizona, and other states; this program serves as one major element for Frito-Lay’s corporate sustainability efforts.



Figure 19. Frito-Lay’s fleet of CNG delivery trucks

Anheuser-Busch - This leading American brewing company has already replaced 66 diesel-powered heavy-duty delivery trucks with CNG versions in its Houston fleet and converted its 97-truck St. Louis fleet (managed by J.B. Hunt) over to operate on CNG. Approximately 30 percent of Anheuser-Busch’s heavy-duty truck fleet now operates on natural gas. Anheuser-Busch is also using renewable energy (including landfill gas / biomethane) to displace conventional energy sources for powering its brewery processes.¹⁶⁰

Proctor & Gamble – P&G is one of the world’s largest consumer products companies. It has established a corporate goal to reduce air pollution and climate-change impacts of its large international trucking fleet. P&G has expressed a long-term corporate vision to completely transition renewable energy to power its corporate fleet and facilities. In 2013, P&G announced plans for its transportation carriers to move 20 percent of its American truck loads by heavy-duty NGVs. As part of its 2015 sustainability report, P&G announced that is has



Figure 20. Anheuser-Busch CNG tractor for beer delivery

¹⁵⁹ Ruan, “Natural Gas in the Trucking Industry, July 2015, https://www.ruan.com/filesimages/New%20PDFs/White_paper_CNG_July%202015.pdf

¹⁶⁰ Anheuser-Busch, “From Seed to Sip: We’re Conserving Every Step, <http://anheuser-busch.com/index.php/our-responsibility/environment-our-earth-our-natural-resources/energy/>.

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

achieved this goal, and “more than tripled” its active CNG lanes since 2014. This represents more than 14 million truck miles for P&G that are powered by heavy-duty natural gas engines. P&G has executed carrier contracts that will enable moving 25 percent of its North America truck transportation to natural gas by the end of 2016.¹⁶¹

The City of Los Angeles – The City has adopted a Clean Fuel Policy, and today owns and maintains more than 5,000 alternative fuel vehicles (AFVs). The largest components of this AFV fleets are NGVs, including heavy-duty NGVs that operate on both CNG and LNG. For example, the City operates hundreds of solid waste trucks and street sweepers on natural gas. Los Angeles is committed to increase its fleet of AFVs by an average of 15 percent each year.¹⁶²

5.6. Market Projections for Heavy-Duty NGVs and Fueling Stations

Over the last decade, the market for heavy-duty NGVs—and the volumes of traditional and renewable fuels they consume—have expanded significantly in many U.S. regions. This is reflected by the above-noted end user examples, and by fuel use statistics. For example, California’s natural gas use for transportation doubled between 2003 and 2013, and NGV use in Texas has increased by more than 300 percent over the last three years. As noted, a ‘sweet spot’ for NGV adoption has been return-to-base fleet operations such as buses and refuse trucks, as well as heavy-duty trucks with high annual mileage. Growth is expected to continue in key states like California; the State’s Integrated Energy Policy Report predicts a six-fold increase between 2012 and 2020.¹⁶³

The actual growth of heavy-duty NGVs in the U.S., and the corresponding volumes of natural gas they will consume, will be dictated by various factors; many of these are difficult to predict. Most market projections assume a technology will follow an S-curve trajectory, increasing slowly in early years, and then rapidly increasing in growth once a critical threshold is reached. This threshold is dependent on a number of factors, but it is often estimated to occur at about five to 10 percent of market penetration. NGVs are currently at approximately three percent of new HHDV sales (an estimated 8,000 heavy-duty NGV units sold in 2014, out of a total HHDV market of 225,000 units).

A report by Citi GPS estimates that the displacement of oil by natural gas could reach five percent (1.3 to 1.8 million barrels per day) by the year 2020¹⁶⁴. At this point, the manufacturers of engine components and fueling infrastructure will be able to reach further economies of scale.¹⁶⁵

¹⁶¹ Proctor & Gamble, 2015 Sustainability Report, http://us.pg.com/-/media/PGCOMUS/Documents/PDF/Sustainability_PDF/sustainability_reports/PG2015SustainabilityReport.pdf?la=en-US&v=1-201512231810

¹⁶² The City of Los Angeles, “Alternative Fuel Vehicles,” <http://www.environmentla.org/programs/altfuelvehicles.htm>.

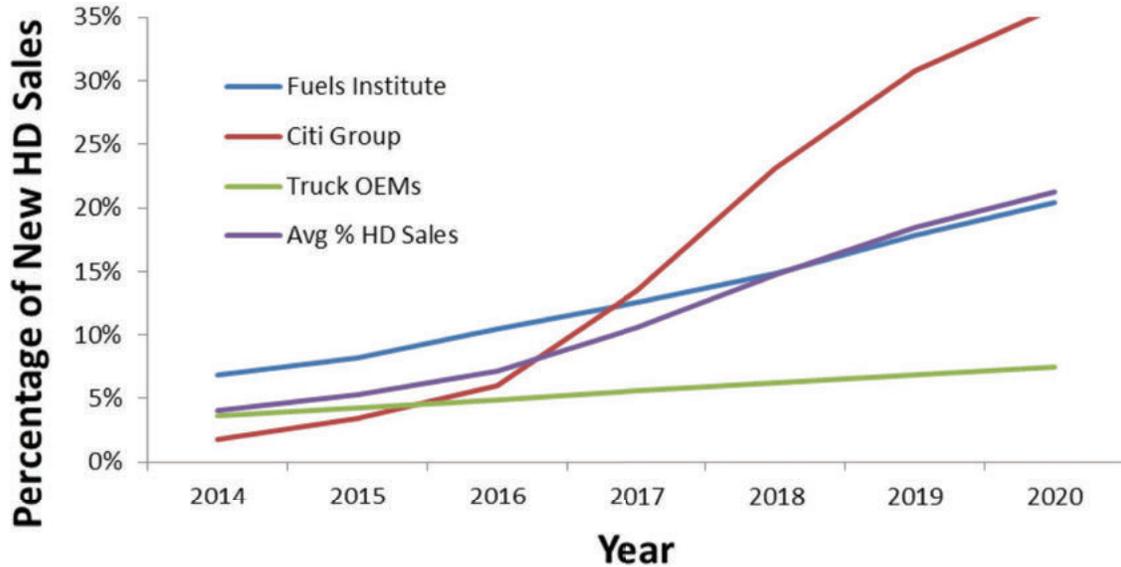
¹⁶³ California Energy Commission, “FY 2016-17 Natural Gas Research Initiatives, presentation to Stakeholders Workshop, January 25, 2016.

¹⁶⁴ Energy 2020: Trucks Trains & Automobiles. Citi GPS: Global Perspectives & Solutions. June 2013. p 11.

¹⁶⁵ *Ibid.* p 15.

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

Figure 21 combines market penetration rate projections from several sources to illustrate the range of expectations for CNG sales in the HHDV market, from 8 percent to 35 percent of new sales by 2020. An average of the individual projections is also provided by averaging the implied HDV sales associated with



References / notes:

- 1) Fuels Institute: "Tomorrow's Vehicles, What will we drive in 2023". Report by Navigant Research, 2013
- 2) Citi Group: "Energy 2020: Trucks Trains & Automobiles. Citi GPS: Global Perspectives & Solutions", 2013
- 3) Truck OEMs: statements by Freightliner, Kenworth and others at ACT Expo 2014 panel discussions, etc.
- 4) Avg % HD Sales: Created by averaging the implied sales from each individual projection.

Figure 21. Various market projections (and average) for heavy-duty CNG vehicles

each projection.

It is important to note that these projections were created prior to the sharp drop in oil prices, which began in 2014 and continues in 2016. Taking this and other market dynamics into account, NGV America recently stated the following about its near- and longer-term sales projections for heavy-duty NGVs (emphasis added by authors):

The availability of the Cummins Westport (CWI) ISX12 G 11.9L engine led to significant sales in a variety of platforms from most of the major truck OEMs. Unit sales showed a healthy increase over 2013, but some analysts had assumed huge early growth that was not attainable. A very strong freight market led many fleets to focus on deploying trucks as quickly as possible to maximize revenue. Combined with longer delivery times and higher incremental costs for natural gas trucks, the pent up demand in trucking resulted

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

*in many fleets deferring their first orders for natural gas units. Low oil prices possibly created further purchase decision delays, but expectations are that as oil rebounds, orders will be placed.*¹⁶⁶

In addition to fuel pricing, expansion of heavy-duty NGV deployments in the U.S. is closely linked to fueling infrastructure. End user fleets must have convenient access to sufficient volumes of CNG or LNG. For companies with large fuel demand and the ability to afford initial capital investments, on-site natural gas fueling infrastructure has been a key to maximizing fuel cost savings. While recent growth in natural gas fueling stations has been quite strong, today there are only about 1,630 CNG stations and 122 LNG stations operating in the U.S.¹⁶⁷ A 2013 Morgan Stanley study estimated that it would take about 50,000 CNG and 3,000 LNG fueling stations for the U.S. to experience a “tipping point” where large-scale adoption of NGVs takes place; this constitutes approximately 30 percent of America’s existing gasoline and diesel station network. The estimated needed infrastructure investments for the CNG portion would total about \$50 billion.¹⁶⁸

¹⁶⁶ NGVAmerica, “2014 NGV Production and Sales Report, 2015,” <https://www.ngvamerica.org/pdfs/2014%20NGV%20Production%20and%20Sales%20Report.pdf>.

¹⁶⁷ NGVAmerica, “Stations,” <https://www.ngvamerica.org/stations/>.

¹⁶⁸ Morgan Stanley, “Natural Gas as a Transportation Fuel, Energy Market Wild Card.” April 16, 2013.

6. Game Changer: Near-Zero-Emission Heavy-Duty NGVs

The world's first ultra-low-NO_x, low-GHG heavy-duty engine has been certified by EPA and CARB, and is ready today to power a wide array of in-use and new HDVs. Other heavy-duty engines using the same ultra-low-NO_x technology are expected to soon follow. Combined with increasing use of RNG as a drop-in replacement for conventional natural gas, a transformation has begun for America's high-impact HDV transportation sector.

6.1. Low-NO_x Certification Status and Commercialization Plans

In mid-2015, Cummins Westport Inc. (CWI) completed development and certification of the world's first heavy-duty engine that emits NO_x levels so low they are considered near-zero. This 9-liter CWI ISL G "NZ" engine has been certified by CARB at 90 percent below the existing heavy-duty engine standard of 0.02 g/bhp-hr NO_x.¹⁶⁹ CWI has publicly announced it will commercially deploy the ISL G NZ engine in Q2 of 2016 for transit bus, refuse, school bus, and medium-duty truck applications (ratings from 250 to 320 horsepower).

By 2018, CWI anticipates commercializing two more heavy-duty natural gas engines that will emit NO_x well below the existing federal standard. Figure 22 provides the anticipated timeline for all three low-NO_x engines. In 2016, CWI plans to certify its 7-liter ISB 6.7G engine to 0.10 g/bhp-hr. This 50 percent NO_x reduction (relative to the current federal standard) will qualify the engine in California as a Low-NO_x engine. Limited production is expected to begin in Q2 2016. CWI does not currently have plans to

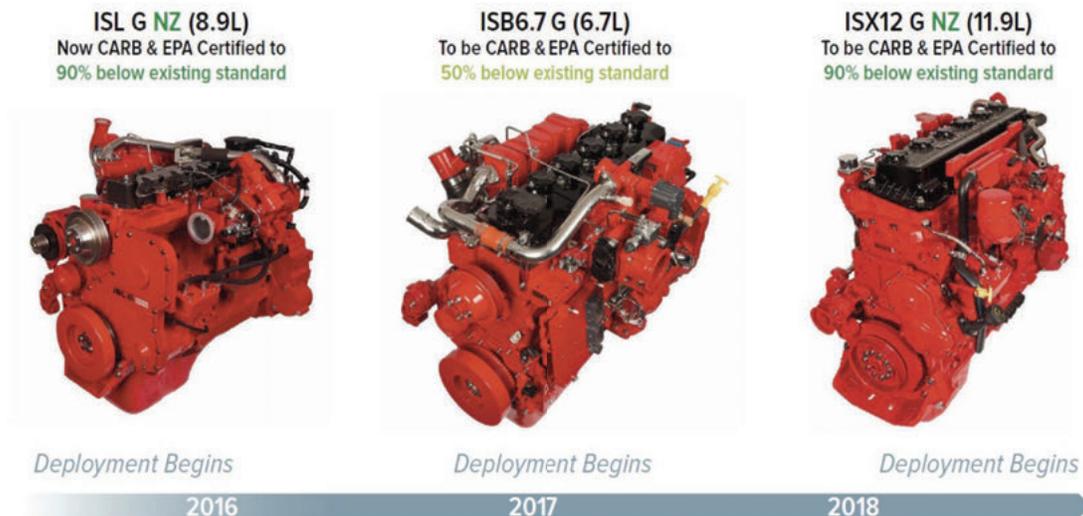


Figure 22. CWI heavy-duty ultra-low-NO_x engines: anticipated timeline for certification and deployment

¹⁶⁹ The term "near-zero-emission" for heavy-duty engines has not yet been formally defined by ARB or EPA. The general working definition is that such engines must emit at least 90 percent lower NO_x than the current NO_x standard for heavy-duty engines. This is the bottom tier of CARB's "optional low-NO_x standards" adopted in 2013.

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

certify this engine down to the “NZ” level of 0.02 g/bhp-hr. However, the far-more-impactful engine is CWI’s 11.9 liter ISX12 G natural gas engine. CWI will begin development of an NZ version in mid-2017, and plans to commercialize this versatile engine for HHDT applications beginning with the 2018 model year.¹⁷⁰

These three CWI low-NOx engines can collectively power a full range of on-road HDV applications that already offer heavy-duty natural gas engines. CWI’s 8.9-liter and 11.9-liter natural gas engines are now offered in many types of HDVs (left side of Figure 23). Its 6.7-liter natural gas engine will work in many smaller trucking applications that currently offer natural gas models (right side).

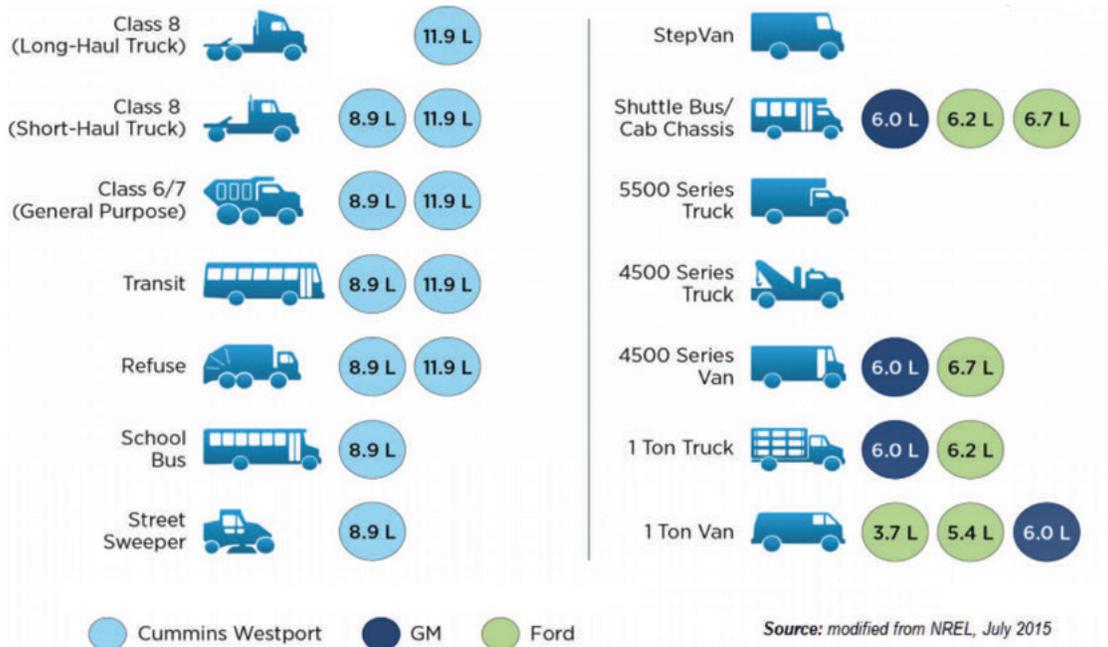
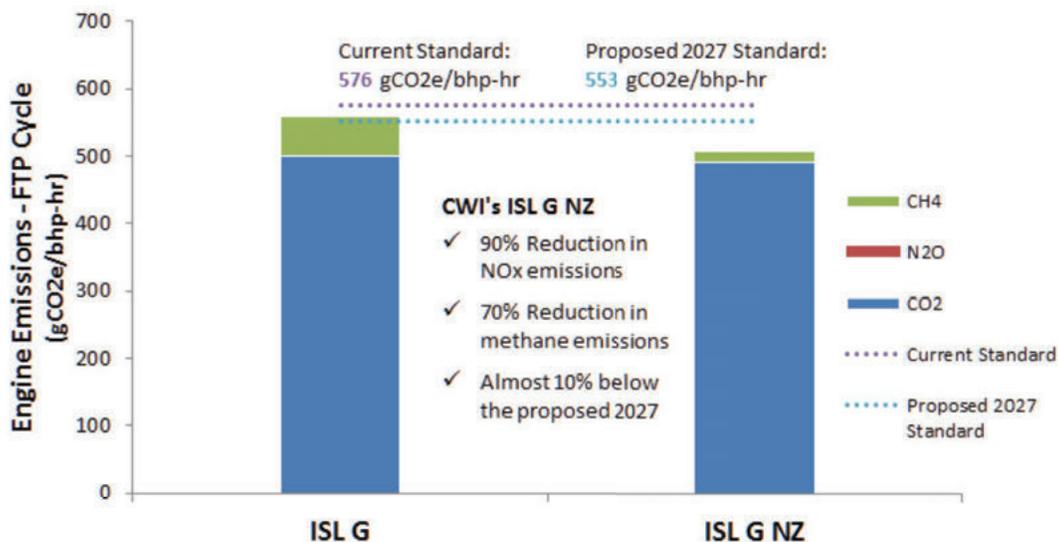


Figure 23. Existing NGV applications and engine sizes that can utilize ultra-low-NOx NG engines

6.2. Engine Efficiency and GHG Emissions

In addition to producing 90 percent lower NO_x emissions compared to the cleanest heavy-duty diesel engines, CWI’s ISL G NZ engine incorporates new technology for higher efficiency and reduced GHG emissions. As Figure 24 shows, compared to the original ISL G natural gas engine, the ISL G NZ version has lower “CO₂e” emissions; it provides a 70 percent reduction in methane, and is nearly 10 percent below the proposed federal GHG standard (in CO₂e) for 2027.

¹⁷⁰ Cummins Westport Inc., personal communication to GNA, February 2016.



Source: US EPA GHG Certification data for 2015 ISL G and ISL G NZ engines for MHHD service class

Figure 24. Comparison of GHG emissions (CO₂e) for CWI ISL-G and ISL-G NZ engines

The key to the ISL G NZ’s 70 percent methane reduction is CWI’s closed crankcase system, which captures and combusts engine “blowby” methane emissions. Reducing such “downstream” methane emissions from heavy-duty NGVs provides very important progress in lowering their WTW GHG emissions footprint, because (as previously described in Section 3.3) methane is a powerful GHG and short-lived climate pollutant.

Similarly, it is important to continue improving the fuel efficiency of heavy-duty NGVs. Heavy-duty compression-ignition (diesel engines) currently achieve fuel efficiency that is about 10 percent higher than spark-ignited heavy-duty engines (gasoline or natural gas). Improvements to the fuel efficiency of heavy-duty natural gas engines (such as the advancements underway by CWI) will further reduce downstream GHG emissions. This will also save additional fuel costs for end users. (NOTE: Section 13 – Appendix 3 discusses important progress that is being made to reduce “upstream” emissions of methane.)

6.3. Comparative NO_x Emission Levels from Other On-Road HDV Engines

It is useful to put in perspective just how low-emitting modern heavy-duty engines have become, and then consider the ultra-low NO_x level that has now been accomplished using natural gas. Figure 25 plots the NO_x and PM levels achieved by various heavy-duty engines during recent certification testing. These include various diesel engines, the CWI ISL G engine, and the CWI ISL G NZ engine. This graph shows that in general, heavy-duty engines are making excellent progress to reduce NO_x emissions, while also driving PM emissions to zero levels. However, only the ISL G NZ natural gas engine is converging on near-zero NO_x levels.

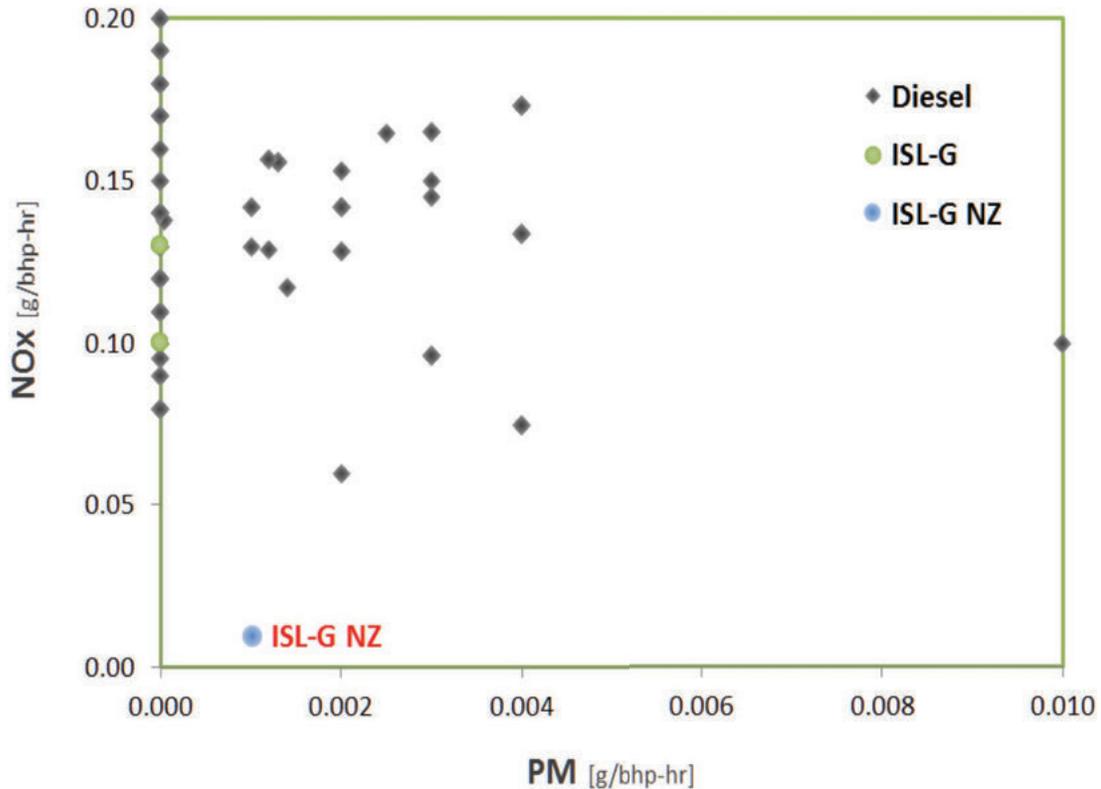


Figure 25. Comparative NOx and PM test levels for recently certified heavy-duty engines

As described in the next section, NOx emissions at this level are as low as, or possibly lower than, NOx emissions from generating electricity to recharge a comparable heavy-duty BEV.

6.4. Comparative NOx Emission Levels from Heavy-Duty BEVs

6.4.1. Background and Introduction

The most-comprehensive, meaningful way to compare potential air quality and GHG-reduction benefits of transportation fuel-technology pathways is to assess their full-fuel-cycle emissions. Using a WTW type of analysis, this process provides a complete energy and emissions comparison by accounting for “upstream” and “downstream” emissions for each individual pathway. Upstream fuel-pathway emissions take into account fuel feedstock recovery, fuel production, fuel delivery to fuel stations, and fuel transfer into the vehicle. Downstream emissions (if any) come directly from the vehicle; for diesel or natural gas HDVs, these include crankcase and tailpipe emissions. The total WTW emissions of a given HDV type are a function of many parameters; each technology-fuel pathway is unique.

Lacking any source of fuel combustion, neither heavy-duty BEVs nor FCVs emit downstream (direct) NOx or GHGs. However, both of these ZEV pathways can produce substantial upstream emissions. In this

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

subsection, we provide a preliminary assessment of the estimated NO_x emissions from heavy-duty battery-electric ZEVs that are associated with generation of electricity to charge them. The objective is to roughly compare how much NO_x is caused by charging a heavy-duty BEV versus the amount emitted at the tailpipe by a comparable heavy-duty NZEV using the newly certified CWI ISL G NZ natural gas engine.

As described below, making such a comparison can be complex. For this analysis, GNA employed a methodology that has been vetted with a leading air quality agency and the electric power industry. The following provides a summary of GNA's methodology and preliminary findings. Section 11 (Appendix 1) provides full details about the methodology and assumptions to derive these preliminary findings.

Note: CARB is in the process of “developing WTW emission factors for important heavy duty sectors,” including on-road trucks. Presumably, this will include emission factors for NO_x in addition to GHGs. On a preliminary basis, CARB's analysis “suggests substantial reductions in WTW emission factors are possible using advanced diesel and natural gas engines and vehicles, and that ZEVs where feasible can provide even greater reductions than advanced conventional technologies. For all fuel-technology pathways, the greatest reduction in WTW emission factors can be achieved through the use of renewable electricity.”¹⁷¹

6.4.2. Limitations and Caveats

The term “NZEV” has not yet been formally defined by either EPA or CARB. Unofficially, it has become synonymous with meeting CARB's bottom-tier optional low-NO_x standard of 0.02 g/bhp-hr. To the authors' knowledge, no publicly available analysis has formally equated full-fuel-cycle NO_x emissions from heavy-duty ZEV technology (BEV or FCV) to any heavy-duty engine emissions standard.

The analysis that follows provides a preliminary comparison of the upstream NO_x emissions from a heavy-duty BEV to the tailpipe NO_x emissions of a heavy-duty NGV powered by the CWI ISL G NZ engine certified to the NO_x level of 0.02 g/bhp-hr. Conducting such an analysis entails complex, regionally-specific parameters, for which the authors have attempted to account. GNA worked with appropriate technical staff at air quality agencies to draft the following analysis. To account for different views and perspectives, meetings were held with representatives from the Electric Power Research Institute (EPRI), as further presented in this section and Section 11 (Appendix 1: Details of Power Plant NO_x Equivalency Analysis). Note: a recommendation of this white paper is that CARB and EPA conduct a more rigorous, fully reviewed analysis, while working together with stakeholders of heavy-duty NGVs, BEVs and FCVs (see Section 10).

It is also worth noting that this analysis is based on the latest power plant emissions and generation data available through EPA's eGRID model. The data in this model represent emissions and power generation from 2012. In the intervening years, emissions regulations have resulted in the shuttering or retrofitting

¹⁷¹ California Air Resources Board, “Draft Heavy-Duty Technology and Fuels Assessment: Overview,” April 2015, http://www.arb.ca.gov/msprog/tech/techreport/ta_overview_v_4_3_2015_final_pdf.pdf.

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

of some high emitting power plants. Additionally, other power plants (notably, the San Onofre Nuclear Generating Station in California) have also been shut down, creating some differences in the average grid generating mix and associated emissions between 2012 and present day.

6.4.3. Methodology and Findings

Quantifying WTW NO_x emissions of BEVs is challenging, due to the complexity and size of the U.S. electrical grid. America's grid is composed of more than 7,200 electrical generators, including combustion-based systems such as coal, natural gas, fuel oil, and biomass; as well as non-combustion systems including wind, solar, nuclear, and hydro. These generators are dispatched to the grid under the direction of authorities that have responsibility for balancing power generation and demand over a particular service area. Each service area has developed over time based on the needs of customers and the particulars of the electrical grid in a given area. Consequently, these regions have very little relation to governmental boundaries such as counties or states.

Further, a great deal of electrical power exchange occurs between balancing authorities, making it difficult or impossible to ascertain exactly how much power supplied to a particular customer is coming from a particular generator, or mix of generators. Therefore, when estimating the mix of generation supplying a geographic area, generators are typically grouped into regions that are defined with the goal of minimizing the net import or export of power in the region; creating a somewhat self-contained region in terms of power generation and demand.

As fully described in Section 11 (Appendix 1) GNA used EPA's Emissions & Generation Resource Integrated Database (eGRID) to evaluate the NO_x emissions from electricity generation in 15 different U.S. sub-regions. Each sub-region is defined by the Electric Power Research Institute and based on its newly created Regional Economy, Greenhouse Gas, and Energy (REGEN) model. These sub-regions represent groupings of states intended to approximately match load and generation demands amongst power balancing authorities while retaining relevance to political boundaries and market behaviors.

GNA then examined the NO_x emission levels from an engine certified to the 0.02 g/bhp-hr standard and compared them to NO_x emissions from power plants supplying the average grid mix in various regions around the country.

This analysis indicates that HDVs powered by near-zero-emission engines (certified to 0.02 g/bhp-hr) have tailpipe NO_x emissions that are comparable to—or possibly lower than—the amount of NO_x emitted to produce electricity used to charge similar heavy-duty BEVs. This is due to the relatively high NO_x emissions rates from a portion of the existing power plant mix—particularly in regions that rely heavily on coal-based generation. See Section 13 (Appendix 1) for additional details.

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

The analysis also considered certain potential 2030 scenarios under which grid mixes in these regions will become cleaner, such as the federal Clean Power Plan¹⁷² and California's Renewable Portfolio Standard. Even under a 30 percent renewable generation portfolio, it was found that heavy-duty engines certified to 0.02 g/bhp-hr NO_x (i.e., CWI's natural gas ISL G NZ) compare very favorably to heavy-duty BEVs for extremely low NO_x emissions.

6.5. Growing Production and Use of Ultra-Low-GHG RNG for Transportation

The term "biogas" refers to gaseous fuel (especially methane) produced by the fermentation of organic matter (agricultural waste, manure, municipal waste, plant material, sewage, green waste, food waste, etc.). When biogas is cleaned up to "pipeline" and/or "NGV fuel specifications," it becomes RNG and can be used as a "drop-in" fuel for heavy-duty NGVs.

The following subsections provide a brief overview about America's increasing production and end use of RNG as a very-low-GHG transportation fuel. Section 7 provides a detailed look at RNG production, supply and cost issues. It further describes the opportunities and challenges in California and across the U.S. associated with realizing the full potential of RNG as an ultra-low GHG fuel for on-road HDV applications.

6.5.1. RNG Production and Supply for Petroleum Displacement

All states can produce RNG, and national efforts are underway to develop this potential. The National Renewable Energy Laboratory (NREL) has found that landfills, wastewater treatment, animal waste, and "industrial, institutional, and commercial" (IIC) sources in the U.S. could annually generate biogas equivalent to approximately 3.1 billion gallons of diesel fuel¹⁷³; this is about 11 percent of the current national diesel demand for HHDVs, and about 8 percent of the demand for the entire on-road HDV sector.¹⁷⁴ NREL noted that this does not account for biogas generation from lignocellulosic feedstocks such as forestry and crop residue or purpose-grown energy crops. A 2012 report by the National Petroleum Council reviewed current literature and estimated the "practical RNG potential" in the U.S. to be much greater, at approximately 35 billion diesel gallon equivalents (DGE) per year.¹⁷⁵ The International Council on Clean Transportation prepared a report in early 2015 entitled "Potential Low-Carbon Fuel Supply to the Pacific Coast Region of North America." The study concluded the following:

Available low-carbon fuels could grow to replace up to 400,000 barrels worth of gasoline and diesel use per day by 2030, representing a factor of three increase from today and a quarter of the Pacific Coast region's road transportation energy demand. First-generation biofuels (e.g.,

¹⁷²The recent U.S. Supreme Court decision to halt enforcement of the national Clean Power Plan interjects new uncertainty regarding the Obama administration's goal to achieve 30 percent renewable energy generation by the 2030 timeframe.

¹⁷³ National Renewable Energy Laboratory (NREL), *Biogas Potential in the United States*. Available at: <http://www.nrel.gov/docs/fy14osti/60178.pdf>

¹⁷⁴ U.S. Energy Information Administration, Monthly Energy Review, September 2015, <http://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf>

¹⁷⁵ National Petroleum Council, Renewable Natural Gas for Transportation: An Overview of the Feedstock Capacity, Economics, and GHG Reduction Benefits of RNG as a Low-Carbon Fuel, Topic Paper #22, August 2012.

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

sugarcane ethanol), second-generation biofuels, advanced cellulosic and drop-in biofuels, renewable and fossil natural gas, electricity in plug-in electric vehicles, and hydrogen in fuel cell vehicles are viable alternative fuels with the potential for substantially increased deployment in the 2020-2030 timeframe. The findings from this analysis indicate that the deployment of these alternative fuels could result in the replacement of 290-410 thousand barrels of oil equivalent per day of petroleum-based fuels in 2030.¹⁷⁶

In its 2015 draft report, the California Energy Commission (CEC) noted that there is “high” potential for in-state production of RNG for use in transportation applications.¹⁷⁷ There are a number of other studies and reviews that estimate U.S. and/or California potentials (technical and/or economic) to produce HDV fuel from biomass; these include

- The American Gas Foundation “Biogas “Potential” study (2011)¹⁷⁸
- The U.S. DOE’s “Billion Ton Update” (2011)¹⁷⁹
- Ongoing studies and assessments by the University of California, Berkeley¹⁸⁰

Section 7.6 provides additional details about RNG production and supply potentials. This includes discussion about the distinction between *technically available* organic waste streams to product RNG, versus what will be *economically realistic* to capture and use for that purpose.

¹⁷⁶ International Council on Clean Transportation prepared a report in early 2015 entitled “Potential Low-Carbon Fuel Supply to the Pacific Coast Region of North America,” January 2015, http://steps.ucdavis.edu/files/09-11-2015-PacificCoastRegionLCF_Jan2015.pdf.

¹⁷⁷ California Energy Commission, “Draft 2016-2017 Investment Plan for the Alternative and Renewable Fuel and Vehicle Technology Program,” October 2015, <http://www.energy.ca.gov/2015publications/CEC-600-2015-014/CEC-600-2015-014-SD.pdf>.

¹⁷⁸ American Gas Foundation, “The Potential for Renewable Gas: Biogas Derived from Biomass Feedstocks and Upgraded to Pipeline Quality,” September 2011.

¹⁷⁹ U.S. Department of Energy, “U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry,” August 2011.

¹⁸⁰ See for example Williams, R.B., B.M. Jenkins and S. Kaffka (California Biomass Collaborative), An Assessment of Biomass Resources in California, 2012 – Draft. Contractor Report to the California Energy Commission. PIER Contract 500-11-020.

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

6.5.2. Current RNG Use as a Heavy-Duty Transportation Fuel

For both “fossil” and renewable gas, California leads the U.S. in using natural gas as a transportation fuel. In 2014, fossil gas and RNG collectively displaced about 150 million gallons of diesel in California’s on-road HDV sector; this was roughly 4.3 percent of the state’s annual diesel use.¹⁸¹ The RNG percentage of this continues to increase (see below) as additional RNG production is brought online and heavy-duty natural gas fleets are increasing their purchase and use of this ultra-low carbon fuel. For



Figure 26. Santa Monica’s transit fleet now operates entirely on RNG (liquefied biomethane)

example, over the last three months of 2015, 100 percent of the NGV fuel provided in California by Clean Energy Fuels at its California-based retail stations was RNG, sold under its Redeem™ brand. Clean Energy sold more than 50 million DGE of Redeem during 2015, of which about 90 percent was sold in California.¹⁸² UPS fueling stations in Sacramento, Fresno and Los Angeles are now pumping landfill-derived RNG. Ryder announced in 2015 that it will use 100 percent RNG at certain stations in California.¹⁸³ CR&R Waste is already using pipeline-delivered RNG and will soon be producing waste-derived biomethane to fuel its fleet of heavy-duty refuse trucks domiciled in Perris, California. The City of Santa Monica’s Big Blue Bus transit operation has switched its entire natural gas bus fleet to operate on 100 percent RNG.¹⁸⁴

This growing volume of RNG used by California’s heavy-duty NGV fleet is reflected in natural gas usage reported under California’s Low Carbon Fuel Standard (LCFS). The black line in Figure 27 shows the trend for volumes of total natural gas fuel reported under the LCFS, from its inception through Q4 of 2015. The blue bars indicate the growing percentage of RNG that is being used in lieu of fossil natural gas to generate LCFS credits. In Q4 of 2015, **57 percent** (19.4 million DGE) of the natural gas reported under

¹⁸¹ California Energy Commission, “Natural Gas Consumption in Vehicle Applications from 6 Sources,” graph dated June 24, 2015, obtained from the California Natural Gas Vehicle Coalition.

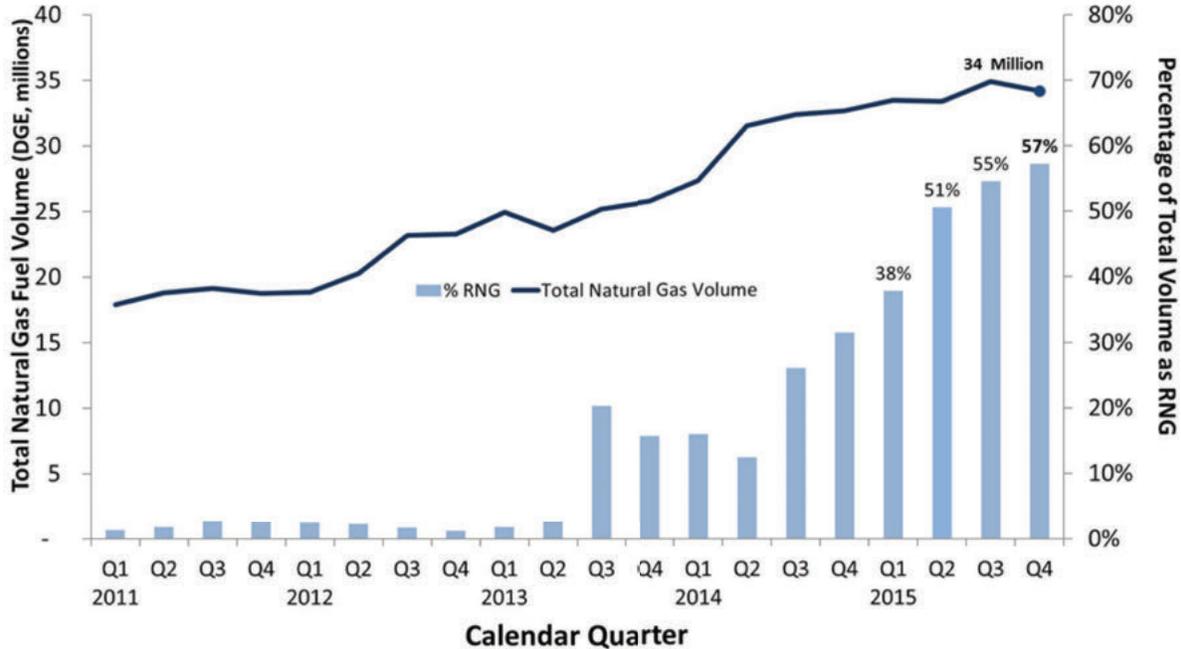
¹⁸² Clean Energy Fuels, Harrison Clay personal communication to GNA, December 10, 2015.

¹⁸³ Fleets and Fuels, “Clean Energy RNG Fuel for Ryder Trucks,” <http://www.fleetsandfuels.com/tag/redeem/>.

¹⁸⁴ Personal communications from Clean Energy to GNA, and “Fleets and Fuels” articles prepared by GNA.

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

the LCFS was RNG. This is a major achievement for the use of RNG in California’s LCFS. The trend for future reporting quarters is difficult to predict, but it is expected that there will be increasing percentages of RNG reported under the LCFS as the program continues through 2020.¹⁸⁵ Additionally, if CARB sets an ambitious post-2020 carbon reduction goal under the LCFS program, this could significantly increase the demand for ultra-low CI fuels. Notably, a recent CEC analysis indicates that the volumes of natural gas (including RNG) that are reported in the LCFS may underestimate California’s use of natural gas as a transportation fuel by about 29 percent.¹⁸⁶



Source: ARB LCFS Quarterly Data. Available at http://www.arb.ca.gov/fuels/lcfs/dashboard/quarterlysummary/media_request_041516.xlsx

Figure 27. Natural gas / RNG volumes generating credits for CA LCFS, 2011 to present

Outside of California, heavy-duty NGV fleet managers are becoming more aware of RNG, and some are initiating efforts to utilize 100 percent RNG, or blend it into their natural gas fuel mix. For example, United Parcel Services (UPS) announced it will use RNG to fuel “upwards of 140 heavy duty trucks” in Tennessee and Mississippi, and more recently has also announced an additional commitment to utilize 500,000 DGE of Redeem RNG per year in its Texas operations to fuel an additional 150 LNG-powered tractor trailers. UPS indicates that RNG is “a critical part of our strategy to expand fuel sources and minimize environmental impact associated with growing customer demand.”¹⁸⁷ Fair Oaks Dairy in Indiana operates 42 heavy-duty milk trucks powered by Cummins natural gas engines burning

¹⁸⁵ California’s LCFS is voluntary for natural gas fuel suppliers. All suppliers may not be aware of the financial opportunity associated with credit generation, or they may choose not to report to the LCFS. Consequently, the precise current to future RNG percentage of statewide natural gas used in transportation is probably unknown, and different than what is reflected in CARB’s LCFS reports.

¹⁸⁶ California Energy Commission, “Natural Gas Consumption in Vehicle Applications from 6 Sources,” graph dated June 24, 2015, obtained from the California Natural Gas Vehicle Coalition.

¹⁸⁷ Fleets and Fuels, “UPS Biomethane in Memphis & Jackson,” December 21, 2015.

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

renewable CNG, which it produces onsite from cow manure. The dairy reports that each truck travels “an astounding” 270,000 miles per year on RNG.¹⁸⁸ Kroger has also recently begun to fuel its LNG trucks operating in Oregon with Redeem RNG.

While much progress is underway in California and across the U.S., there are many barriers that must be overcome to unlock the full potential for RNG as a major HDV transportation fuel. One challenge will be to ensure that sufficient volumes of RNG are available for transportation markets, given that there will be competition for its use in stationary power generation and other uses. One dynamic is that using RNG to fuel HDVs is generally considered to be a “higher-value market” compared to power generation and other potential uses.¹⁸⁹ Section 7 provides additional discussion about the production, supply and cost of RNG.

6.6. Continuity of Progress and Avoidance of Stranded Investments

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*¹⁹⁰ to purchase NGVs, build fueling infrastructure, upgrade maintenance facilities, train personnel and otherwise work to expand this still-developing market (see examples in Section 3.6). Invested public funds such as those that help end users “buy down” the incremental costs of NGVs have strongly contributed to local and regional economies.¹⁹¹

Today, many different manufacturers 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 very large capital and resources to develop and offer NGV products. As this happens, mainstream OEMs are transitioning to Tier 1 supplier relationships with fuel system providers such as Agility, Momentum and Quantum. Concurrently, these fuel system providers are entering into long-term strategic partnerships with, and receiving direct equity investments from, OEMs such as Freightliner, Cummins and others. 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 and overall efficiency.

As the availability of OEM NGV product has continued to expand, so too has the build-out of natural gas refueling infrastructure throughout North America. Several key U.S. fueling corridors have been developed to enable inter-regional use of heavy-duty NGVs. Specially equipped CNG and LNG stations have been built across the country to serve an estimated 65,000 heavy-duty NGVs. This station count is steadily growing, as fuel providers such as Clean Energy Fuels, Love’s Travel Stops (which recently purchased Trillium CNG), TruStar Energy, Questar, U.S. Gain and numerous others continue to make

¹⁸⁸ Fortune, “Big Agriculture Gets Its Sh*t Together,” <http://fortune.com/fair-oaks-dairy-manure-fuel-farming/>

¹⁸⁹ See for example “Natural Gas Will Challenge Oils Monopoly as a Transportation Fuel, IHS Study Says,” news release, June 3, 2015, <http://press.ihs.com/press-release/energy-power-media/natural-gas-will-challenge-oils-monopoly-transportation-fuel-ihs-st>.

¹⁹⁰ This is GNA’s rough estimate applying extensive industry knowledge.

¹⁹¹ See for example Florida Department of Agriculture and Consumer Services, “FY 2014-2015 Natural Gas Vehicle Rebate Annual Assessment,” file:///C:/Users/jon.leonard/Downloads/Media-Files-Energy-Files2-NGV+Rebate+Assessment+FINAL.pdf

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

very large investments in America's natural gas fuel infrastructure. Shell has also entered the market, reportedly investing \$300 million¹⁹² to build natural gas refueling infrastructure throughout the U.S. and Canada. Shell has now opened natural gas fueling stations in states such as Texas and Louisiana.¹⁹³

In aggregate, this alignment 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 consistent public policy, commitment and public sector investment in this market—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.

This accomplishment is unique in the American transportation sector. Only natural gas has reached—or even come close to reaching—this “critical mass” of investments, product offerings, fueling station networks, training programs, incentive offerings, stakeholders, and vehicle deployments. Collectively, this culminates today with natural gas being able to solidly compete with diesel as a mainstream HDV fuel, and displace hundreds of millions of diesel gallons, even as the price of crude oil drops below \$30 per barrel. No mainstream heavy-duty OEMs have announced plans to commercialize any other type of heavy-duty 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. No mainstream transportation fuel providers have announced commercialization plans to widely dispense any other type of heavy-duty alternative fuel.

As noted throughout this report, an expedited transformation is needed for America's heavy-duty transportation sector. Game changing low-NOx heavy-duty natural gas engine technology, combined with the use of drop-in RNG in progressively higher volumes, is the only technology-fuel pathway that is positioned to enable such a transformation.

6.7. Ability to Maintain Regional Integration and Connectivity

In fact, this transformation has already begun, and it will proceed further without the need to disrupt continuity and strand assets that were systematically built over two decades, using billions of dollars from private and public funds. A major advantage provided by near-zero-emission HDVs powered by RNG is that these ultra-low-emitting vehicles can immediately meet challenging goods movement duty cycles and use logistics (range, performance on steep grades, fast refueling time, etc.). Moreover, their use will not be region-specific or severely limited to small special niche applications. For example, as noted in the quotes below, high-use trucking corridors in California's San Joaquin Valley require heavy-duty trucks that can travel long distances between fueling stops, and climb steep grades pulling full loads at 80,000 pounds. Heavy-duty NGVs therefore help ensure network continuity and connectivity across geographic regions and political jurisdictions, as heavy-duty regional and long-haul trucking fleets transition to the cleanest commercially available fuel-technology platforms.

¹⁹² *Forbes*, “Shell Investing \$300 M to Fuel LNG-Powered Trucks,” June 13, 2012, <http://www.forbes.com/sites/christopherhelman/2012/06/13/shell-investing-300m-to-fuel-Ing-powered-trucks/#2ad5cf451552>.

¹⁹³ Shell Global, “Shell Opens LNG Lanes at Two Additional Truck Fueling Stations in the US,” press release, June 4, 2015, <http://www.shell.com/energy-and-innovation/natural-gas/Ing-for-transport/news-and-media-releases/shell-opens-Ing-lanes.html>.

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

“Truck technologies must be capable of meeting challenges posed by long distances and mountain ranges characteristic of the Valley.”

Near-zero emissions natural gas truck technology (is) vital to addressing the Valley’s needs for attaining federal (ozone) standards.”

—San Joaquin Valley Air Pollution Control District, May 2015

6.8. Role in Lowering the Carbon Intensity of High-Impact HDV Sectors

Transforming America’s HDV sector requires systematically reducing the “carbon intensity” (CI) of transportation fuels. There are two basic approaches: 1) reduce the CI of today’s “baseline” diesel fuel, or 2) substitute alternative (and often renewable) transportation fuels that have inherently lower CI values.

6.8.1. California Comparisons for Transportation Fuel Pathways

Through the LCFS and other means, CARB leads the nation in efforts to lower the CI of heavy-duty transportation fuels. Figure 28 compares CARB’s “illustrative” CI ratings (in grams per mega joule of “CO₂ equivalent” GHGs) for eight different heavy-duty transportation fuel pathways.

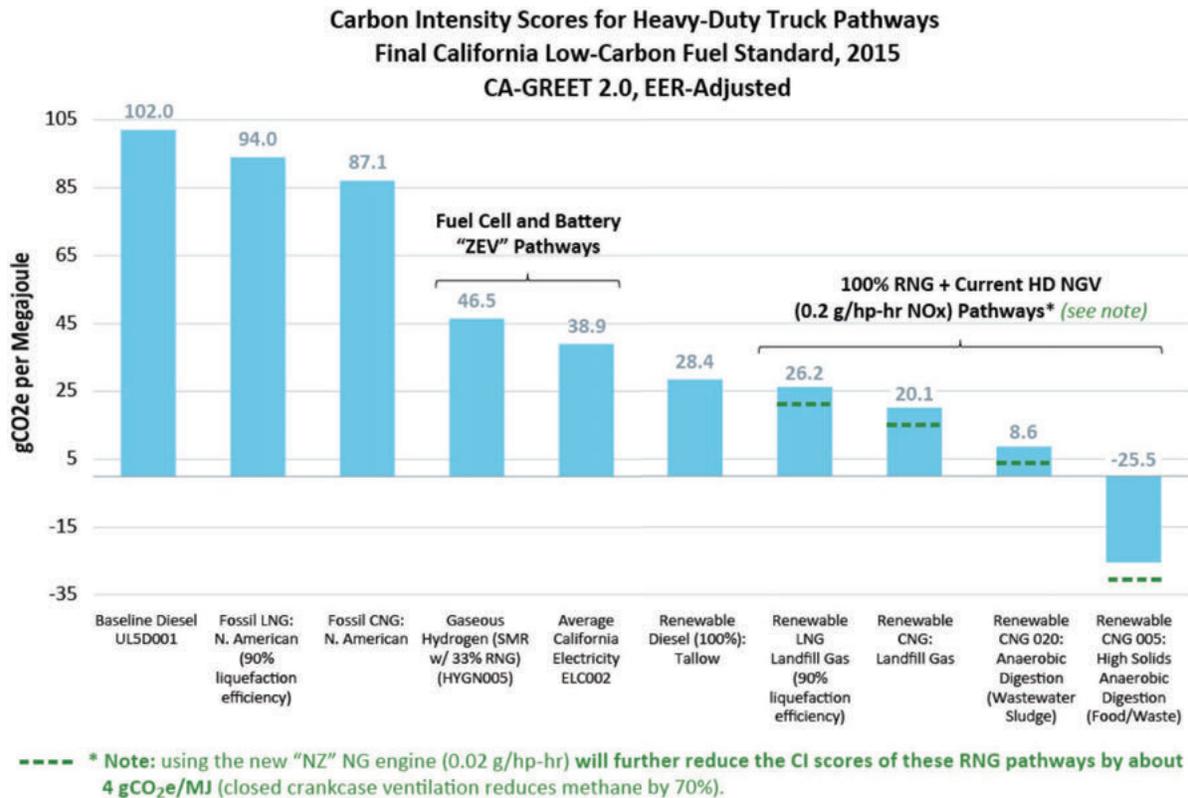
According to this illustrative data from CARB, when fossil CNG or LNG are combusted in currently available spark-ignited heavy-duty engines, they provide CI reductions of approximately 15 and 9 percent, respectively (relative to the baseline diesel pathway).¹⁹⁴ The CI values of CNG and LNG are decreased 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 nearly 75 percent for “Renewable LNG: Landfill Gas,” up to 125 percent for “Renewable CNG: High Solids Anaerobic Digestion.” Moreover, an additional CI benefit (approximately 4 gCO₂e/MJ) will be achievable for each of these RNG pathways when the new CWI NZ engine becomes available in mid-2016. This is attributable to the NZ engine’s closed crankcase ventilation system, which reduces “downstream” methane emissions by 70 percent. Note that all four RNG pathways in CARB’s illustrative data have lower CI values than the “Average California Electricity” pathway (CI value of 31.0 gCO₂e/MJ) assumed to recharge heavy-duty BEVs. This is a particularly important point, as California has one of the lowest grid CI values in our nation. It is noteworthy that the CI value of California’s grid will be further reduced as increasing percentages of renewable energy are added to the mix, per RPS requirements.

¹⁹⁴ 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.

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

In many early applications—especially outside of California—RNG will gradually be blended in with fossil natural gas. Section 7.4.1 discusses the case study of CR&R Refuse Services in Perris California, which is making a major push for the use of RNG in its refuse trucks. This includes an example (based on CR&R) of how the CI score of refuse trucks fueling with natural gas will be progressively lowered by using increased amounts of RNG produced from the High Solids Anaerobic Digestion (HASD) pathway that is carbon negative.

Figure 28 also indicates that the “Gaseous Hydrogen (SMR with 33% RNG)” pathway has a fairly low CI score, albeit not as low as the four RNG pathways. This ARB-estimated CI score of 46.5 gCO₂e/MJ represents a 54.5 percent reduction from the baseline diesel pathway. It represents how hydrogen is likely to be produced in California for near-term demonstrations of heavy-duty FCVs such as transit buses. This is because California now requires that 33 percent of the hydrogen dispensed into vehicles from state-funded stations must come from renewable sources, such as solar, wind, or biogas. Notably, the California Hydrogen Business Council indicates that certain hydrogen stations in California now



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 28. Comparative C.I. scores for heavy-duty truck pathways (CARB, 2015)

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

dispense 100 percent renewable hydrogen; thus, the Council estimates that the average renewable content may be as high as 40 percent.¹⁹⁵ Because there is no other such requirement in the U.S., assuming a 33 percent renewable content for transportation hydrogen probably yields a best-case overall estimate for the carbon intensity of transportation hydrogen today.

Over the longer term, the CI value of hydrogen-FCV pathways is likely to decrease. Currently, it is difficult to quantify how much (and when) the CI score will improve. For hydrogen that is produced from steam methane reformation (SMR) using increasing amounts of RNG, the pathway CI score will vary depending on the blend percentage and the CI for the pathway used to produce the RNG (see the last four bars of the Figure 28). If the hydrogen is produced using electrolysis powered by grid electricity—especially if in a region that does not have a low-carbon grid—the CI score for this pathway is likely to be relatively high (poor). If the hydrogen is produced using *wind- or solar-powered* electrolysis, then the CI score could be among the lowest of all transportation fuel pathways.

However, there are tradeoffs associated with using dedicated renewable energy resources to power water electrolysis as the hydrogen-production pathway; one is likely to be a relatively high cost of the hydrogen on a per kilogram basis. Clearly, it is challenging to assess the future CI score of hydrogen as the fuel for heavy-duty FCVs, at this early point in the commercialization of this fuel-technology pathway.

The middle bar of Figure 28 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. It can be made from either animal fat (e.g., “tallow” from Australian or New Zealand sheep) or vegetable sources. 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.¹⁹⁶ To date, however, no heavy-duty diesel engine (using conventional or renewable diesel) has been certified below the existing NOx standard of 0.2 g/bhp-hr. Engine manufacturers have noted that challenging “NOx-GHG” tradeoff issues must be resolved before heavy-duty diesel engines can be certified to the 0.02 g/bhp-hr NOx level, which as noted has already been achieved by CWI’s ISL G NZ natural gas engine. Section 14 further describes the opportunities and challenges for heavy-duty diesel engines using renewable diesel to help shape America’s future clean heavy-duty transportation sector.

6.8.2. National CI Comparisons for Transportation Fuel Pathways

The CI benefits of natural gas pathways aren’t just relevant in California, which has one of the “cleanest” electricity grids for GHG (and NOx) emissions. On average nationwide, today’s heavy-duty natural gas engines using “fossil” natural gas provide CI scores that are approximately 11 percent lower than the baseline diesel pathway (ULSD). RNG made from landfill gas provides a CI score approximately 56

¹⁹⁵ Personal communication to GNA from Jeff Serfass of the California Hydrogen Business Council, January 13, 2016.

¹⁹⁶ California Environmental Protection Agency, “Staff Report: Multimedia Evaluation of Renewable Diesel, Prepared by the Multimedia Working Group, May 2015, http://www.arb.ca.gov/fuels/diesel/altdiesel/20150521RD_StaffReport.pdf

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

percent lower than ULSD. “Clean-grid” states like California, Oregon and Washington have CI values for their average electricity mix that is equally low as RNG from landfill gas. However, states (e.g. in the mid-west) that are heavily dependent on coal to generate electricity have much higher CI scores. As in California, renewable diesel (RD) offers a very low CI pathway in all parts of the country.¹⁹⁷

6.9. Immediately Available, Affordable Emissions Reductions

The following subsections assess heavy-duty ZEV and NZEV technologies for their relative costs to achieve certain types of emissions reductions. [Section 12 \(Appendix 2\)](#) provides the key assumptions (vehicle operational parameters, costs, emissions, etc.) that were used to prepare the assessments and Figures that follow.

6.9.1. What Can \$500 Million Buy?

Significant investments will be needed to transition America’s heavy-duty on-road freight system to ultra-low NO_x and GHG technologies. Below, a comparison is provided that 1) quantifies the numbers of HDVs that could be purchased with \$500 million (assumed to be government incentive funds), and 2) estimates how much mass of key pollutants could be reduced.

In this assessment, short-haul heavy-duty trucks powered by one near-zero-emission technology and two zero-emission technologies (as defined by CARB) are assumed to be ready for purchase and deployment. These technologies and their fuels are:

1. NZEV: CNG truck with CWI NZ engine using RNG from landfill gas (CNG NZ - LFG)
(**Note:** Similar results are achieved when using an LNG truck as the NZEV case)
2. ZEV: Battery electric truck recharged with the average California mix (EV - Ca Grid)
3. ZEV: Fuel cell truck using 33 percent renewable hydrogen (FCV – 33% RH2)

NOTE: while based on currently available manufacturer information (see assumptions in Section 12 – Appendix 2.), this comparison is strictly hypothetical. As noted in Figure 29, only the NZEV natural gas truck is commercially available (effective April 2016) for short-haul Class 8 trucking. The two ZEV technologies have not yet progressed past proof-of-concept, pre-commercialization phases for this application. Similar to how major HDV incentive programs are structured (e.g., California’s Carl Moyer), this analysis is based on the incremental purchase prices of the selected HDV fuel-technology types, and does not consider life-cycle costs for end users.

Each of these three options can provide major reductions of criteria pollutants and GHG emissions, relative to the baseline technology (today’s cleanest diesel HDV). However, there are significant differences in their incremental costs. Figure 29 provides a preliminary comparison of what \$500 million could buy, in terms of 1) numbers of heavy-duty trucks, 2) tailpipe criteria pollutants that would be reduced, and 3) well-to-wheel (WTW) GHG emissions that would be reduced.

¹⁹⁷ These figures are based on an analysis performed for GNA by ICF, September 2015.

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

As Figure 29 demonstrates, \$500 million could “buy down” 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, respectively, would be reduced. 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 greater WTW GHG reductions (relative to baseline diesel) than using the \$500 million to purchase either battery-electric or fuel cell trucks. This is largely due to the greater numbers of low-GHG natural gas trucks that can be purchased for the same amount of money.

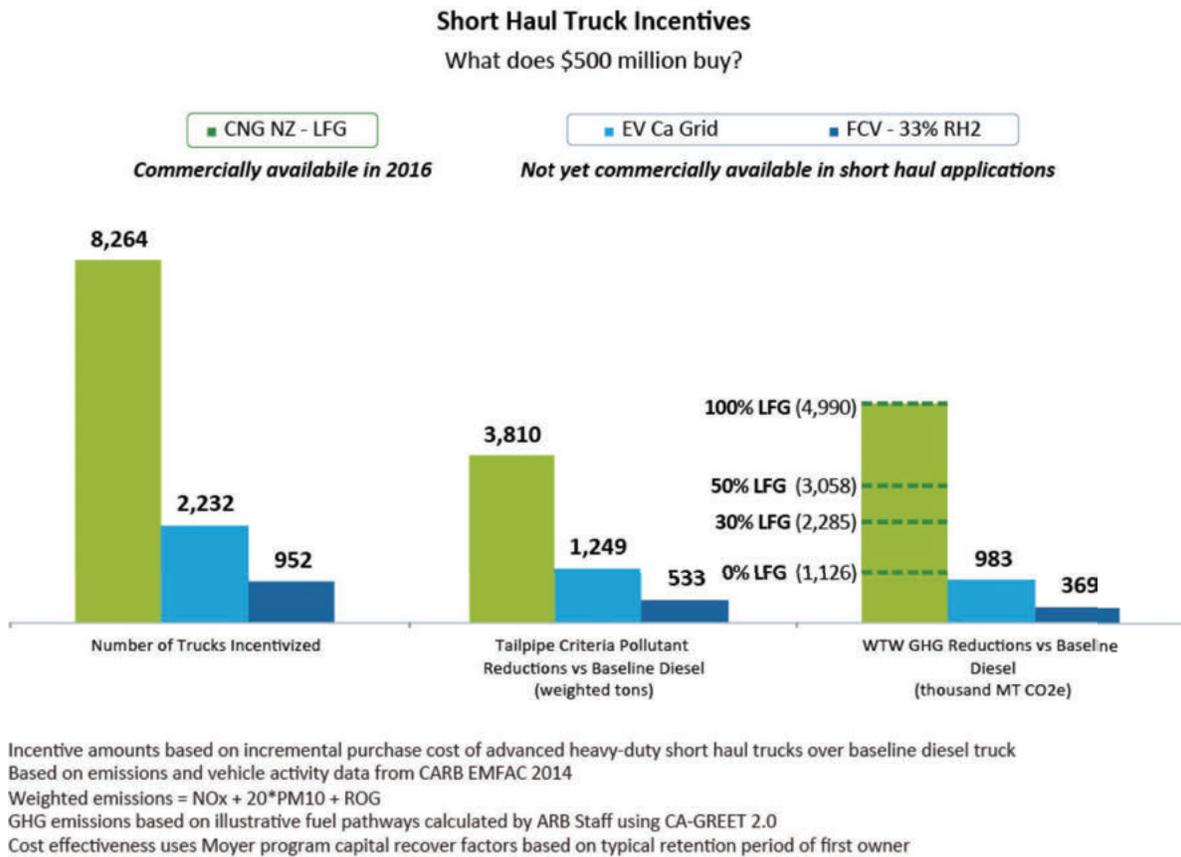


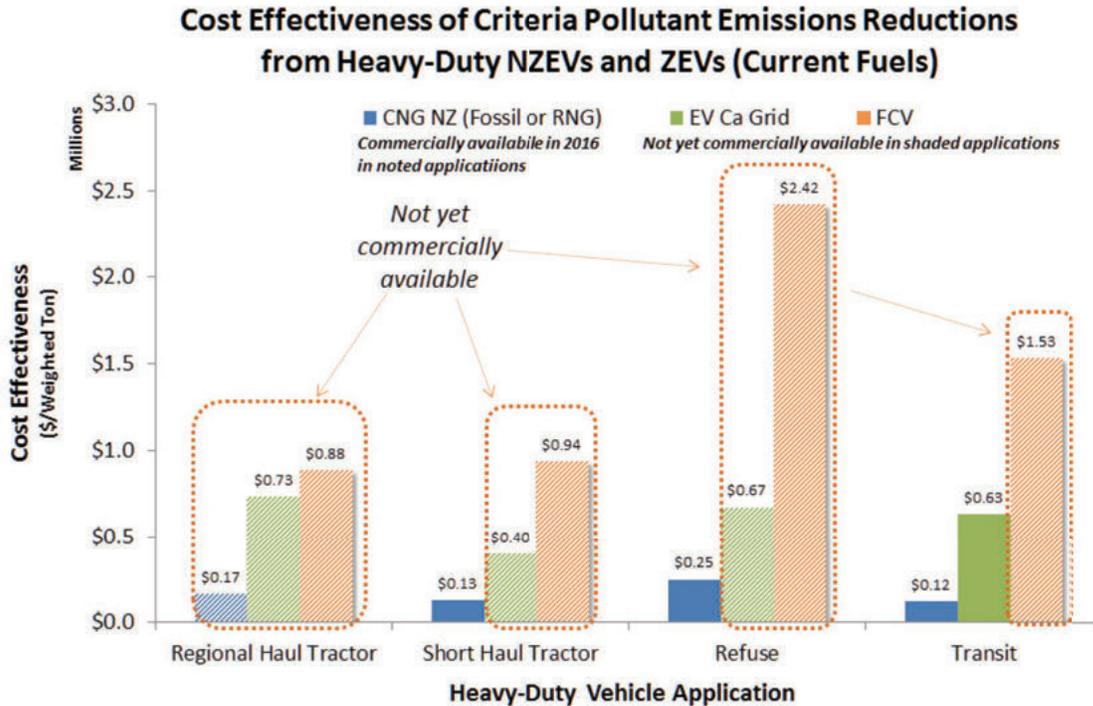
Figure 29. Hypothetical comparison of truck deployments and benefits based on a \$500 million investment

6.9.2. Cost Effectiveness Considerations

It is also important to consider the “cost effectiveness” of each option to reduce criteria pollutants and GHG emissions. Below, two different figures are provided. These compare the estimated cost effectiveness of public resource investments to reduce criteria pollutants (\$/weighted ton of reductions) and GHG emissions (\$/MT CO₂e), when those investments are used to help buy down the incremental

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

costs of the same three NZEV and ZEV technologies. In both cases, this analysis is performed for four different HDV applications. As Figure 30 indicates, the NZEV option (heavy-duty CNG engine) achieves the best (lowest) cost effectiveness for reducing criteria pollutants, across all four HDV applications.



Based on emissions and vehicle activity data from CARB EMFAC 2014
 Weighted emissions = NOx + 20*PM10 + ROG
 Cost effectiveness uses Moyer program capital recover factors based on typical retention period of first owner

Figure 30. Criteria pollutant reduction cost effectiveness by HDV type and application

Similarly, when a WTW analysis is conducted on GHG reductions, the natural gas NZEV option again provides the more cost-effective option across all four HDV applications (see Figure 31). This is the case with or without RNG (landfill gas in this example).

The point of this comparison is not that all three options shouldn't be funded, or that one option is "better" than the other. In areas where people are highly impacted by emissions of any kind (e.g., schools near intermodal yards, towns bordering large ports), the only desired HDV type may be one of these two zero-tailpipe-emission technologies (or others, if and when they emerge). As CARB has clearly stated, zero-emission technologies are needed "wherever feasible" and near-zero-emission technologies with renewable fuels are needed "everywhere else." If and when battery-electric and/or fuel cell HDVs become commercially mature for the high-impact goods movement sector—and assuming their costs are commensurate with benefits—there is likely to be strong demand for their deployment.

Cost Effectiveness of WTW GHG Emissions Reductions from Low Carbon Fuels in Advanced Heavy-Duty Vehicles

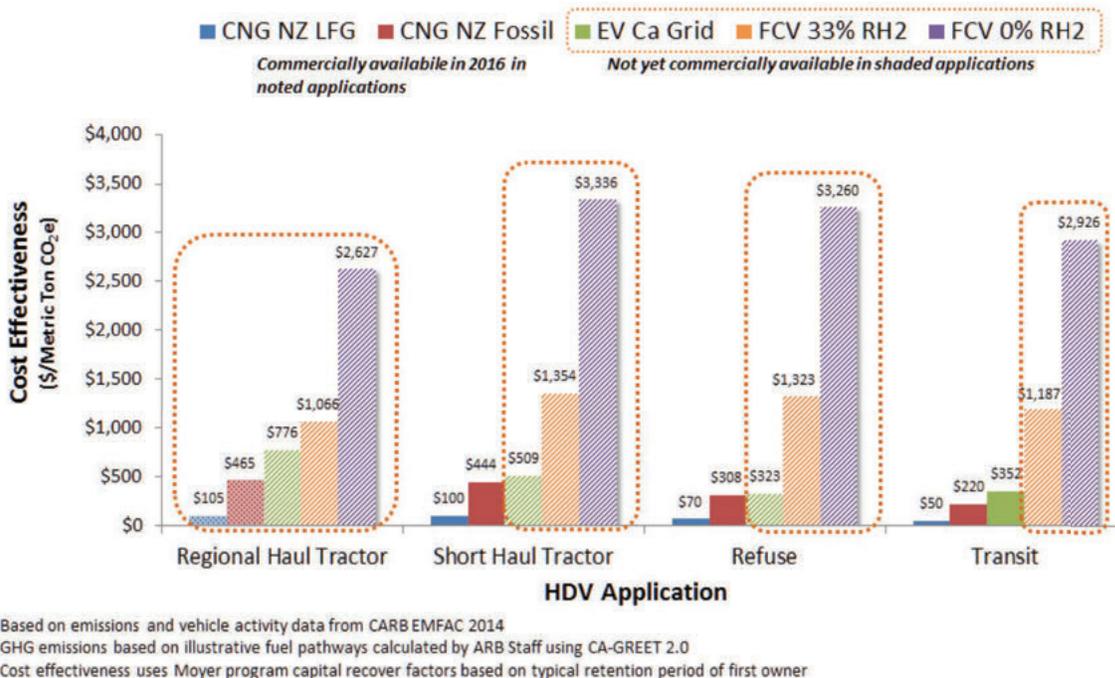


Figure 31. GHG reduction cost effectiveness by HDV type and application

However, near-zero-emission heavy-duty NGVs provide commercially proven, affordable technology today. They can immediately begin addressing the major NOx reductions from on-road HDVs—including HDDVs—that are needed throughout America for attainment of ozone and/or PM2.5 NAAQS. Beginning with the 8.9 liter CWI NZ engine—and likely augmented by the 11.9 liter version within two years—wide-scale deployments will be possible across an array of highly impactful on-road HDV applications. In regions where RNG is readily available, heavy-duty fleets will be able to choose the pace for systematically switching over to this ultra-low-GHG transportation fuel.

6.9.3. Urgency to Address Ambient Air Quality Needs

America’s most heavily impacted urban areas need to achieve systematic, steep reductions in criteria pollutant emissions from HDVs. As described, many regions and cities across the U.S. are under tight deadlines to attain federal NAAQS for ozone and/or PM2.5. This goes well beyond reducing NOx and volatile organic compounds (VOCs), which are the two key ozone-precursor emissions. Efforts must also address street-level emissions of DPM and other TACs, most of which come from heavy-duty diesel trucks moving freight (see box, below). Millions of people who live, work, play and attend school near high concentrations of HDV activity are paying a high price in terms of adverse health impacts.

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

As one example of the urgency, in November 2015 mayors from five Southern California cities that are located near high-emissions freeway corridors joined together to advocate for “cleaner heavy duty trucks” serving those corridors. They cited disproportional health impacts on “disadvantaged communities near or around major transportation corridors and ports.” Joined by leaders from the California Energy Commission and the South Coast Air Quality Management District, they specifically noted that CWI’s newly certified near-zero-emission heavy-duty natural gas engine (the ISL G NZ) can quickly start making a major difference to reduce harmful criteria pollutants and TACs along goods movement corridors that pass through their cities.¹⁹⁸

“Local communities will benefit from improved health from reduced emissions of particulate matter from heavy-duty natural gas vehicles over diesel fueled vehicles in this sector, which encompasses intensive urban deployment, particularly for refuse and transit sectors. Additional emission reduction benefits can be realized through the use of renewable natural gas.”

-California Energy Commission, “Program Highlights: Natural Gas 8.9 Liter Engine Achieves “Near-Zero” NOx Emissions, January 2016.

"There is a solution that exists today to improve air quality in my city and in the surrounding region. We must act now to encourage cleaner technology within the heavy duty transportation industry so that my child and the children of South Gate can breathe cleaner air."

-South Gate (CA) Mayor Jorge Morales, November 2015.

This reinforces a critical point: heavy-duty NGVs with low-NOx engines using fossil natural gas can immediately be deployed across America to deliver a 90-percent NOx reduction (and no DPM), while also providing lower GHG emissions relative to baseline diesel. Over time, as increasing RNG production comes on line and RNG gradually replaces fossil gas, deep GHG reductions will be realized by this fuel-technology combination. This affordable, effective strategy to reduce NOX and GHG emissions is now available. Equally important, it provides a sustainable pathway to transform America’s HDV transportation sector over the next several decades.

6.10. Potential for Expansion into High-Horsepower Off-Road Sectors

Over the next five years, the prospects appear good that heavy-duty engine manufacturers can begin transferring near-zero-emission heavy-duty natural gas engine technology *from on-road to off-road applications*. Currently off-road HDV applications such as mine haul trucks and cargo-handling equipment are almost exclusively powered by conventional diesel engines, although there has been increasing interest to use natural gas for some of these applications. Like on-road HHDTs, many of these

¹⁹⁸“Freeway Mayors Call for Less Pollution, Cleaner Trucks Along Freeway Corridors of South Gate, Bell, Commerce, Compton and Maywood,” press release, <http://www.prnewswire.com/news-releases/freeway-mayors-call-for-less-pollution-cleaner-trucks-along-freeway-corridors-of-south-gate-bell-commerce-compton-and-maywood-300179478.html>.

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

off-road HDV applications do not appear to be good candidates for today's battery electric and fuel cell technologies. CEC has recognized the potential to develop and demonstrate low-NO_x off-road natural gas engines for some of these applications, and has identified this as a priority for California's FY 2016-17 Natural Gas Research Initiatives program.¹⁹⁹

Precedence with this type of technology transfer points to good prospects for success. Historically, on- and off-road vehicles have shared many of the same technologies. Emission standards for off-road engines almost always lag behind those for on-road engines. As off-road standards become more stringent, many of the same emission control technologies used in on-road vehicles (e.g., exhaust gas recirculation, oxidation catalysts, and diesel particulate filters) have been transferred over to off-road applications. In fact, the overall trend for technology development in off-road applications is to adopt technologies that were first deployed in on-road applications.

There is also policy precedence for using on-road heavy-duty natural gas engines to achieve surplus emission reductions in off-road applications. For example, the Ports of Los Angeles and Long Beach have adopted policies for their tenants to use clean fuel-technology platforms to power their off-road cargo-handling equipment. Partly due to the demand created, manufacturers of terminal tractors have introduced models that meet today's most stringent heavy-duty on-road and off-road emission standards. Specifically, some of these off-road vehicles are offered with the same CWI ISL G natural gas engine used in Class 7 and 8 on-road "drayage" trucks. Thus, it is reasonable to conclude that low-NO_x natural gas engine technology could also be transferable to terminal tractors. Potential also exists to repower in-use terminal tractors with CWI ISL G engines, to achieve NO_x emissions at the very low level of 0.02 g/bhp-hr.

This potential for transferring NZEV technology to off-road applications goes beyond terminal tractors. For example, Cummins makes 7-, 9- and 12-liter diesel engines that are widely used for propulsion or auxiliary power within recreational and vocational marine applications. As emissions standards applicable to these off-road engines are further ratcheted down (e.g., if EPA adopts a "Tier 5" standard), it's possible that off-road equipment and vehicle manufacturers will want to utilize very-low-NO_x natural gas versions of their products. In sum, it is plausible to assume that natural gas engines fueled by RNG and using advanced low-NO_x technology can gradually be migrated into many heavy-duty off-road applications, without need for significant technology breakthroughs or major directional changes by manufacturers. However, this will depend on many market factors, most which are not yet known or well defined.

6.11. Synergy with Advancement of Heavy-Duty ZEVs

Immediate and growing deployment of ultra-clean heavy-duty NGVs will support, rather than hinder, the longer-term commercialization and deployment of battery-electric and fuel cell technologies in challenging heavy-heavy-duty trucking applications. Fleets that utilize heavy-duty NGVs today will gain

¹⁹⁹ California Energy Commission, "FY 2016-17 Natural Gas Research Initiatives, presented at the Stakeholders Workshop, January 25, 2016.

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

important alternative fuel experience and knowledge, which can later be applied to maximize utility of heavy-duty BEVs and FCVs that are highly likely to offer reduced range and longer refueling time compared to diesel. Class 7 and 8 NGVs will also help advance lower-cost, higher-energy-density hydrogen storage tanks for heavy-duty FCVs.

And perhaps most importantly, expansion of RNG production across the U.S. can offer increased renewable feedstock that will reduce the CI value of electricity and hydrogen used to power heavy-duty battery-electric and fuel cell vehicles. In fact, these processes are already underway. For example, the CEC notes that:

Natural gas is also playing an important role in the development of the emerging hydrogen vehicle industry. There are currently several options available for producing low-carbon intensity hydrogen fuel for transportation purposes. The majority of the existing hydrogen fueling stations currently use hydrogen made by a steam reformation process that converts natural gas or biomethane to hydrogen. This process and other technologies could allow hydrogen fueling stations and centralized fuel producers to utilize the existing natural gas infrastructure as a secure source of fuel for hydrogen production. Based on the latest automaker survey by ARB, roughly 18,500 fuel cell electric vehicles utilizing hydrogen are expected by 2020.²⁰⁰

In fact, heavy-duty NGVs using increasing volumes of RNG can provide important market pull for expanded RNG production, in California and nationwide. More RNG production will spur expansions in the entire RNG infrastructure and supply chain. This in turn can be used to “ramp up” production of RNG that is strongly needed to help meet renewable energy requirements and goals established for the two ZEV pathways, BEVs and FCVs.

As previously noted, however, there are challenging barriers that must be overcome to unlock the full potential for RNG as a major HDV transportation fuel. The important issue of RNG production and supply, and various opportunities and barriers, are addressed in Section 7. To realize the highest possible near-term GHG reductions from investing in natural gas transportation fueling that is shifting to increasing concentrations of RNG, it will be important to limit and control methane leakage in the natural gas and RNG vehicle fuel supply chains. The following subsection describes how the natural gas industry is making major progress to steadily reduce such emissions.

6.12. Industry Efforts to Reduce Upstream Methane Emissions

Methane—a potent GHG and the dominant constituent of natural gas—can be emitted during “upstream” production, processing, and delivery segments of the natural gas supply chain. Methane accounted for about 10 percent of total U.S. GHG emissions in 2013, according to EPA’s latest inventory. Beyond being a GHG, methane is considered a “short-lived climate pollutant” (SLCP). These types of gases remain in the atmosphere for a much shorter period of time than longer-lived climate pollutants

²⁰⁰ California Energy Commission, “AB 1257 Natural Gas Act Report: Strategies to Maximize the Benefits Obtained from Natural Gas as an Energy Source,” Draft Staff Report, September 16, 2015.

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

(e.g, CO₂); but their impacts on heating the atmosphere can be far greater than CO₂. This higher relative GHG potency compared to longer-lived climate pollutants makes methane an especially urgent target for effective controls.²⁰¹

The full national breakout of methane emissions by source is provided in Figure 32. As shown, agricultural sources in livestock and farming operations (enteric fermentation and manure management) are the largest U.S. emitters of methane, collectively accounting for approximately 36 percent. Natural gas and petroleum systems emit approximately 29 percent of the national methane inventory.²⁰² In cattle-rich California, approximately 55 percent of the annual methane emissions result from manure management and enteric fermentation, primarily for beef and dairy cow operations. California's oil and gas industry accounts for six percent of the State's annual methane inventory²⁰³.

For natural gas to become a full-scale replacement for diesel in America's heavy-duty transportation

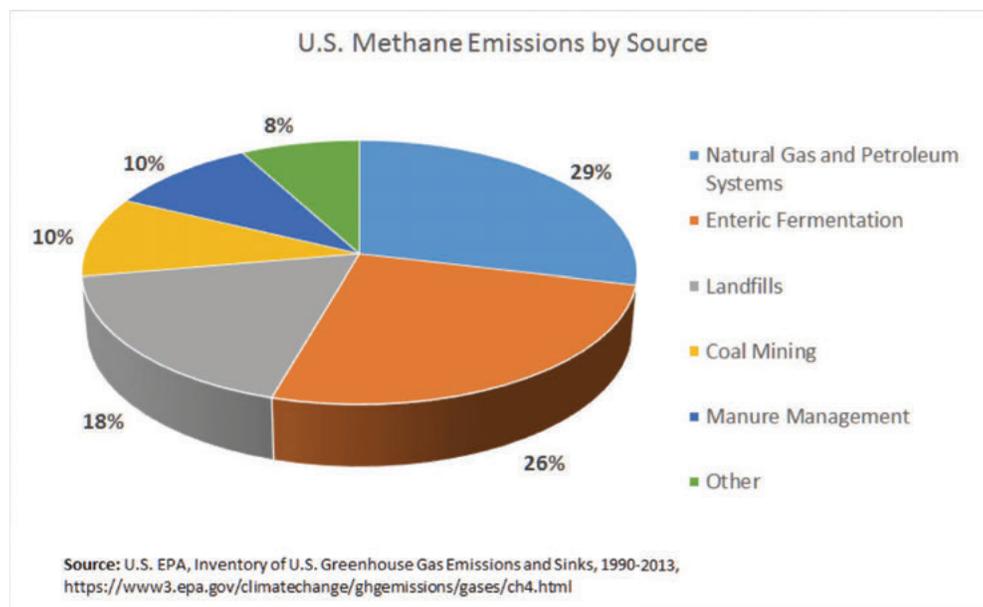


Figure 32. Breakout of national methane emissions by source (U.S. EPA)

sector, it will be important to reduce its upstream release of methane into the atmosphere wherever possible. These types of efforts are well underway by the natural gas industry; further discussion is provided in Section 13 (Appendix 3).

²⁰¹ U.S. EPA, "Inventory of U.S. Greenhouse Gas Emission and Sinks: 1990-2013," <http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf>.

²⁰² U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013, April 15, 2015, <http://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf>.

²⁰³ California Air Resources Board, "Draft Short-Lived Climate Pollutant Reduction Strategy," September 2015, accessed online at <http://www.arb.ca.gov/cc/shortlived/2015draft.pdf>.

7. RNG for NGVs: Supply, Costs, Opportunities and Challenges

RNG is the second critical element of this game-changing fuel-technology pathway. The combination of ultra-low-NOx heavy-duty natural gas engines and extremely low-carbon-intensity RNG can immediately begin to transform America’s on-road HDV transportation sector, by providing major reductions in NOx and GHG emissions. Because there is no “blend wall” for RNG; it is a drop-in fuel for today’s heavy-duty natural gas engines at any mixture with conventional natural gas. No other fuel-technology pathway exists today—or in the foreseeable future—that can “address” the major NOx and GHG reductions needed from high-impact HHDV applications.

7.1. Introduction

RNG is a gaseous mixture of methane and other compounds that is produced from renewable sources, using either biological or chemical processes. Generally, to be used as a transportation fuel in NGVs, RNG must have similar fuel qualities as pipeline natural gas and meet any applicable fuel specifications imposed by either NGV manufacturers or government regulators.²⁰⁴ For example, CWI approves RNG for its heavy-duty NGV engines if it “meets Cummins published standard natural gas fuel specifications” (see CWI’s “Fuel Quality Calculator”, accessed online at: <http://www.cumminswestport.com/fuel-quality-calculator>). The key point is that regardless of how RNG is produced (see below), its quality must generally be equivalent to pipeline natural gas before it can be used as a transportation fuel.

This section provides an overview of how RNG is typically produced and supplied for transportation markets. As with the entire White Paper, the overall scope of this section is national. Given that much important progress and activities are underway in California, highlights are provided about key initiatives and policies in that state.

7.2. Major Production Pathways

There are three major pathways used to produce RNG: 1) digestion/decomposition; 2) gasification and methanization, and 3) electrolysis and methanization. These are further summarized in Table 11. The processes used for each pathway vary significantly, as do their current utilization and full potentials to produce RNG as a transportation fuel.

²⁰⁴ California has established specifications for CNG motor fuel, including a minimum methane content of 88 percent. The Society of Automotive Engineers (SAE) is in the process of updating its J1616 guideline into a new specification entitled Recommended Practice for Compressed Natural Gas Vehicle Fuel. This is specifically being done in acknowledgement that today, not all CNG is produced from pipeline quality natural gas.

Table 11. Summary of Major Pathways to Produce RNG

Process	Feedstock / Energy Source	Interim Product / Cleanup Requirements for Transportation Use
Digestion / Decomposition	Organic waste (landfill gas, animal waste, wastewater, food/green waste)	Biogas / requires “upgrading” (significant cleanup) to become RNG
Gasification and Methanation	Woody biomass (poplar trees, forest thinnings)	Biogas / requires relatively simple cleanup to become RNG
Electrolysis and Methanation	Water / renewable power (solar, wind)	Renewable methane / requires little or no further processing to become RNG

7.2.1. Digestion / Decomposition of Organic Waste

The U.S. Department of Energy defines biogas as “the gaseous product of the decomposition of organic matter.”²⁰⁵ The California Energy Commission (CEC), which is responsible for defining eligible resources under the California’s Renewables Portfolio Standard program, has defined biogas as “digester gas, landfill gas, and any gas derived from an eligible biomass feedstock.”²⁰⁶ As these definitions imply, the major way to produce biogas is through the use of *biochemical* processing of various biomass sources. These feedstocks are found (for example) at landfills, livestock operations and wastewater treatment

The Roadmap identified more than 2,000 sites across the United States that produce biogas, as well as the potential for an additional 11,000 biogas systems. If this full potential is reached, the climate and environmental benefits are expected to be great.

–“Biogas Opportunities Roadmap Progress Report,” USDA, EPA and DOE, 2015.

With minor cleanup, biogas can be used to generate electricity and heat. To fuel vehicles, biogas must be processed to a higher purity standard. This process is called conditioning or upgrading, and involves the removal of water, carbon dioxide, hydrogen sulfide, and other trace elements. The resulting RNG, or biomethane, has a higher content of methane than raw biogas, which makes it comparable to conventional natural gas and thus a suitable energy source in applications that require pipeline-quality gas

U.S. DOE http://www.afdc.energy.gov/fuels/natural_gas_renewable.html

²⁰⁵ U.S. Department of Energy, Alternative Fuels Data Center, “Renewable Natural Gas (Biomethane) Production,” http://www.afdc.energy.gov/fuels/natural_gas_renewable.html.

²⁰⁶ See, for example, *Renewables Portfolio Standard Eligibility Guidebook* (6th ed. August 2012) at page 16.

facilities.

7.2.2. Gasification and Methanation of Woody Biomass

Biogas can also be produced from biomass using a *thermochemical* process, such as thermal gasification of woody biomass (e.g., forest trimmings). The gasification process produces syngas that is primarily composed of carbon monoxide (CO) and hydrogen (H₂). Next, the CO and H₂ are combined to produce methane (CH₄) and water. This is one form of “methanation,” which simply refers to the process of converting a chemical compound into methane (the primary constituent of natural gas).

Pyrolysis is a thermochemical step in gasification. It involves the decomposition of organic matter at high temperatures in the absence of oxygen. Because this process is anaerobic, materials do not combust but instead break down into gases and char, a very pure form of carbon. The gases that are produced from pyrolysis include methane, hydrogen, carbon monoxide and other complex hydrocarbons.

While some policies provide a more restrictive definition of biogas to include only gas produced by anaerobic digestion,²⁰⁷ there are no environmental or technical reasons to limit the definition this way. Such a definition unnecessarily restricts the potential for biogas production, particularly since more than half of the organic waste that can be used to generate biogas is better suited to other conversion technologies such as gasification or pyrolysis.²⁰⁸

7.2.3. Electrolysis and Methanation Using Renewable Power

RNG can also be produced chemically without biomass, using surplus renewable power to split water into hydrogen and oxygen. The hydrogen that is generated is then reacted with CO₂ to produce CH₄. This form of methanation is one type of “Power-to-Gas” technology. When produced in this way (not involving biological processes), RNG is technically “renewable methane” and not biomethane.

Power-to-Gas through this methanation process was initially developed as a means to store excess solar and wind power, by injecting this synthetically produced methane into the pipeline. Uniquely, Power-to-Gas energy storage technology closes the loop between the grid and the natural gas infrastructure. It adds grid and gas pipeline flexibility, and leverages resources already in place while preserving and storing energy that otherwise would be lost. The flexibility it offers can enable greater usage of intermittent grid-tied renewable energy sources (further described below).

The focus in this White Paper, however, is about making RNG for use in heavy-duty NGVs. An advantage of the Power-to-Gas methanation process is the minimal need for further cleanup of the renewable methane it produces, to meet transportation fuel requirements.

²⁰⁷ AB 1900 (Gatto) Statutes of 2012, Chapter 602.

²⁰⁸ Presentation by Jacques Franco, CalRecycle, at Renewable Energy from Waste conference, November 18, 2014, slide 3.

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

There are now about 35 Power-to-Gas facilities in Europe that combine these attributes to provide energy storage, decarbonized pipeline gas and renewable transportation fuel.²⁰⁹ However, use of this process in the U.S. to make transportation fuel is currently negligible.

7.3. A Closer Look at Biogas Feedstocks

In the U.S., the most common way to make RNG is to produce biogas using one of the biochemical processes described above, and then performing the necessary clean-up. Biogas can be produced from a wide array of feedstocks that include agricultural residue; animal manure; dedicated energy crops; fats, oils and greases (collectively referred to as FOGs); forestry and forest product residues; landfill gas;²¹⁰ municipal solid waste; and waste water treatment gas. Table 12 further describes these feedstocks.

Table 12. Summary of feedstocks for production of biogas (for potential upgrading to RNG)

Biogas Feedstock	Description
Agricultural residue	The material left in the field, orchard, vineyard, or other agricultural setting after a crop has been harvested. Inclusive of unusable portion of crop, stalks, stems, leaves, branches, and seed pods.
Animal manure	Manure produced by livestock, including dairy cows, beef cattle, swine, sheep, goats, poultry, and horses.
Energy crops	Energy crops are inclusive of perennial grasses, trees, and some annual crops that can be grown specifically to supply large volumes of uniform, consistent quality feedstocks for energy production.
Fats, oils, and greases (FOGs)	Long chain fatty compounds that are byproducts of cooking, such as fryer grease (yellow grease) and grease traps (brown grease).
Forestry and forest product residue	Biomass generated from logging, forest and fire management activities, and milling. Inclusive of logging residues (e.g., bark, stems, leaves, branches), forest thinnings (e.g., removal of small trees to reduce fire danger), and mill residues (e.g., slabs, edgings, trimmings, sawdust). Includes materials from public forestlands (e.g., state, federal), but not specially designated forests (e.g., road-less areas, national parks, wilderness areas) and includes sustainable harvesting criteria as described in the U.S. Department of Energy <i>Billion Ton Update</i> (see below).
Landfill gas (LFG)	The anaerobic digestion of biogenic waste in landfills produces a mix of gases, including methane (40-60%).
Municipal solid waste (MSW)	Refers to the organic fraction of waste which is typically landfilled, such as food waste and some yard trimmings.
Wastewater treatment (WWT) gas	Wastewater consists of waste liquids and solids from household, commercial and industrial water use, which can be anaerobically digested to produce methane.

²⁰⁹ See, for example, <http://www.dena.de/en/projects/renewables/power-to-gas-strategy-platform.html>; <http://www.europeanpowertogas.com>.

²¹⁰ Notably, the role of landfills in producing biogas will likely diminish significantly over the next 35 years. For example, in California there will be diversion of both food and green waste from landfills in the near to mid term. This will reduce the amount of methane produced. Further discussion about how this biogas production will shift is provided in subsequent section.

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

It is important to note that these various feedstocks may not be freely available for biogas production, as many are currently used for other purposes. Consequently, their price and/or availability may depend largely on those other markets. For example, animal manure is widely used as an alternative to chemical fertilizers. The price and availability of animal manure will therefore be somewhat dictated by the prevailing market for fertilizer, rather than for biogas. Further distinction between *technically recoverable* biogas and what can be produced *economically* is provided in subsequent sections.

7.4. Overview of RNG's Direct Benefits for Climate Change and Air Quality

RNG can help improve ambient air quality, address climate change, and deliver local economic benefits where the fuel is produced. Production of RNG is environmentally and economically sustainable, as waste streams are converted to energy in processes that reduce the environmental impact of the feedstock waste and of the energy that is displaced, while simultaneously generating economic value.

Additional discussion about these various benefits is provided below. Most (if not all) benefits are inter-related through the nexus of energy efficiency, air quality and climate change.

7.4.1. Reduction of Full-Fuel Cycle GHG Emissions from HDVs

RNG can provide major reductions in full-fuel-cycle GHG emissions associated with operating HDVs. As described in Section 6, various RNG production pathways have been assigned very low carbon intensity (CI) values. CI values measure a given fuel's lifecycle GHG emissions per unit of energy consumed (expressed in gCO₂e/MJ). Table 13 lists CARB's estimated CI values for RNG and other heavy-duty transportation fuel pathways; these were calculated using California's recently updated model for the LCFS program (CA-GREET 2.0). As shown, at least four different RNG pathways provide CI values that are 74 to 125 percent lower than the baseline diesel pathway (also refer to back to Section 6).²¹¹ Each of these four RNG pathways has a CI value under the California LCFS program that is actually lower than those of 1) heavy-duty BEVs recharged on the California electrical grid (among the nation's cleanest grids; see Section 6); and 2) heavy-duty FCVs using 33 percent renewable hydrogen.

Biogas produced from one particular CARB-approved RNG pathway—the High Solids Anaerobic Digester (HSAD) pathway—results in RNG transportation fuel that is “carbon negative.” This pathway generates biogas from diverted food and green waste that would otherwise be landfilled. The biogas is then upgraded to 95 percent biomethane. CNG as an HDV fuel from the HSAD pathway has a CARB-rated CI value of -25.50 gCO₂e/MJ. In other words, this RNG pathway *reduces* (rather than generates) climate-changing GHG emissions when used as a motor vehicle fuel. Several HDV fleets in California are already using—or will soon start using—this carbon-negative type of RNG. These include the South San

²¹¹ 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** "LCFS Final Regulation Order, Table 6; note that *HASD pathway has been EER-adjusted per CARB's formula (-22.93 base CI divided by EER of .9). For negative CI scores, the formula should require multiplying by the EER. Thus, -22.93 X .9 = -20.64 for the correct EER-adjusted CI score.

Table 13. Carbon intensity values (gCO₂e/MJ) for representative fuel pathways

Heavy-Duty Transportation Fuel Pathway	CI Value (includes Indirect Land Use and EER)	CI Value Relative to Baseline Diesel
Baseline Diesel (Ultra Low Sulfur)	102.01	–
Gaseous Hydrogen (SMR w/ 33% RNG)	46.50	-54.4%
California Electricity (Average grid mix)	38.9	-61.8%
Renewable Diesel (100%) from Tallow	28.4	-72.1%
Renewable LNG (100%), (Landfill Gas, 90% Liquefaction Efficiency)	26.2	-74.3%
Renewable CNG (100%), (Landfill Gas)	20.1	-80.3%
Renewable CNG (100%), (Anaerobic Digestion of Wastewater Sludge)	8.6	-91.6%
Renewable CNG (100%), (High Solids Anaerobic Digestion of Food / Waste)	-25.50	-125.0%
Source: California Air Resources Board, CA-GREET 2.0 2015		

San Francisco Scavenger Company,²¹² CR&R Waste Services (see Case Study, Section 7.6.2), and the East Bay Municipal Utility District.²¹³

Further, one RNG pathway not shown above (dairy biogas to CNG) has been preliminarily approved by CARB for an ultra-low CI value of -276.4 gCO₂e/MJ. This accounts for “avoided methane emissions” at the facility through capture methods deployed at dairy lagoons. CARB staff have reviewed the pathway application, “replicated” the calculated CI value, and recommended approval of the application on a “prospective” basis. The dairy will be required to provide operational data to further corroborate the CI value and gain CARB’s approval to start generating LCFS credits.²¹⁴

Production and use of various types of RNG can also help address climate change in other

In California, about half of methane emissions come from organic waste streams that can be put to valuable use as sources of renewable energy or fuel and soil amendments.

-California Air Resources Board, 2016

Diversion of organic materials to anaerobic digestion facilities provides reduced land use, decreased methane emissions from material decomposition and produces both biomethane and secondary goods such as fertilizer.

-California Energy Commission, 2015

Strategically deployed biogas systems offer the nation a cost-effective and profitable solution to reducing emissions, diverting waste streams, and producing renewable energy.

-U.S. DOE, EPA, and USDA, 2015

²¹² Presentation by the City of South San Francisco to the California Energy Commission, Lead Commissioner’s Workshop on Biofuel and Biomethane Project Success, September 18, 2015.

²¹³ U.S. Department of Energy, “Waste to Wheels,” December 2010, <http://energy-vision.org/ev-publications/Waste2Wheels110608.pdf>.

²¹⁴ California Air Resources Board, “Staff Summary Method 2B Application: Prospective Pathway Dairy Biogas to CNG,” posted for public comment 12-22-15, <http://www.arb.ca.gov/fuels/lcfs/2a2b/apps/calbio-sum-122115.pdf>.

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

important ways that are related to, but not necessarily accounted for by, their assigned carbon intensity values. Organic waste is a major source of methane emissions, a short lived climate pollutant (SLCP) that is far more potent as a climate “forcer” than carbon dioxide (also see Sections 1.3 and 3.3). Methane emissions can be significantly reduced by capturing it from waste sources such as livestock operations, landfills and wastewater treatment facilities, and using it to generate RNG for transportation fuel. (See the CR&R case study further described below.) Because of these various benefits, CARB has prioritized greater utilization of organic waste as a means to reduce SLCP emissions and produce maximum value from the energy and nutrients that remain in these waste sources.²¹⁵

7.4.2. Reduced Emissions of Black Carbon, DPM and TACs

Increasing the use of RNG as a transportation fuel can reduce emissions of black carbon (BC) and TACs such as diesel particulate matter (DPM). Like methane, BC is an SLCP and its global warming potential is 900 to 3,200 times more powerful than carbon dioxide. In addition, BC causes major damage to public health, crops, forests and water quality, and can disrupt rainfall precipitation patterns. It has been identified as “a leading environmental risk factor for premature death.”²¹⁶

BC is formed by the incomplete combustion of fossil fuels or biomass. In the U.S., 52 percent of BC emissions come from mobile sources (especially diesel HDVs), and 35 percent comes from open biomass burning (including wildfires).²¹⁷ Since production of RNG from biomass can result in reduced biomass burning, whether intentional or during wildfires (see next section), it is part of the solution to reduce biomass sources of BC emissions.

Also, as previously noted, diesel engines emit many different TACs; DPM is the most-abundant TAC in urban areas that heavily rely on diesel engines. In California’s SCAB, DPM has been found to be “the major contributor to air toxics risk, accounting on average for about 68% of the total” airborne cancer risk.²¹⁸

Modern on-road diesel HDVs (2007 model year and newer) are equipped with diesel particulate filters (and other control technologies) that are very effective at reducing DPM and other TAC emissions. Thus, it is hard to quantify—and important not to overstate—the incremental value of RNG-fueled heavy-duty NGVs as a strategy to reduce DPM and other TACs found in diesel exhaust. However, older on-road diesel HDVs (and most off-road diesel engines) pre-date such technology and emit

BC’s short atmospheric lifetime (days to weeks), combined with its strong warming potential, means that targeted strategies to reduce BC emissions can be expected to provide climate benefits within the next several decades. Particles emitted by mobile diesel engines are about 75 percent BC.

-U.S. EPA

²¹⁵ CARB SLCP Concept Paper, page 14.

²¹⁶ CARB, SLCP Concept Paper, page 5.

²¹⁷ U.S. EPA, “What is Black Carbon?”, <http://www3.epa.gov/blackcarbon/basic.html>.

²¹⁸ South Coast Air Quality Management District, “Multiple Air Toxics Exposure Study in the South Coast Air Basin, Final Report, May 2015, <http://www.aqmd.gov/docs/default-source/air-quality/air-toxic-studies/mates-iv/mates-iv-final-draft-report-4-1-15.pdf?sfvrsn=7>

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

high levels of these harmful pollutants. To the extent that fleet modernization strategies can be used to replace older diesel HDVs and engines with ultra-low NOx engines (fueled by either fossil gas or RNG), the maximum reductions of DPM and TACs can be achieved (refer back to the discussion in Section 3.2.2).

The following provides an example of potential synergies: in California, wildfire is the source of two-thirds of the state's BC carbon emissions, and 10 percent of its total climate change emissions.²¹⁹ HDVs (particularly pre-2007 models) are also significant sources of BC (see the quote from EPA in the box). Increasing the production of RNG from forest waste in California is one strategy that may help cut the state's BC emissions by reducing emissions from forest fires²²⁰. Using that RNG to displace diesel in older conventionally fueled HDVs will further reduce BC emissions, as well as toxic DPM emissions and other TACs that are emitted from diesel engines.

7.5. Overview of Other Societal Benefits Associated with RNG Production

Production of RNG can provide numerous other important societal benefits that may indirectly improve air quality, help address climate change, or alleviate other problems. For example, RNG produced via a power-to-gas process may be able to alleviate excess renewable generation on the electric grid (this is a complex issue beyond the scope of this white paper). Below are some other types of societal benefits that can be realized by expanding RNG production.

7.5.1. Reduction of Landfilling

“Landfilling” refers to the process of disposing waste material in landfills. California has adopted several policies to limit landfilling, including a goal to reduce using the process by 75 percent overall.²²¹ Other states are also taking steps to reduce landfilling, as this process is land intensive and can create negative economic and environmental impacts.

Increasing biogas production can be a very important element of strategies to achieve landfill diversion goals such as those adopted in California. Biogas production from the separated organic fraction of municipal solid waste can be developed in every community as an alternative to landfilling. Recent waste composition studies estimate that approximately 72 percent of the municipal waste stream going to landfills in America is organic.²²² To begin to phase out landfilling of organic waste, California recently enacted a requirement to divert commercially produced food waste, and restrictions on the use of green waste as alternative daily cover in the state's landfills.²²³ In addition, CARB's *Draft Strategy to Reduce*

²¹⁹ Black carbon constitutes 15% of California's total climate change emissions (based on its 20 year Global Warming Potential) and wildfire now causes 66% of California's black carbon emissions. See AB 32 Scoping Plan Update, adopted 2014, and CARB's Draft SLCP Strategy.

²²⁰ See for example “Energy to Burn: Clean Energy and Fire Hazard Reduction Go Hand in Hand,” http://www2.humboldt.edu/fwr/files/news/Han_CFA2009.pdf, and “Wildfire Fuels and Fuel Reduction,” <http://nationalaglawcenter.org/wp-content/uploads/assets/crs/R40811.pdf>.

²²¹ AB 341 (Chesbro) Statutes of 2011, Chapter 476.

²²² US Composting Council, “Keeping Organics Out of Landfills,” <http://compostingcouncil.org/admin/wp-content/uploads/2011/11/Keeping-Organics-Out-of-Landfills-Position-Paper.pdf>.

²²³ AB 1826 (Chesbro) Statutes of 2014, Chapter 727, AB 1594 (Williams) Statutes of 2014, Chapter 719.

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

Short-Lived Climate Pollutants calls for effectively eliminating all organic waste disposal in landfills by 2025.²²⁴

Even if states like California halt landfilling of organic waste, decomposing materials already in landfills will continue to produce significant volumes of biogas for several decades. In California, existing landfill gas represents 20 to 25 percent of in-state total biogas potential, but this potential has not been fully realized. Landfills are required to capture the biogas that they produce, but currently 60 percent of the gas captured in California is flared (burned) rather than being used as a transportation fuel or to produce electricity.²²⁵ Flaring destroys the methane, but this process releases carbon dioxide and other pollutants (e.g., some NOx) into the atmosphere. Clearly, even as the volume of landfilled organic material diminishes over time, it is in the interest of California and other states to capture landfill gas and convert it to very-low-CI RNG for use in transportation applications.

7.5.2. Reduction of Catastrophic Wildfires

Forest detritus is one of the largest potential waste resources for production of biofuels and bioenergy in the United States. Many states have set goals to sustainably convert waste materials from forest restoration activities into low carbon transportation fuels like RNG. In addition to providing benefits associated with this use of RNG, culling forest waste can help reduce catastrophic wildfires in America's forests, which roughly occupy one-third of our nation's land area.²²⁶

Again, California provides a good example of potential benefits. Wildfire danger throughout the western United States is at its highest in decades. Historic wildfire suppression, drought, invasive pests and climate change have all led to a dangerous and highly combustible level of forest biomass. According to the United States Forest Service, California has lost more acres to wildfire in the past five years than in the previous 70 years.²²⁷ The ongoing danger is so dire that Governor Brown recently issued a "Proclamation of a State of Emergency" and Executive Order calling for more forest fuel removal and facilities that can convert the forest biomass to fuels and energy.²²⁸

California's focus is on removing dead or dying trees, and the shrubs and "ladder fuels" that allow wildfire to reach tree tops to burn hotter and more quickly. The Governor's emergency order calls for expedited and expanded removal of highly combustible forest biomass in zones of high wildfire hazard, for conversion to energy and other useful products.

Removing these dangerous forest fuels will reduce the likelihood and impacts of catastrophic fires and provide many other economic and health benefits.²²⁹ For example, a recent study by the U.S. Forest

²²⁴ California Air Resources Board, *Draft Short-Lived Climate Pollutant Strategy*, September 2015, at page ES-8. (hereinafter, "SLCP Strategy Draft") Available at: <http://www.arb.ca.gov/cc/shortlived/2015draft.pdf>

²²⁵ CalRecycle, Landfill Gas Master List.

²²⁶ Estimated by the World Bank in 2012.

²²⁷ August 5 presentation by Jerry Bird, U.S. Forest Service, at the Governor's 5 Pillars Workshop on Natural and Working Lands, CalEPA. Slide 249, available at: <http://www.arb.ca.gov/cc/pillars/natworklands/nwl-slides-8-5-15.pdf>.

²²⁸ https://www.gov.ca.gov/docs/10.30.15_Tree_Mortality_State_of_Emergency.pdf.

²²⁹ Governor Jerry Brown, State of California, "Proclamation of a State of Emergency," October 2015, https://www.gov.ca.gov/docs/10.30.15_Tree_Mortality_State_of_Emergency.pdf.

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

Service (for the CEC)²³⁰ demonstrated that collecting and converting excess forest biomass to energy can:

- Cut GHG emissions from wildfire by 65 percent;
- Dramatically reduce fire severity and cut the number of acres burned by 20 percent or more;
- Save hundreds of millions of dollars in avoided wildfire damage to forests, buildings and infrastructure and save tens of millions of dollars in avoided fire suppression costs.

In addition, a study by the Placer County Air District found that converting forest biomass to energy (rather than burning or disposing it in open piles) can result in major emissions reductions of GHGs, fine PM and other pollutants.²³¹ Investing in forest biomass-to-energy facilities will also help protect forest communities; infrastructure; water supply and quality; fish and wildlife habitat; and provide other ecosystem and public health benefits. Reducing wildfire is particularly important for clean water. For example, California's Sierra Nevada forests are the origin of 60 percent of the state's developed water supply, and wildfire can have disastrous impacts on the state's potable water infrastructure.²³² The Placer County Air District found that the forest waste collected to protect a single community—Foresthill—could produce enough biogas to power nearly 5,000 light-duty NGVs for a year, while cutting fire risks and reducing emissions from gasoline or diesel.²³³

7.5.3. Improvements in Agriculture

Increasing biogas production from agricultural and livestock waste can help America's agriculture operations, by providing a new source of income and/or onsite energy production, reducing pollution from dairies and other livestock operations, and providing organic soil amendments that increase soil productivity and water retention. This presents major opportunity in California, which is home to more than 76,000 farms that produce almost half of all the fruits, vegetables and nuts grown in the United States.

California's agricultural operations generate more than \$30 billion in annual revenue²³⁴ and employ an estimated 36 percent of the nation's farmworkers.²³⁵

"Investments to cut methane and black carbon emissions as part of an integrated strategy to reduce emissions from agriculture and waste can provide important benefits for the Central Valley and other agricultural communities. They can help build an increasingly resilient and competitive agricultural sector by supporting jobs and economic growth, healthy soils, and improved air quality, water quality, and public health in those communities."

-CARB, "Proposed Short-Lived Climate Pollutant Reduction Strategy," April 2016.

²³⁰ California Energy Commission, "Biomass to Energy: Forest Management for Wildfire Reduction, Energy Production, and Other Benefits," Prepared by the USDA Forest Service, January 2010, at page 3. CEC-500-2009-080.

²³¹ State of California, Sierra Nevada Conservancy, "The State of the Sierra Nevada's Forests," September 2014, available at: <http://sierranevada.ca.gov/our-work/state-of-the-sierra>.

²³² Ibid.

²³³ County of Placer, "New Clean Energy Technology Debuts in Placer County," news release, September 14, 2015, <http://placer.ca.gov/news/2015/sept/clean-energy-tech-debuts>.

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

Each form of biogas production generates beneficial byproducts that can be used to restore carbon and nutrients to soil, conserve water, and reduce the need for fossil-fuel-based fertilizers. For example, anaerobic digestion of food and green waste produces digestate that can be further treated and converted to compost for use as an organic soil amendment. Anaerobic digestion at wastewater treatment facilities produces biosolids, which can be used as organic soil amendments and to stabilize and restore wildfire ravaged lands. Gasification of organic waste produces biochar, which can be used to return carbon to soil, helping the soil to absorb and retain nutrients and water, sequestering carbon and providing other benefits. Biochar can also be converted to activated carbon and used for water filtration and purification.

While the markets for these byproducts are still immature, there is significant potential upside for California and other states as they seek to restore healthy soils, reduce petroleum based fertilizers, and increase water efficiency. Converting organic waste to low carbon fuels and organic soil amendments provides a quadruple climate benefit by reducing methane or black carbon upstream, replacing fossil transportation fuels and petroleum based fertilizers, and increasing water efficiency.²³⁶

7.5.4. Creation of Local Jobs and Economic Development

Nationwide, the American Gas Association estimates that development of RNG “can create up to nearly 257,000 new jobs under scenarios of high biomass utilization” (including indirect and induced employment).²³⁷ Since all communities produce organic waste and wastewater—and many rural communities also produce agricultural, dairy or forest waste—biogas-related “green” jobs can be created in virtually any community across America. The University of California, Berkeley has estimated that biogas production can generate two to six times more jobs (per unit of energy produced) than fossil fuel production, depending on the source of the organic waste. In part, this is because organic waste requires ongoing collection and treatment.²³⁸ The Renewable

“Building infrastructure to better manage organic waste streams could lead to billions of dollars of investment and thousands of jobs in the State. This infrastructure could provide valuable new sources of renewable electricity or biogas, clean transportation fuels, compost other beneficial soil amendments, and other products. Adopting state policies to promote biogas from organic waste would provide a strong durable market signal to industry, agencies, and investors. In addition, this biogas can help the State meet its 33 percent renewable mandate for hydrogen transportation fuel.”

-CARB, “Proposed Short-Lived Climate Pollutant Reduction Strategy,” April 2016

²³⁴ U.S. Department of Agriculture, “California Farm News,”

http://www.nass.usda.gov/Statistics_by_State/California/Publications/Other_Files/200708receipts.pdf.

²³⁵ Aguirre International, “The California Farm Labor Force Overview and Trends from the National Agriculture Workers Survey,” June 2005, <http://agcenter.ucdavis.edu/documents/CaliffarmLaborForceNAWS.pdf>.

²³⁶ *Short-Lived Climate Pollutant Strategy* Concept Paper, pages 13-14.

²³⁷ American Gas Association, “The Potential for Renewable Natural Gas,” September 2011,

<http://www.gasfoundation.org/researchstudies/agf-renewable-gas-assessment-report-110901.pdf>

²³⁸ University of California, Berkeley, “Green Jobs Calculator,” Renewable & Appropriate Energy Laboratory, rael.berkeley.edu/greenjobs.

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

Natural Gas Coalition (RNGC) has indicated that biomethane projects result in the creation of more jobs per year on average than any other renewable energy technology.

Increasing local production of RNG can also help states reduce their dependence on imported fuels, resulting in related economic benefits. California, for example, currently imports nearly two-thirds of the petroleum²³⁹ and 91 percent of the natural gas²⁴⁰ that it uses. According to the Bioenergy Association of California, producing RNG in local California communities could reinvest billions of dollars within the state, and potentially stimulate many times that amount of economic development.²⁴¹

7.6. Current Status of RNG for Transportation (Production, Cost and Price)

7.6.1. Overview of Existing Biogas Production Facilities

About 95 percent of the biogas currently consumed today in the U.S. is produced from captured landfill gas. Clean Energy has used this production pathway to become North America's largest producer, marketer, and distributor of RNG as a vehicle fuel. Marketed as Redeem™, more than 90 percent of the RNG sold by Clean Energy is produced from landfill gas at facilities such as the one shown in Figure 33, near Dallas.

Table 14 lists the three major landfill-gas-to-biomethane production facilities that Clean Energy has built, owned and operated (two of which it continues to operate). In addition, the company has biomethane supply contracts in place with more than a dozen third-party producers that help Clean Energy supply RNG for transportation markets.

Table 14. Clean Energy's U.S. production facilities for RNG from landfill gas

RNG Production Facility	Facility Location	RNG Production Capacity (DGE per day)
McCommas Bluff Landfill (sold interest in 2015)	Dallas, Texas	53,000
Sauk Trail Hills Landfill	Canton, Michigan	18,000
North Shelby Landfill	Millington, Tennessee	18,000

Source: Clean Energy, <http://redeem.cleanenergyfuels.com/images/redeem-clean-energy-factsheet.pdf>

The remaining five percent of RNG produced in the U.S. for transportation applications comes from biogas production at wastewater treatment plants, municipal solid waste digesters and dairy farms. In California, there are about a dozen operating dairy digesters and a several more in development. Fewer

²³⁹ California Energy Commission's Energy Almanac, October 2015,

http://www.energyalmanac.ca.gov/petroleum/statistics/crude_oil_receipts.html.

²⁴⁰ California Gas and Electric Utilities' *California Gas Report: Issues 2004-2013*.

http://www.pge.com/pipeline/library/regulatory/cgr_index.shtml; CEC Energy Almanac, Table 2,

http://energyalmanac.ca.gov/naturalgas/natural_gas_supply.html.

²⁴¹ Bioenergy Association of California, "Decarbonizing the Gas Sector: Why California Needs a Renewable Gas Standard," November 2014, http://www.bioenergyca.org/wp-content/uploads/2015/03/BAC_RenewableGasStandard_2015.pdf.

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

than 10 facilities are converting diverted organic waste to energy, and only two community-scale (non-combustion) projects are converting forest and agricultural waste to biogas. These relatively few facilities represent a small fraction of the total number of facilities needed to produce and process the available biogas feedstocks in California. By way of comparison, Germany has more than 7,500 operating digesters producing biogas for energy.²⁴²

Despite the many benefits that biogas can provide to America—and especially for high-value use when upgraded to transportation-quality RNG (see Section 7.6.3)—actual production of biogas for this purpose remains quite limited in the U.S. Among the barriers to expanded production are the high costs (compared to fossil gas) of producing biogas, cleaning it up to RNG, and injecting it into the pipeline system. Even in California, which is the leading U.S. market, biogas production currently comprises less than one percent of the state’s natural gas supply. However, production facilities are increasing as interest grows to realize the many national, state and local benefits. This includes companies and organizations that are producing their own RNG on-site, specifically to fuel heavy-duty NGVs. Section 7.6.2 describes one such major RNG production project in California, the CR&R Environmental Services anaerobic digester being built in Perris to fuel refuse trucks. Other examples include Blue Line Transfer (San Francisco Bay) and Atlas Disposal (Sacramento area), which both now operate refuse trucks on RNG produced from municipal solid waste digesters. Building of these waste-to-RNG production facilities have been partially enabled by funds from the State of California.

7.6.2. Case Study: CR&R Refuse Trucks in Perris California

CR&R Environmental Services (CR&R), a waste services and recycling company that serves approximately 2.5 million customers in Southern California, is currently building its Perris Anaerobic Digestion and Biomethane Facility Expansion Project. This four-phase project broke ground in mid-2014 with Phase 1. The project’s initial phase is scheduled to be completed in Q2 of 2016, at which point it will begin accepting organic feedstock and producing RNG shortly thereafter. Phase 2 was initiated in July 2015, and is scheduled to be completed in Q4 of 2016.

Phase 1 of the project will convert approximately 83,600 tons of green and food waste (from 10 local cities) into approximately one million diesel gallon equivalents (DGE) of RNG. Upon completion of all four phases, the CR&R facility will produce approximately four million DGE from 335,000 tons of organic material annually. The RNG will be used by CR&R to fuel its fleet of 900 CNG refuse collection



Figure 33. Landfill-based RNG production near Dallas (Fleets & Fuels)

²⁴² SeeNews, <http://renewables.seenews.com/news>.

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

trucks and to deliver excess low-carbon RNG into the local pipeline network via a utility interconnect, where it can be purchased by other third party buyers for additional use as a vehicle fuel, or for other traditional uses of natural gas.

The RNG produced at this facility will use a high-solids anaerobic digester (HSAD). As previously described, the HSAD RNG pathway is one of the only transportation fuel sources recognized by CARB as currently being a net negative carbon pathway. That's because this process diverts food and green waste from landfills or composting facilities that emit GHG emissions into the atmosphere, and instead uses this waste to produce RNG. This avoids potential CO₂e emissions from reaching the atmosphere (see the box and CARB

The HSAD pathway primarily converts two categories of organic wastes into biogas, and eventually, biomethane. By diverting organic food and green wastes destined for a landfill or a composting facility to an anaerobic digester, a useful transportation fuel can be produced, a valuable co-product (fertilizer) can be derived, and GHG emissions can be avoided.

— CARB, “Proposed Low Carbon Fuel Standard (LCFS) Pathway for the Production of Biomethane from High Solids Anaerobic Digestion (HSAD) of Organic (Food and Green) Wastes, Staff Report,” July 2012, <http://www.arb.ca.gov/fuels/lcfs/2a2b/internal/hsad-rng-rpt-062812.pdf>

quote). Although the Perris HASD production facility itself has not yet been scored, the default value assigned by CARB (with application of the efficiency factor associated with heavy-duty NGVs) is -25.4 gCO₂e per MJ of RNG combusted. (Refer back to the “CI” graph in Section 6.)

In addition to its cutting-edge HSAD RNG production facility, CR&R will be an early recipient of trash trucks powered by the CWI ISL G NZ engine. This completes the game-changing tandem of near-zero-emission engines and ultra-low-CI fuel. The result will be that CR&R will operate the cleanest full-function heavy-duty refuse trucks in the world, achieving NO_x emissions levels at 0.02 g/bhp-hr while fueled by CNG with increasingly higher percentages of RNG. A net negative carbon rating will occur with natural gas blends at or above about 73 percent RNG (see Figure 35 for the estimated declining GHG emissions of refuse trucks using varying percentages of HSAD RNG, based on CR&R's case).

CR&R's project may be a harbinger for many potential anaerobic digester projects nationwide. As noted, California is implementing various policies and programs to reduce landfilling of solid waste, phase out



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

the use of green waste as alternative daily cover, and make food waste from commercial operations available for organics recycling. CR&R's waste-to-RNG production project serves as a model for converting large amounts of readily available organic waste into exceptionally low CI RNG that can potentially displace tens of millions of diesel gallons (see Section 7.7). This presents the opportunity to fuel California's vast HDV fleet with RNG produced in state from waste streams, while significantly reducing GHG emissions from the HDV sector. Used in tandem with near-zero-emission heavy-duty NGVs—as CR&R is now doing for beta testing—this provides a replicate-able strategy for many HDV fleets to reduce NOx emissions by 90 percent relative to the best diesel technology, thereby helping local air basins to achieve and/or maintain NAAQS.

7.6.3. Cost to Produce RNG

The current cost to produce RNG is a major impediment to its increased use in America. While it depends on the feedstock and specific process, in rough terms, it currently costs at least an additional \$8 per MMBtu²⁴³ to produce RNG compared to conventional natural gas. Given that the spot price of fossil gas is below \$2 per MMBtu (as of the writing of this report), high production costs for RNG are a formidable barrier to it widely replacing fossil gas, in the absence of market incentives. On a straight dollars-per-energy basis, RNG is simply not competitive with fossil gas.

There are many variables that come into play to dictate such higher costs. These include but are not limited to the following:

- Feedstock and production pathway (this dictates transportation costs, conversion efficiency, gas conditioning / clean-up requirements, etc.)
- Volume of gas produced (this largely determines potential for achieving economies of scale)
- Variability of construction costs
- Interconnection with gas pipeline system (distance, land use, pipeline diameter, incremental compression costs)
- Gathering/aggregating organic feedstock
- Disposal of contaminants
- Incremental testing, monitoring and recordkeeping

Transportation fuel markets present a unique opportunity for RNG producers to mitigate the relatively high price of RNG compared to conventional natural gas. Two valuable mechanisms exist today that generate supplemental revenue streams, based on the societal benefits provided by RNG production and use. These mechanisms are 1) Renewable Identification Numbers (RINs) under the federal Renewable Fuel Standard (RFS), and 2) credits under California's Low Carbon Fuel Standard (LCFS). Figure 36 shows the average monthly prices / values for RINs (blue line, in \$ per RIN) and LCFS credits

²⁴³ Personal communication from RNG industry representative to GNA, March 2016.

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

(gray line, in \$ per MT of CO₂e). As can be seen, RINs and LCFS credits are currently at or near their highest values over the last 15 months.

The monetary value of using RNG as a transportation fuel in these two programs is further described below.

The Federal RFS – The RFS requires fuel providers to integrate a percentage of renewable fuel into their fuel products. This has created a market in which fuel providers can purchase the renewable value of a fuel to meet their requirements. The result is a robust market for RINs, which are created when a renewable fuel is delivered to a transportation customer for use. One RIN is equivalent to 77,500 British Thermal Units, or the lower heating value of neat ethanol. The economics can be complex, but the bottom line is that RNG used as a transportation fuel can generate important revenue through the RFS. In calendar year 2015, with the average D3 RIN value for an “advanced biofuel” (e.g., RNG) at

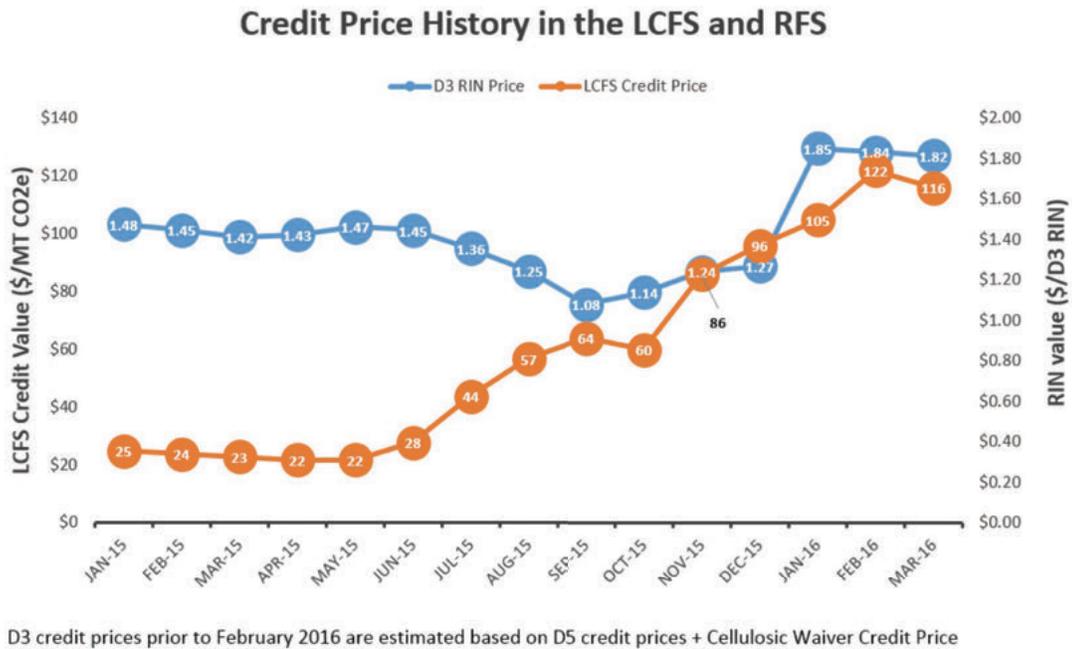


Figure 36. 2015 credit value history in U.S. RFS (D5 RINs) and California’s LCFS

approximately \$1.33, this translated to a \$2.21 credit for each DGE of RNG produced and consumed as a transportation fuel.²⁴⁴ In the first part of 2016, these D3 RINS have produced as much as \$1.86, which is approximately \$3.00 per DGE of RNG produced

California’s Low Carbon Fuel Standard – Under the LCFS, CARB requires transportation fuel providers to reduce the carbon content of all transportation fuels sold in California by 10 percent by 2020. Producers

²⁴⁴ Internal calculation by GNA. **Note:** D3 RIN prices for 2016 are based on actual reported credit transactions; prices prior to 2016 are calculated using the D5 credit price plus the Cellulosic Credit Wavier cost of \$0.64/RIN.

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

of low-CI fuels can generate and trade GHG credits based on the difference in the CI of the alternative fuel (e.g., RNG) and the conventional fuel it displaces (diesel in the case of most HDVs). Credits can then be purchased by petroleum fuel producers to comply with the regulation's required 10 percent CI reduction of baseline diesel or gasoline. Since various RNG pathways have among the lowest CI values recognized by CARB, they can generate relatively high amounts of revenue when RNG is used as a substitute transportation fuel. For example, at the applicable price in March 2016,²⁴⁵ a supplier of RNG produced through the very-low-CI high-solids anaerobic digester (HSAD) process would have received an LCFS credit of \$1.77 per DGE of RNG produced.

For RNG used in California, producers can take advantage of RINs under the federal RFS and credits under California's LCFS. As of March 2016, the estimated D3 RIN value was \$3.01 per DGE, and the LCFS credit added another \$1.77 per DGE, resulting in a combined value of about \$4.78 per DGE of RNG. This reflects a snapshot in time, and (as the previous figure showed) there has been some volatility in the prices of both RINs and LCFS credits. But, it is clear that the combined value of RINs and LCFS credits has proven to be a compelling driver for RNG to replace fossil gas as a transportation fuel in California (recall that 17 million DGE of RNG were used to generate LCFS credits in Q3 of 2015 alone). Market dynamics can be complex with many parties involved²⁴⁵, but the bottom line is that end users today are generally able to purchase ultra-low CI RNG at the same (or lower) price as fossil natural gas (see next subsection). As a result, RNG is successfully replacing diesel (and fossil gas) as a HDV fuel in California.

At this early stage of market development, transportation fuels appear to offer a viable market for RNG, when these types of incentives exist. Over the next several years, it appears that RINs and LCFS credits will continue to offer major sources of supplemental revenue for RNG producers if associated with producing RNG (e.g., tipping fees and digestate as compost), this revenue linked to environmental value significantly helps improve the economics of producing RNG from waste and using it as a transportation fuel. This is true for commercial RNG providers (e.g., Clean Energy) and end user fleets that produce their own biogas onsite (e.g., Waste Management in Altamont, CA, and CR&R in Perris, CA, etc.).

However, there are economic and policy uncertainties that must be addressed, to the extent possible, for RNG to become a wide-scale replacement for fossil natural gas, even in the relatively lucrative transportation fuel market. These include, but are not limited to the following:

- Prices / values for RINs and LCFS credits are determined by market forces and regulations that are subject to change; this makes them fluctuate and difficult to predict. In fact, due to policy-related uncertainties about the federal RFS2 and California's LCFS, there are no guarantees about the longevity of their associated monetary incentives.
- Such uncertainty surrounding these programs and RIN or LCFS credit prices prevents investors and financial institutions from utilizing these potential revenue streams in their evaluation of the credit worthiness of proposed new RNG-production projects.

²⁴⁵ LCFS and/or RIN transactions for RNG as a transportation fuel typically involve multiple parties; the renewable fuel producer, a marketer (which may be the producer), a distributor and an end user. The important end result is that end users can purchase RNG at the same (or lower) price as fossil natural gas.

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

- Even if investors are willing to consider RIN and LCFS revenue, it can be difficult to secure long-term contracts from fleet fuel buyers; thus, major uncertainty remains about how to collateralize RIN and LCFS revenue.
- If project developers are unable to utilize RIN and LCFS credits to secure financing, they can be compelled to turn to other mechanisms to secure capital, such as diverting substantial RNG resources to produce renewable electricity, where long-term (albeit less lucrative) contracts can be secured.

7.7. Feedstock Potential for Expanded RNG Production in America

This section discusses the potential for expanded U.S. production of RNG. There are many variables and assumptions associated with the various production pathways and feedstocks. Thus, depending on the assumptions made (for example, technically recoverable vs. economically recoverable feedstock), various government, industry and academic sources have put forth a wide range of estimates for RNG production. Further discussion is provided below.

7.7.1. National Potential from Biogas Production

The U.S. Department of Energy (DOE) prepares an ongoing report entitled Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply. Generally referred to as the “Billion-Ton Study,” DOE updates this report approximately every five years. The Billion-Ton Study estimates “potential” biomass within the contiguous United States that could be converted into various types of renewable energy. One objective has been to determine if enough dry tons of biomass (i.e., a billion tons) exist in the U.S. to annually produce (in “a sustainable manner”) enough renewable energy to displace approximately 30 percent of U.S. petroleum consumption.

DOE updated and improved this study in 2011, and validated its key 2005 conclusion that the U.S. does have sufficient resources to replace at least 30 percent of its petroleum use with renewable biomass by 2030. However, the study also cautioned that this refers only to *technical feasibility*; it does not take into account key factors such as cost, price, and land use changes. Stating the intuitively obvious, the report noted that “at this time, the market to purchase and process all the potential biomass resources into biofuel does not exist.” DOE is now in the process of further improving the modeling and preparing a 2016 update.²⁴⁶ Notably, DOE’s Billion-Ton Study does not focus on renewable *transportation* fuels. Where mentioned, reference is primarily made to the potential for producing *liquid* vehicle fuels (e.g., biodiesel and ethanol).

DOE’s National Renewable Energy Laboratory (NREL) is the federal organization most dedicated to research, development, commercialization and deployment of renewable energy. NREL has specifically assessed the potential for U.S. production of biomethane from various biogas pathways, including use as transportation RNG. In its 2013 study entitled “Biogas Potential in the United States,” NREL recently

²⁴⁶ U.S. Department of Energy, U.S. Billion-Ton Update: Biomass Supply for Bioenergy and Bioproducts Industry, August 2011, https://www1.eere.energy.gov/bioenergy/pdfs/billion_ton_update.pdf.

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

estimated that biomethane derived from landfills, wastewater treatment, animal waste, and “industrial, institutional, and commercial” (IIC) sources could amount to nearly 7.9 million metric tonnes per year of technically convertible biomass. This is equivalent to **2.9 billion DGE per year** of RNG, or roughly 10 to 13 percent of our nation’s current diesel use for on-road HDV goods movement.²⁴⁷ NREL noted that this does not account for biogas generation from lignocellulosic feedstocks such as forestry and crop residue or purpose-grown energy crops.²⁴⁸

Figure 37 graphically depicts NREL’s state-by-state estimates for this potential to produce biomethane, broken out by individual counties.²⁴⁹ As indicated, good potential generally exists for RNG production (in metric tonnes per year) throughout the U.S. Particularly strong states and regions include California, Oregon, Washington, Arizona, Florida, numerous Great Lakes states, parts of Texas, and the entire Eastern Seaboard. Given that the methodology in this study does not account for lignocellulosic biogas feedstocks (forestry and crop residue or purpose-grown energy crops.), it’s not surprising the highest potentials on the map correspond to centers with large human populations and/or major dairy operations (i.e., large sources of human and/or animal waste).

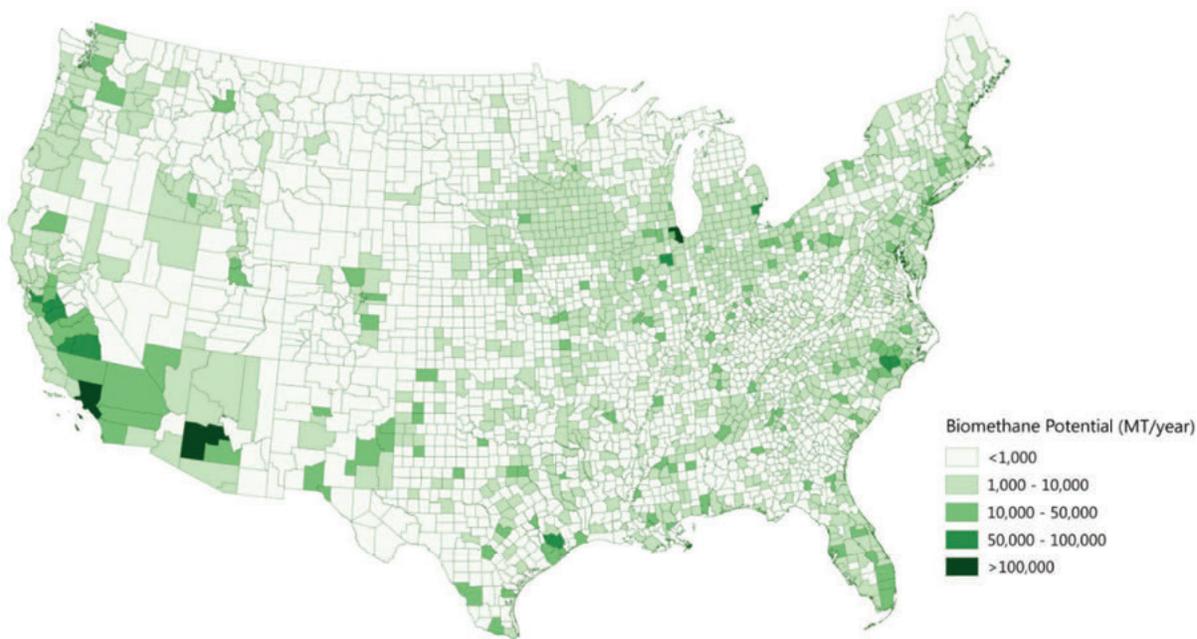


Figure 37. U.S. biomethane potential (landfills, animal waste, wastewater, IIC sources)

Source: NREL Biofuels Atlas <http://maps.nrel.gov/biofuels-atlas/> . Map produced by GNA

²⁴⁷ As noted in Section 1, America’s uses about 29 billion diesel gallons per year to transport freight with heavy-duty trucks.

²⁴⁸ National Renewable Energy Laboratory, “Biogas Potential in the United States,” August 2013, <http://www.nrel.gov/docs/fy14osti/60178.pdf>.

²⁴⁹ National Renewable Energy Laboratory, “Biofuels Atlas,” <http://maps.nrel.gov/biofuels-atlas/>.

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

A separate assessment from the Union of Concerned Scientists estimated that the U.S. could produce **3.9 billion DGE per year** of RNG solely from the organic portion of waste that is currently landfilled and treated at wastewater facilities.²⁵⁰ The assessment also notes that the U.S. currently only captures about 18 percent of these resources. Of the biogas fraction that is captured, only 45 percent is used for energy production. The remaining 55 percent is flared (combusted into CO₂). This highlights the significant potential to increase biomethane production from existing biogas sources, while also reducing upstream GHG emissions.

The National Petroleum Council (NPC) led another important study in 2012 on potential domestic production of RNG as a transportation fuel. NPC analyzed the theoretical U.S. potential for RNG production during the 2035 to 2050 timeframe, taking into account all energy crops, agricultural wastes, forestry wastes and other gasified wastes. Transmission criteria, such as access to the pipeline grid, were not considered. This yielded NPC's estimated "practical RNG potential" for the U.S. of approximately 4.7 trillion cubic feet per year, defined as the biomass resource "that could reasonably be used based on technical and economic constraints." The NPC study converted this annual RNG-production potential to 40 billion gasoline gallon equivalents (GGE) of transportation fuel, which equates to approximately **35 billion DGE per year**.²⁵¹ Roughly, this is 1.2 times the volume of diesel consumed each year by the entire U.S. on-road heavy-duty truck fleet engaged in freight movement (refer back to Section 2).

The American Gas Association (AGA) derived an even larger estimate for the technical potential of RNG production in the U.S. Based on an assumption of "complete utilization of all available feedstocks," the AGA study estimated the U.S. total annual RNG production potential to be 9.5 quadrillion Btu's, which is roughly equivalent to **70 billion DGE per year**.²⁵²

7.7.2. National Power-to-Gas Potential

The long-term potential for using Power-to-Gas technology to produce RNG in America has not yet been quantified to the same degree as production using biogas pathways. However, this potential appears to be very large. Unlike biogas-to-biomethane production of RNG from waste or residue streams, Power-to-Gas technology to make renewable methane (i.e., RNG) is not limited by feedstock supply. It requires only renewable power and relatively small volumes of water.²⁵³

Today, there is growing interest within the U.S. about Power-to-Gas conversion as a potential energy storage solution that could offer attractive costs and operating characteristics. DOE reports that this potential storage solution is undergoing advanced study and approaching commercial application.²⁵⁴ Specifically, Power-to-Gas technology can help provide large-scale storage of renewable energy

²⁵⁰ Union of Concerned Scientists, "Trash to Treasure," above.

²⁵¹ National Petroleum Council, "An Overview of the Feedstock Capacity, Economics, and GHG Emissions Reduction Benefits of RNG as a Low-Carbon Transportation Fuel," March 2012, http://www.npc.org/FTF_Topic_papers/22-RNG.pdf.

²⁵² American Gas Association, "The Potential for Renewable Natural Gas," September 2011, <http://www.gasfoundation.org/researchstudies/agf-renewable-gas-assessment-report-110901.pdf>

²⁵³ California Hydrogen Business Council, Power to Gas – The Case for Hydrogen, Summary of Key Findings, October 2015, <https://www.californiahydrogen.org/content/chbc-releases-white-paper-power-gas-and-hydrogen-energy-storage>.

²⁵⁴ U.S. Energy Information Administration, "Power-to-gas brings a new focus to the issue of energy storage from renewable sources," July 24, 2015, <https://www.eia.gov/todayinenergy/detail.cfm?id=22212>.

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

generated by intermittent solar and wind power. Power producers and grid operators can capture surplus power from these sources and use it to split water into hydrogen and oxygen, using commercially mature electrolysis technology. The methanation process (also well-understood, and used today at commercial scale) is used to turn the renewable hydrogen into methane, which can be more easily transported and stored.

Currently, exploratory efforts in the U.S. involving Power-to-Gas technology are focused on storing renewable energy for use in electricity generation. As noted, Power-to-Gas also has important potential to produce clean, low-carbon renewable methane for near-zero-emission heavy-duty NGVs. The subsystems that make up Power-to-Gas technology have been commercially available in industrial applications for decades. However, technical challenges exist with integrating and optimizing those subsystems into complete commercial systems that can efficiently make and store cost-competitive renewable energy. Thus far, there are no commercial Power-to-Gas projects in the U.S., and research efforts are not focused specifically on using methanation to make RNG for fueling NGVs. By contrast, there are an estimated 35 Power-to-Gas operations in Europe (23 in Germany), some of which include this feature.

7.7.3. California's Potential for In-State RNG Production

Looking at California's case is both informative and important to better understand the big-picture potential of RNG as an HDV fuel in the U.S. As further described, California has resources to potentially meet a significant share of its current transportation fuel consumption, through production of RNG and other renewable fuels from local organic matter waste streams. With addition of Power-to-Gas facilities and the potential for energy crops grown for biogas production, RNG production within California's borders has potential to displace major percentages of the state's current diesel consumption (about 3.5 billion gallons per year). As noted earlier in this report, CARB has identified the need for hundreds of thousands of heavy-duty HDVs with low-NOx engines to be phased into the state's goods movement sector. The RNG industry indicates that there is sufficient biomethane available today—and projected to be available in the future—for these HDVs to run primarily on RNG.

The University of California, Davis (UC-Davis) has taken a lead role in helping CEC and CARB assess the potential to produce RNG (and other renewable transportation fuels) from biogas-related pathways. Table 15 summarizes work conducted by UC-Davis to estimate the volume of California-generated organic waste that is *technically available* to produce bio-based RNG. Figure 38 provides a graphic version of these values. As both the table and figure show, the UC-Davis team estimated that California has sufficient in-state sources of biogas to *technically* produce 1.858 billion DGE of RNG per year.²⁵⁵ This constitutes approximately 62 percent of California's annual consumption of diesel fuel in its entire transportation sector. It should be noted that some knowledgeable parties have questioned if UC-Davis's methodologies overstate the potentials for *technically available* organic waste in California.

²⁵⁵ Data compiled by Rob Williams, University of California, Davis. April 2014 (revised 19 May, 2014). Source material: Williams, R.B., B.M. Jenkins and S. Kafka (California Biomass Collaborative). 2014. An Assessment of Biomass Resources in California, 2012 – Draft. Contractor Report to the California Energy Commission. PIER Contract 500-11-020.

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

Table 15. Estimated annual biomass and RNG potential in California (UC-Davis)

Type of Feedstock for Biogas Production	Amount Technically Available	Technical Potential for RNG Fuel Production (Diesel Gallon Equivalents)
Forestry and Forest Product Residue	14.2 M BDT ^a	628 million
Landfill Gas	106 BCF ^b (gas)	404 million
Municipal Solid Waste (lignocellulosic fraction)	7.0 M BDT ^a	310 million
Agricultural Residue (Lignocellulosic)	5.4 M BDT	241 million
Animal Manure	3.4 M BDT ^a	90 million
Municipal Solid Waste (food, leaves, grass)	0.94 M BDT ^a	76 million
Waste Water Treatment Gas	11.8 BCF ^b (gas)	58 million
Fats, Oils and Greases	207,000 tons	50 million
Total Potential Annual Volume (if Converted to RNG)		1.858 Billion DGE
^a M BDT = million bone dry (short) tons ^b BCF = billion cubic feet Source: these values were compiled by Rob Williams et al, University of California, Davis. For details and assumptions on all entries, see "Research Results Forum for Renewable Energy Technology and Resource Assessment," September 3, 2014, http://www.energy.ca.gov/research/notices/2014-09-03_workshop/2014-09-03_CREC_presentation_for_Workshop.pdf		

It is important to recognize that the *economically realistic* volume of RNG that can be produced in California is likely to be significantly less than the volumes estimated based on *technically available* organic waste. For example, it may not be economically feasible to convert dairy waste from small dairies to transportation fuels. But, it is clear that the technical potential for biogas production from organic waste in California is quite large. In fact, sufficient volumes of RNG can be produced from landfills and dairy operations to displace a large fraction of the state’s on-road diesel use.

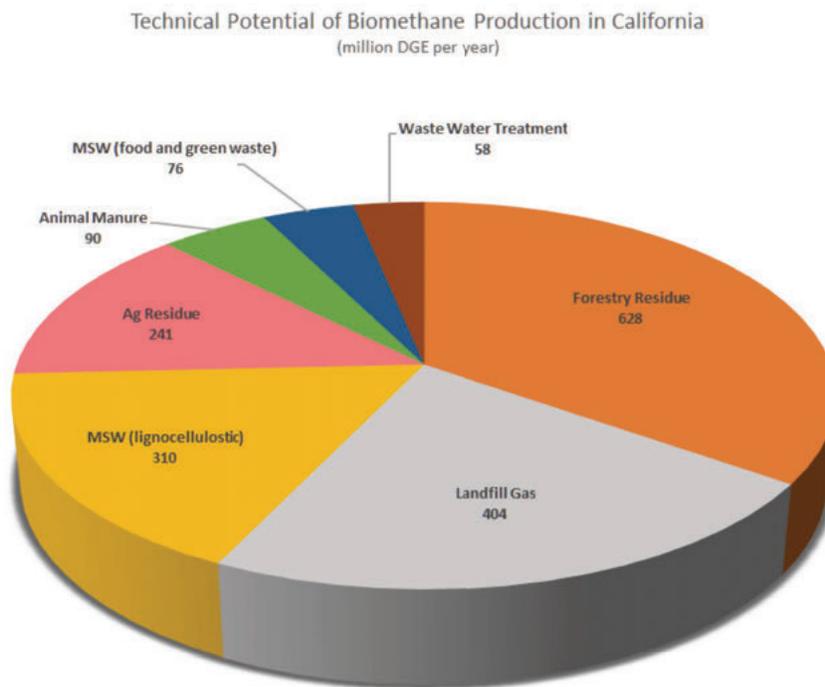


Figure 38. Technical potential of biomethane production in California (UC-Davis 2014)

In practical application, there are a number of limitations to reach the full potential for actually producing RNG as a transportation fuel. Examples of factors that come into play include 1) the availability of various feedstocks, 2) the costs of upgrading biogas to meet gas quality specifications applicable to grid injection and/or vehicle use, and 3) the costs of pipeline interconnection and injection of biomethane. These challenges are being addressed and largely overcome, for the current relatively small scale of RNG production and use.

In the future, other untapped additional sources of biogas have potential to provide biogas production in California, and nationwide. These include algae-based production, or crops grown on land not farmable for food. Advocacy organizations such as the Bioenergy Association of California envision a confluence of favorable policies, regulations, incentives and economics where the state could produce enough RNG by the 2050 timeframe to entirely displace diesel fuel consumed by the state's HDV goods movement sector (i.e., more than 3 billion gallons per year).²⁵⁶

7.8. Current Policy Framework for Increased RNG Production for Transportation

There are a number of federal, state and local policies that exist now, or are under consideration, that may help increase production and end use of RNG in America as a transportation fuel. Brief summaries are provided below.

²⁵⁶ Information provided to GNA by Julia Levin, Executive Director, Bioenergy Association of California.

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

7.8.1. Federal Policies

As noted, EPA administers the federal RFS, which is governed by a system of environmental attributes referred to as RINs. RINs, which are generated based on the general category of fuel rather than the specific production facility, can provide a significant additional source of funding for RNG when used as a transportation fuel. To date, the volume of cellulosic biofuels used under RFS2 are well behind the statutory schedule, but the expectation is that large increases in volume will be realized in the near future. In August 2014, EPA made changes to the RFS that improve opportunities for biogas to be utilized as a vehicular fuel. Specifically, EPA qualified biogas as a cellulosic biofuel, which is the RFS category that delivers the greatest climate benefit per gallon. EPA has approved pathways for cellulosic biogas that include biogas-derived CNG and LNG produced from landfills, municipal waste-water treatment facility digesters, agricultural digesters, and separated municipal solid waste digesters. These technologies are more mature than other processes to make cellulosic biofuel. The produced biogas can either be upgraded to RNG to fuel NGVs (with no blend wall, unlike ethanol), or used to make electricity that powers BEVs. To date, facilities have been approved for blending upgraded biogas into transportation CNG or LNG, but the BEV route has not yet been utilized.²⁵⁷

7.8.2. California Policies

California has adopted a number of policies in recent years to accelerate biogas development and commercial growth. Examples (some of which have been previously described) include the following:

The 2012 Bioenergy Action Plan – This plan was adopted by nine California agencies and Governor Brown’s Office. It details 55 separate actions that state agencies should take to increase production and use of bioenergy.

Assembly Bill 1900 (Gatto, 2012) required the CPUC to set new standards for pipeline biogas injection and to adopt policies and allocated funding to promote and facilitate biogas development and transmission.

The Low Carbon Fuel Standard – The LCFS requires California fuel providers to reduce the average carbon intensity (CI) of California’s transportation fuel supply by 10 percent by 2020, and maintain that 10 percent reduction post-2020. Fuels that have a lower CI than the baseline diesel or gasoline fuel they replace generate LCFS credits. It has helped to incentivize new biogas production projects in California, such as CR&R’s HSAD facility in Perris. Notably, recent run ups in the price of LCFS credits are improving the economics of biogas projects.²⁵⁸ CARB is now considering “more aggressive targets” for the LCFS, such as 15 to 20 percent reductions (below 2010 levels) in the average CI by 2030.²⁵⁹

²⁵⁷ International Council on Clean Transportation, “Final EPA Rule for Renewable Fuel Standard 2014-2016 Volumes,” December 2015, <http://www.theicct.org/sites/default/files/publications/RFS%20Policy%20Update%20vFinal.pdf>.

²⁵⁸ Between May 2015 and February 2016 the price of an LCFS credit has risen from \$22/metric tonne (MT) to \$127/MT. See <http://www.arb.ca.gov/fuels/lcfs/lrtmonthlycreditreports.htm>.

²⁵⁹ California Environmental Protection Agency, First Update to the Climate Change Scoping Plan, http://www.arb.ca.gov/cc/scopingplan/2013_update/first_update_climate_change_scoping_plan.pdf.

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

The Alternative and Renewable Fuel and Vehicle Technology Program - This program was established by Assembly Bill 118 in 2007, and is supported by Cap-and-Trade auction proceeds. Recently, Assembly Bill 8 extended the funding until January 2024. The focus of this CEC-administered program is “to develop and deploy innovative technologies that transform California’s fuel and vehicle types to help attain the state’s climate change policies.” As Table 16 shows, since the ARFVTP’s inception in 2009, approximately \$606 million has been invested in advanced vehicle technologies and alternative fuels; of this, \$58 million has specifically been allocated towards biomethane production.

Table 16. ARFVTP Funding Summary 2009 – 2015

Investment Areas	Funding Amount (millions)	Percent of Total (%)	Number of Awards
Biofuels (37% Biomethane)	\$158	26	61
Electric Drive	\$199	33	153
Natural Gas	\$95	16	185
Hydrogen	\$113	19	72
Workforce Development	\$28	4	58
Market & Program Development	\$13	2	16
Totals	\$606	100	545

Source: Jim McKinney, Program Manager, California Energy Commission, February 2016

Greenhouse Gas Reduction Fund (GGRF) - California’s 2014-2015 Budget included \$832 million in Cap-and-Trade revenues, of which the state allocated a total of \$22 million to biogas projects in the dairy and solid waste sectors. The state budget included \$200 million for a Low Carbon Transportation Fund. CARB, which implements GGRF program, did not allocate funding to biogas projects, despite its status offering the lowest CI score of any transportation fuel. To date, no Cap-and-Trade funds have been used to fund biogas development in the wastewater, landfill, forestry or agricultural sectors. CARB’s Second Investment Plan (for fiscal years 2016-2017 through 2017-2018) was submitted to the Legislature in January 2016. It identifies potential State investment priorities to help achieve GHG emission reduction goals, benefit disadvantaged communities, and yield valuable co-benefits in California. This new draft plan recognizes the value of small scale projects to produce RNG. Cited examples are 1) “a cooperative of dairy digesters located in close proximity and providing renewable natural gas for trucks or other heavy equipment in the Central Valley”; and 2) “a clean, efficient biomass plant located close to forestry activities that uses dead or diseased trees removed for fuel as an alternative to open burning the waste in slash piles.”

The Electricity Program Investment Charge – EPIC funds clean electricity R&D, technology deployment, and market facilitation. The CEC allocated more than \$37 million to bioenergy projects in 2014, including

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

both anaerobic digestion and gasification projects, but it is not clear how much will be allocated to bioenergy in future years.

7.9. Current Barriers to Increased Production and Use of Transportation RNG

Despite considerable progress in California and other states, there are formidable barriers that must be overcome to unlock the full potential of RNG to become a major transportation fuel in America. The policies enacted in recent years are helping to incentivize new projects to produce RNG from various pathways (primarily involving biogas). However, challenges remain before cost-effective RNG production can be realized in the large volumes needed to transform America's HDV transportation sector. CARB summarized this in its April 2016 "Proposed Short-Lived Climate Pollutant Reduction Strategy":

Stubborn barriers remain, including connecting distributed electricity and biogas projects, which have slowed previous efforts to reduce emissions of SLCPs and capture a wide array of benefits. These barriers are not insurmountable, and now is the time to solve them. State agencies, utilities, and other stakeholders need to work immediately to identify and resolve remaining obstacles to connecting distributed electricity with the grid and injecting renewable natural gas into the pipeline. Supporting the use of the cleanest technologies with funding and strategies that maximize air quality, climate, and water quality benefits can accelerate their introduction. Building market certainty and value for the energy, soil amendment, and other products that come from compost or anaerobic digestion facilities will help to secure financing to accelerate and scale project development.²⁶⁰

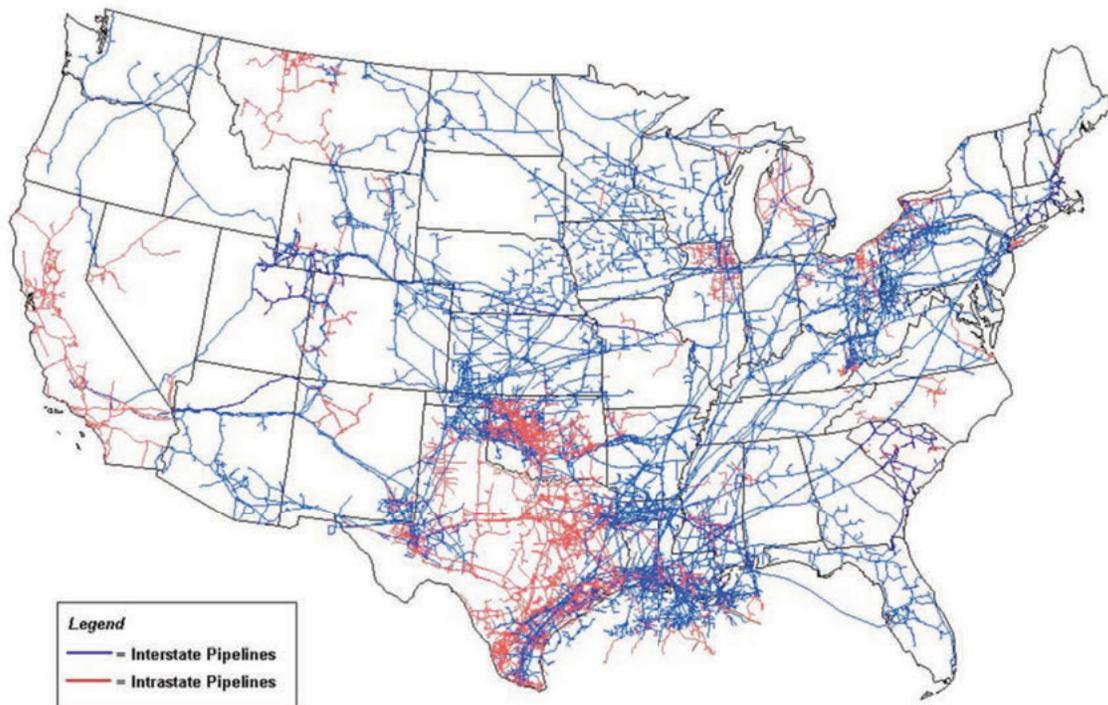
Examples of barriers specific to RNG production and its distribution to heavy-duty NGV fueling stations are summarized below.

7.9.1. Lack of Market Supply and Demand Certainty for Biogas

²⁶⁰ California Air Resources Board, "Proposed Short-Lived Climate Pollutant Reduction Strategy," April 2016, <http://www.arb.ca.gov/cc/shortlived/meetings/04112016/proposedstrategy.pdf>.

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

One of the biggest barriers for developing biogas—especially if intended for use as a transportation fuel—is the lack of market certainty. On the policy side, both the federal RFS and California’s LCFS have faced numerous legal and political challenges. Since LCFS credits and RFS RINs are critical for biogas to compete with the costs of fossil fuels, uncertainty associated with challenges and revisions to these programs can make project financing difficult to obtain. If it is challenging for project developers to secure long-term contracts to sell biogas as a transportation fuel, they may choose instead to sell it for electricity generation. While this is a less-lucrative market, such arrangements may be more secure and “bankable.” Moreover, the market for RNG as a vehicle fuel in California is getting tight—recent CARB data shows that more than 60 percent of the NGV fuel consumed in California is already biomethane.



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

Figure 39. U.S. intrastate and interstate natural gas pipeline system

The market for NGV in Oregon (which also has an LCFS program) is very small. As is noted above, the LCFS credits available in California and potentially Oregon are a critical economic driver for many RNG-production projects. The California (and Oregon) markets for RNG as a vehicle fuel must expand to send demand signals to the marketplace that can stimulate greater investment in biomethane production facilities.

7.9.2. Existing or Potential Competing Uses for Biogas Feedstock and RNG

As America’s energy sector moves increasingly toward the use of renewable feedstock, there will be competing uses for biogas. One overarching challenge will be to ensure that sufficient volumes of RNG

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

are available for transportation markets, given that there will be competition for its use in stationary power generation and other uses (e.g., space and water heating in buildings). An advantage is that transportation use of RNG is a “higher-value market” compared to power generation and other potential uses.²⁶¹ However, as described above, there are disadvantages and barriers associated with using RNG for this purpose. Even if RNG is specifically produced for transportation markets, it will not necessarily be available for heavy-duty NGVs with ultra-low-NOx engines. There may be competition (over the long term, at least) to use the RNG for 1) making renewable hydrogen to fuel FCVS, or 2) generating renewable electricity to recharge BEVs.

7.9.3. Requirements for Biomethane Pipeline Access and Transmission

Biogas can be used where it is produced, for onsite power generation, process heat and (if upgraded to RNG/biomethane) nominated for use via pipeline as a vehicle fuel or at an offsite power plant. In fact, in most cases biogas is produced for uses away from the production site. Typically, it will be transported by pipeline. This requires conditioning and upgrading the biogas to pipeline quality, and then injecting it as RNG into the vast U.S. intrastate and interstate common carrier natural gas pipeline system (Figure 39). Successfully navigating the policies, regulations, logistics, and economics of pipeline injection and transport can be complex for biogas-derived RNG. This has caused its practical implementation to develop somewhat slowly.

For example, statutes governing RNG injection into common carrier pipelines have undergone significant changes in recent years. As public policy has shifted to encourage increased RNG production and consumption (especially in California), regulatory agencies such as the California Public Utilities Commission (CPUC) have developed new regulations, guidelines and requirements. In 2012, California enacted a trio of bills (AB 1900, AB 2196, SB 1122) designed to adopt new standards and improve the ability to safely transport RNG by pipeline. In early 2014, the CPUC adopted new standards for pipeline injection of biogas from landfills, dairies and wastewater treatment facilities. The new standards include gas quality specifications for biomethane that identify constituents of concern and establish new testing and monitoring protocols. Although discussed, the injected gas’s minimum heating value (Btu requirement) for each California Local Distribution Company, LDC) was not changed.²⁶² The pipeline gas standards adopted in California by the CPUC are some of the strictest in the U.S., and are meant to protect the health and safety of the LDC’s employees, customers and the general public. At the same time, application of these standards creates unique financial risks and costs for any biomethane project that intends to interconnect with a California gas utility.

One of the high project start-up costs associated with biogas upgrading is the cost of connecting a biomethane production facility to the common carrier pipeline network. In particular, pipeline interconnection costs in California—reportedly more than \$1 million per mile of interconnection—can

²⁶¹ See for example “Natural Gas Will Challenge Oils Monopoly as a Transportation Fuel, IHS Study Says,” news release, June 3, 2015, <http://press.ihs.com/press-release/energy-power-media/natural-gas-will-challenge-oils-monopoly-transportation-fuel-ihs-st>.

²⁶² CPUC Decision 14-01-034, adopted January 2014 in Rulemaking 13-02-008.

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

be many times those of other states.²⁶³ Since biogas developers currently have to bear such costs, this makes it much less attractive to develop pipeline biogas projects—especially if relatively long interconnections are required. Additionally, it places the burden on the developer to consolidate enough feedstock in a centralized location such that the cost of production is economically viable.

In early 2015, the CPUC adopted a new incentive program to help defray the costs of pipeline biogas interconnection. Adopted pursuant to AB 1900, the CPUC allocated \$40 million in ratepayer funds to pay up to \$1.5 million or 50 percent of a biogas project's interconnection costs. The funds can only be used to help offset the costs of interconnection for pipeline quality biomethane; they cannot be used to help condition and upgrade the biogas to meet the new pipeline biomethane standards. While the bioenergy industry favors this biogas interconnection incentive as “a good step in the right direction,” the industry has stated that it is not nearly sufficient to significantly reduce the overall costs of producing pipeline quality biomethane to help stimulate new projects.²⁶⁴

New legislation initiatives such as California's AB 1900 are generally intended to help facilitate and promote development of biomethane production, and transport of the resulting RNG by common carrier pipelines.²⁶⁵ However, the desired results have not yet been fully realized. For example, since the CPUC adopted new pipeline standards in California, no biogas projects have started injecting biomethane into common carrier pipelines. According to the Bioenergy Association of California, the new standards made the hurdle rate for biogas projects a major challenge.²⁶⁶ Meeting the minimum BTU requirement may be financially difficult, depending on the biogas composition (e.g., landfills can have high nitrogen and oxygen levels).

7.9.4. General Lack of Knowledge by Policy and Decision Makers

According to the biogas industry, a general lack of knowledge on the part of policy and decision makers continues to hamper expansion of RNG production and end use in the U.S. This can result in misconceptions or out-of-date information about the environmental benefits and/or impacts. Examples cited by the industry include the following:

- There can be confusion between burning trash or biomass and producing biogas; the latter process uses only organic waste as the feedstock and does not utilize combustion, which releases criteria pollutants and carbon dioxide (a GHG).
- For agricultural and forestry waste, there are concerns about sustainability and how to ensure that only waste is collected and used, according to science-based sustainability criteria.
- There is concern that beneficially using landfill gas could perpetuate the practice of landfilling organic waste. However, such concern may be alleviated as new policies are being adopted by California and other states that seek to reduce or phase out landfilling.

²⁶³ Joint Opening Comments of the Bioenergy Association of California and California Association of Sanitation Agencies, filed May 22, 2014, in CPUC Rulemaking 13-02-008.

²⁶⁴ *Ibid.*

²⁶⁵ AB 1900, SEC. 5, 399.24(a).

²⁶⁶ Bioenergy Association of California, information provided to GNA by Julia Levin, Executive Director.

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

- There is concern that federal, state or local regulatory agencies sometimes adopt regulations and/or incentives that clearly favor specific technologies, rather than establishing performance-based criteria. For instance, California agencies have received state GGRF (from Cap-and-Trade auction proceeds) to fund organic waste diversion and dairy waste-to-energy projects. In soliciting projects to fund, eligible projects were limited to anaerobic digester pathways. The most productive and equitable approach is to allow a variety of technologies to compete based on performance criteria. In this case, gasification and pyrolysis technologies could be better suited to program goals.
- While key agencies like EPA, CARB, DOE and CEC have recognized the major GHG-reduction benefits of RNG as a transportation fuel, greater progress is needed to adopt or strengthen government incentive programs designed to increase RNG production specifically for use in heavy-duty NGVs.

7.10. Summary: Production, Supply and Cost of RNG for Transportation

RNG is a gaseous mixture of methane and other compounds that is produced from renewable sources, using either biological or chemical processes. RNG production from multiple pathways is highly sustainable, environmentally. Waste streams are converted to energy sources that ultimately displace higher-pollution fuels, while simultaneously generating economic value and other benefits. Even if not used as a transportation fuel, RNG offers several important societal benefits; these include reduction of upstream methane leakage and flaring, mitigation of catastrophic wildfire, and improvements to agricultural processes and yields. RNG production facilities can help create local jobs and economic development in virtually any community across America.

RNG's game-changing benefits relate to its potential for fueling large numbers of near-zero-emission heavy-duty NGVs. Used together to replace conventional diesel HDVs, this fuel and engine technology can immediately begin delivering 90 percent reductions in NOx emissions for the large U.S. fleet of on-road HDVs. Simultaneously, RNG will also 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.

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 RFS RINs and California LCFS credits. The net result is that currently, RNG is an affordable ultra-clean fuel. Hundreds of millions of DGE are currently being consumed by many heavy-duty NGV fleets 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, including beta testing of CWI's near-zero-emission ISL G NZ engine. RNG is a "drop-in" ultra-low-GHG fuel for today's existing heavy-duty natural gas engines; it can be blended at any mixture with conventional natural gas. That means an estimated 65,000 in-use medium- and heavy-duty NGVs that are currently moving goods and people on America's highways can potentially start using RNG, where locally available and price competitive.

To date, actual production of RNG to fuel heavy-duty NGVs is relatively limited in America. Barriers and challenges must be addressed before production will occur on a very wide scale. However, with concentrated focus and strong efforts to develop this important resource, the potential for greatly expanded production is significant. Several robust and credible studies estimate there are sufficient

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

technically recoverable feedstocks in the U.S. to produce tens of billions of RNG DGEs. This is enough RNG to fuel large portions of America's heavy-duty on-road goods movement sector.

Subsequent sections of this report provide further discussion and specific recommendations about how to unlock our nation's large 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 increased management of environmental waste streams, capture of "fugitive" methane emissions to produce RNG, and use it as a substitute for diesel to power 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 clean, environmentally benign renewable fuels.

8. Importance of Proportionally Allocated, Cost-Effective Incentives

8.1. Introduction

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. EPA has found that incentives “provide a unique contribution to environmental management” and can “generate benefits beyond what is possible with traditional regulations.” In addition to helping realize environmental benefits, incentives can provide impetus for technological change. Not surprisingly, incentive programs specifically designed to reduce air pollution from motor vehicles and displace petroleum have become increasingly widespread, diverse and effective over the last several decades.²⁶⁷

In particular, incentives funds have been extremely important in accelerating commercialization of alternative fuel HDVs, and their replacement of older in-use diesel vehicles. To help on the supply side, incentives have encouraged manufacturers to build and market cleaner HDVs by driving production economies of scale and reducing technology costs. On the demand side, incentives have encouraged fleet operators to purchase alternative fuel HDVs despite their higher first costs and requirements to undergo new learning curves (e.g., fueling and maintenance) for operation. Success across all these facets is exemplified by the instrumental role government incentives have played over the last two decades to deploy heavy-duty NGVs. This has been strongly justified by the major surplus reductions of NO_x and DPM achieved when replacing baseline diesel HDVs (especially pre-2007) with HDVs powered by natural gas engines using either fossil natural gas or RNG.

As all this suggests, 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. Furthermore, 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.

California continues to lead the nation in funding programs designed to help reduce the incremental costs of low- and zero-emission HDVs. Currently, California has many active programs that will allocate hundreds of millions of dollars in grant funds over the next several years to reduce emissions from in-use diesel vehicles and equipment. CARB is generally the lead state agency, although some programs are implemented in partnership with CEC and California’s local air districts such as SCAQMD, SJVAPCD, Bay Area AQMD, and others. California’s programs that most involve on-road HDVs include:

- Low Carbon Transportation Investment and Air Quality Improvement Program (AQIP)
- Hybrid and Zero-Emission Truck and Voucher Incentive Project (HVIP)

²⁶⁷ U.S. EPA, “The United States Experience with Economic Incentives for Protecting the Environment,” accessed online at <http://yosemite.epa.gov/ee/epa/erm.nsf/vwrepnumlookup/ee-0216b?opendocument>.

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

- Carl Moyer Program
- Goods Movement Emissions Reduction Program (aka, Proposition 1B)
- Alternative and Renewable Fuel and Vehicle Technology Program (ARFVTP)

Many other states are also using federal, state or local funds for incentive programs that help deploy cleaner HDV technologies and fuels. For example, Texas has been extremely active and effective in using incentive programs to deploy such vehicles. Federal funding from the Congestion Mitigation and Air Quality (CMAQ) Program and the Diesel Emission Reduction Act (DERA) Program have been successfully used to fund low- or zero-emission vehicle projects, including deployments in Kentucky, Mississippi, New Hampshire, New Jersey, New York, South Carolina, Ohio Pennsylvania and Tennessee. Local-level programs, such as New York's Truck Voucher Incentive Program and the City of Chicago's Drive Clean Truck Program, also support deployment of low- or zero-emission heavy-duty vehicles. In 2015 alone, approximately 100 different solicitations were opened across the nation to deploy low- or zero-emission HDVs. The solicitations accounted for nearly \$750 million in grant funding dedicated to natural gas, battery-electric, and fuel cell vehicles in the heavy-duty market.²⁶⁸

8.2. Addition of Near-Zero-Emission Natural Gas Engines into the Equation

In 2014, CARB specifically adopted its optional low-NOx emissions standards to help incentivize development, manufacture and deployment of HDVs powered by near-zero-emission engines (of any fuel type). This was instrumental in accelerating CWI's development, certification and commercialization of the near-zero-emission ISL G NZ engine. Field demonstrations of ISL G NZ engines are well underway, and commercial deployments are now beginning for HDV applications such as transit buses and refuse haulers.

Relative to CWI's standard ISL G natural gas engine, preliminary estimates indicate that end users will pay an *additional* incremental cost for the CWI ISL G NZ engine of approximately \$8,000, including applicable taxes.²⁶⁹ In other words, if the current price of a heavy-duty NGV with the ISL G engine is \$50,000 higher than a comparable (baseline) diesel HDV, the price of the same NGV with an ISL G NZ engine will be approximately \$58,000 higher than the diesel baseline.

The benefits of CWI's new NZ engine technology—a 90 percent NOx reduction, combined with deep GHG reductions when using RNG—appear to far outweigh its additional incremental cost. Still, with diesel fuel priced as low as \$2 per gallon, it is more important than ever for government agencies to provide strong incentives to accelerate deployment of such ultra-low emission technologies. The combination of today's low diesel prices and the NZ engine's even higher incremental cost make it harder for HDV diesel fleets that switch to heavy-duty near-zero-emission NGVs to offset the associated capital investments.

²⁶⁸ This is based on GNA's internal knowledge gained through its Funding 360 Program.

²⁶⁹ This figure is based on statements made by CWI and its authorized dealers at the NGV Industry Summit, February 24, 2016, and verified by GNA via direct communication with HDV OEMs as well as several "first mover" fleet operators pursuing the purchase and deployment of ISL-G NZ technology in their operations.

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

To continue addressing its extraordinary air pollution problems, California is leading the push for commercialization and deployment of heavy-duty NZEV and ZEV technologies. It is difficult to overstate the importance of the State using incentives to expedite these deployments. This point is summarized by CARB in its draft Mobile Source Strategy²⁷⁰ (emphasis added by author):

- *Early investments and incentives that accelerate deployment of zero and near-zero technologies in the heavy-duty sector are essential.*
- *Incentives will not only encourage increased development and deployment of zero and near-zero emission technologies in heavy-duty applications, they will also help encourage acceptance of new technology with consumers.*
- *Investments that bring the cleanest technologies to market as quickly as possible are essential for achieving near-term criteria pollutant reductions to our air quality and climate goals.*

8.3. The Best (and Most-Immediate) “Bang for the Buck”

CARB’s statements highlight the importance of using public investments for clean vehicle deployments that provide the best and most-immediate “bang for the buck.” As was clearly demonstrated by the three graphs in Section 6.9 (refer back to page 106), 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 immediate application of public incentive dollars for reducing mobile source air pollution is to allocate the largest portion towards deployment of near-zero-emission on-road heavy-duty NGVs using increasing volumes of RNG. This will enable deployments starting in 2016 for transit and refuse—and expanding in 2018 to high-impact Class 8 goods movement trucking—to achieve the greatest volumes of key pollutant reductions at the lowest cost, in the fastest timeframe possible.

SCAQMD and SJVAPCD—the local air districts in charge of rapidly achieving very large NOx reductions in California’s two extreme ozone nonattainment areas—have recognized that there is no viable “stick” approach here. Even if CARB adopts a mandatory low-NOx standard for on-road heavy-duty engines, it will likely not take effect before the 2024 model year. Thus, SCAQMD and SJVAPCD must rely on incentives to achieve maximum early deployment of near-zero-emission heavy-duty NGVs, and thus have a chance to meet near-term ozone attainment deadlines. For example,

- In the SCAB, SCAQMD has identified incentives for early deployment of heavy-duty ZEVs and NZEVs as a major strategy under its emerging 2016 AQMP. SCAQMD has noted that government investments should deploy technologies that meet multiple objectives - air quality, climate, toxics, and energy efficiency. SCAQMD’s specific focus will be on deployment of “existing commercialized” NZEV and ZEV technologies and energy sources, or newer technologies that are nearing commercialization.²⁷¹

²⁷⁰ CARB, “Draft Mobile Source Strategy,” October 2015.

²⁷¹ South Coast Air Quality Management District, “Blueprint for Clean Air,” 2016 AQMP White Paper, October 2015, <http://www.aqmd.gov/docs/default-source/Agendas/aqmp/white-paper-working-groups/wp-blueprint-final.pdf?sfvrsn=2>.

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

- SCAQMD and CARB staff have jointly estimated that “approximately 100,000 to 150,000” near-zero-emission heavy-duty trucks would need to be deployed in the SCAB by 2023 to meet goals for early penetration of these cleaner heavy-duty technologies. If incentive funding is the primary mechanism to achieve these deployments, it would require funding for approximately 15,000 to 20,000 trucks per year over a seven-year period, depending on truck availability. CARB notes that “the incentive funding required for this effort would go beyond the amount currently authorized for existing programs through 2023.”²⁷²
- In California’s Central Valley (the SJVAB), SJVAPCD is strongly pursuing incentives that specifically focus on large-scale deployment of Class 8 natural gas trucks using low-NOx engines. This includes SJVAPCD’s advocacy for CARB to 1) increase funding for heavy-duty NGVs and fueling infrastructure, 2) include conventional (fossil) natural gas (in addition to RNG) as an ongoing fuel eligible for incentives, and 3) increase overall funding totals for these categories through more-inclusive award rules, particularly under the Greenhouse Gas Reduction Funds (from Cap-and-Trade auction proceeds) and the Proposition 1B goods movement program.²⁷³

8.4. Tensions between Goals to Reduce NOx and/or GHG

Today’s clean HDV incentive programs tend to be focused on reducing 1) NOx emissions (to meet *legally enforceable* federal deadlines to attain ozone and PM_{2.5} NAAQS); 2) GHG emissions (to meet climate change *goals*); or 3) both pollutants simultaneously. Due to inherent tradeoffs in controlling these pollutants, incentive programs for clean HDVs can have “tensions” between meeting these two goals. This is especially the case if the funding source is specific to reducing one or the other pollutant. In California, statutory requirements have forced CARB to strongly focus on the State’s aggressive GHG-reduction goals. From the perspective of many stakeholders in the NGV industry, this has resulted in disproportionately high amounts of incentive funds going towards non-combustion BEV and FCV technologies. Simply put, many key State policy makers have strongly favored heavy-duty BEVs and FCVs for being the foundation of California’s long-term GHG reduction strategy.²⁷⁴

The result (to date) has been that insufficient incentive dollars have been allocated for large-scale deployment of commercially ready near-zero-emission heavy-duty NGVs. It is these high-impact HDV applications—where there are no foreseeable commercial pathways to heavy-duty BEVs and FCVs 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. Moreover, heavy-duty NGVs provide significant GHG reductions by using fossil natural gas, and those that already use RNG are achieving deep GHG reductions. Thus, strong 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 gradually blended into the fuel mix.

²⁷² California Air Resources Board, “Mobile Source Strategy – Discussion Draft” (page 72), October 2015.

²⁷³ San Joaquin Valley Air Pollution Control District, “Review and Approve Action Plan for Promoting the Use of Natural Gas Technology for Goods Movement in the San Joaquin Valley,” staff presentation at Governing Board Study Session, May 6-7, 2015, http://www.valleyair.org/Board_meetings/GB/agenda_minutes/Agenda/2015/May/StudySession/final/05.pdf.

²⁷⁴ This has essentially been stated in public by high-level representatives of California agencies such as CARB and CEC.

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

There are multiple incentive programs in California where increased grant funding allocations are warranted for rapid deployment of heavy-duty near-zero-emission NGVs, given their immediate and large addressable NOx- and GHG-reduction benefits. Key current examples are the CARB-administered AQIP and Low Carbon Transportation Advanced Technology Demonstration Projects. California has appropriated \$325 million to CARB over the last three budget cycles for these projects. These funds are focused on low carbon transportation investments that can reduce GHG emissions. Under AQIP, CARB is now implementing a program using GGRF funds to help develop and demonstrate ZEV and NZEV technologies. There are two separate project categories, “Zero Emission Truck Demonstration” and “Multi-Source Facility Demonstration,” which allow “applicants” such as port, air quality management districts or other government entities to develop and administer “large-scale zero-emission” demonstration” projects.

While this California program targets both zero emission and near-zero emission technologies, it currently does not allow funding of near-zero-emission heavy-duty NGVs. As noted, this is the only fuel-engine technology certified to California’s optional low-NOx standard, which was specifically established by CARB to facilitate incentive fund allocations. Further, the program does not currently allow funding for heavy-duty NGVs when using RNG, which can provide negative CI values from certain pathways.²⁷⁵ The program uses a definition for “near-zero” that is restricted to internal combustion engines used in electric-drive HDVs as range extenders. Zero-emission operation is required within certain areas designed as “disadvantaged communities” (e.g., in port boundaries, a railyard, an intermodal facility, etc. The greater the “zero-emission miles” that can be provided, the higher these projects are scored. Yet, when not in a zero-emission mode, the truck can be powered by a standard U.S. EPA 2010 diesel engine certified to 0.2 g/bhp-hr NOx.

Some tangible progress is being made towards better allocating government incentive funds for clean HDV technologies, to make awards more proportional with their ability to rapidly effect large NOx and GHG reductions. Perhaps most significant, California officials appear to now be considering increased funding for near-zero-emission heavy-duty NGVs under incentive programs such as AQIP. CARB staff are now recommending a maximum \$15,000 per engine incentive to cover the incremental cost for CWI’s certified 8.9 liter near-zero-emission natural gas engine. Specifically, this will cover costs above the purchase and installation costs of a conventional natural gas engine. This funding is proposed for both new vehicle purchases and engine repowers. CARB will allow these incentives to be combined with other State incentives such as CEC’s NGV support program. CARB staff are also supporting “an additional modest incentive” (to be determined) to support the required use of RNG. This is currently specific to CWI’s ISL G NZ engine, but CARB intends to recommend appropriate incentive amounts for other engines certified to the optional low-NOx emissions standard as they come to market.²⁷⁶

²⁷⁵ It is worth noting that a negative CI value provides greater GHG emission benefits than does a BEV charged by a renewable energy source, such as a solar array or wind turbine.

²⁷⁶ California Air Resources Board, “Discussion Document on the 2016-2017 Funding Plan for Low Carbon Transportation and Fuels Investments and the Air Quality Improvement Program (AQIP),” March 25, 2016.

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

For FY 2016-17, CARB staff is recommending that \$23 million in Low Carbon Transportation funding be allocated to deploy these natural gas engines, to “meet the expected demand for the funding cycle.” While significant, \$23 million would help buy down the incremental cost of only 1,533 deployments (at \$15,000 per near-zero-emission engine, which is the current assumption by CARB including installation costs). This amount of funding per year over the next seven years would help buy down the “extra incremental” costs of roughly 11,000 heavy-duty near-zero-emission NGVs. Assuming the balance of the incremental NGV costs can be obtained from other California sources, this would deploy an order-of-magnitude fewer near-zero-emission HDVs than CARB and SCAQMD estimate are needed in the SCAB by 2023, to deliver sufficient NOx reductions from this sector to achieve ozone attainment.

As of mid-2016, there are positive signs that CARB staff are investigating funding sources and mechanisms to allocate significantly larger State incentives for deployment of near-zero-emission heavy-duty NGVs (and RNG). Other examples of positive developments to recognize the emergence of commercially available near-zero-emission heavy-duty NGV technology include the following:

- EPA’s fiscal year 2016 Clean Diesel Funding Assistance Program is offering \$26 million in new incentive funds through the Diesel Emissions Reduction Act (DERA). Under this program, EPA will provide extra incentive funds for HDV replacement and repower projects if they incorporate engines that meet CARB’s Optional Low-NOx standards. For example, EPA will cover 35 percent of the total costs (i.e., not just incremental) for a 2015 model year or newer non-drayage HDV equipped with an engine certified to CARB’s highest tier Optional Low-NOx standard of 0.02 g/bhp-hr. (Currently, only the CWI ISL G NZ natural gas engine meets this standard.) While not a trivial amount of funding, it is notable that the same HDV with an engine meeting EPA’s national NOx standard (i.e., 10 X higher NOx emissions) is eligible for up to 25 percent of the total costs. Notably, the program will pay 45 percent of the total costs for an “all-electric” HDV, which does not yet exist commercially in HHDV applications like short- or long-haul trucking.
- Under California’s Proposition 1B Goods Movement Program, the newest (2015) guidelines include some higher allowances for NZEV technology. For example, truck owners can receive up to \$100,000 per truck when they replace an eligible older diesel truck with a new truck powered by a new engine that has certified to the lowest tier (0.02 g/bhp-hr) of CARB’s optional NOx standard. However, the program offers \$200,000 to replace an eligible diesel truck with a new zero-emission truck.
- CEC continues to proactively push for heavy-duty NGVs. CEC provides up to \$100 million per year for projects that “will transform California fuel and vehicle types” to help attain the state’s climate and air quality policies. Among the CEC’s key policy objectives are to increase the use of alternative and renewable fuels, produce RNG in California, expand the State’s natural gas fueling station network, and improve the efficiency of heavy-duty natural gas engines.²⁷⁷

Despite this recent progress, incentive funding levels in California and across the country are disproportionately too low for immediately available near-zero-emission heavy-duty NGVs. Since no regulatory mechanism appears likely to drive deployments of near-zero-emissions NGVs in California prior to 2024, incentives are the only mechanism to spur meaningful early penetration into the HDV

²⁷⁷ California Energy Commission, AB 1257 Natural Gas Act Report: Strategies to Maximize the Benefits Obtained from Natural Gas as an Energy Source, Draft Staff Report, September 16, 2015.

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

sector, as CARB and other regulators have identified to be so important. 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. It is therefore critical that federal, state and local transportation and air quality officials work together to maximize incentive funding for deployments of heavy-duty near-zero-emission NGVs (or any other fuel-technology pathway that can achieve the NOx and GHG reduction targets).

8.5. Summary: Major Incentive Increases Needed for Heavy-Duty NGVs

Government incentives are an essential mechanism for accelerating commercialization of low- and zero-emission HDVs to replace older in-use diesel vehicles. Agencies that allocate public funds to reduce HDV emissions must carefully consider the magnitude, type and timeline of air quality benefits that can be achieved. In other words, such awards must be cost-effective and proportional with their ability to rapidly achieve large NOx and GHG reductions.

The use of government incentives to rapidly deploy near-zero-emission heavy-duty NGVs provides an extremely cost effective, immediate approach for rapidly achieving essential NOx reductions from on-road HDVs. These incentives will also provide deep climate change benefits, as growing deployments of heavy-duty NGVs increasingly fuel with drop-in, ultra-low-GHG RNG. As described in Section 6.9 (see the graph in Section 6.9.1), \$500 million in incentive funds could "buy" much greater quantities of NOx and GHG reductions by supporting deployments of natural gas trucks, compared to deployments of heavy-duty BEVs or FCVs (for further discussion on NOx emissions from heavy-duty BEVs, see Section 11 Appendix 1: Details of Power Plant NOx Equivalency Analysis). This \$500 million analysis is hypothetical, because only the natural gas option is available today. Heavy-heavy-duty trucks powered by batteries and/or fuel cell technologies are not expected to be commercially available for one to two decades.

Despite immediate availability of near-zero-emission heavy-duty NGVs, insufficient incentive dollars are currently allocated for their deployment in very large numbers. High-impact heavy-duty trucking applications most need such incentive funds. Without immediate start to deployment of near-zero-emission heavy-duty trucks, attainment of federal ozone and PM2.5 NAAQS may not be achievable for many urban areas within legally required timeframes. Because RNG is an extremely low (and in some cases negative) fuel for carbon intensity, support and incentives are also needed to increase its use in heavy-duty NGVs. This will strongly contribute to meeting GHG-reduction goals in California (included those focused on reducing SLCPs), and across the nation.

It is therefore critical that federal, state and local transportation and air quality officials work together to maximize incentive funding for deployment of heavy-duty near-zero-emission NGVs and fueling infrastructure. Section 10 provides specific recommendations on key actions.

9. White Paper Conclusions

9.1. Heavy-Duty Diesel Engines and Trucks: Workhorses, at a High Price

Heavy-duty diesel engines are formidable power-plants, and the “workhorses” for America’s on-road transportation of goods and people. Large “heavy-heavy duty trucks” (HHDTs) powered by diesel engines currently serve an *essential* role in America’s “goods movement” economy. HHDTs constitute the second largest and fastest-growing segment of the U.S. transportation system, for both energy use and emissions of harmful pollutants. They emit disproportionately high levels of NO_x, PM, various TACs, and GHGs. More than any other sector, it is imperative that air quality and transportation officials take rapid action to reverse these HHDT trends, and reduce their negative societal impacts. However, this must be done without disrupting or unnecessarily compromising the indispensable services provided by America’s heavy-duty on-road transportation sector.

9.2. Game Changing Ultra-Low NO_x Engine Technology for Wide-Scale HDV Use

An estimated 65,000 medium- and heavy-duty NGVs using conventional (fossil) natural gas and/or RNG are operating on America’s roadways today, logging millions of miles while emitting very low NO_x, zero cancer-causing DPM and lower-than-diesel GHGs. Now, game-changing heavy-duty engine technology has emerged as the direct descendant of that same robust, commercially proven fuel-technology combination. In 2016, Cummins Westport Inc. (CWI) and its OEM partners are joining together to launch the cleanest commercially available heavy-duty truck technology in the market today, and for the foreseeable future.

The new CWI 9L NZ engine can be immediately deployed to achieve 90 percent NO_x reductions (compared to the cleanest diesel HDVs on the road today) in a wide array of high-impact HDV applications. These include transit buses, refuse trucks, and short-haul delivery trucks. Because the engine has the same footprint and basic requirements as the conventional CWI 9L engine, the NZ version can be deployed using either a repower or a replacement strategy. In 2018, CWI is expected to complete the game-changing paradigm by certifying and commercializing its 11.9 liter ISX12 G NZ engine to a near-zero-emission level (90 percent below the existing federal NO_x standard). This engine can work extremely well in the most challenging HHDT application: long- or regional-haul trucks. Additionally, by 2017 CWI expects to roll out its 7 liter ISB low-NO_x natural engine, which will be certified to achieve (at a minimum) a 50 percent NO_x reduction below the existing federal standard.

The emissions performance of heavy-duty NGVs equipped with this NZ engine technology are even more impressive when compared to the “upstream” (i.e., electricity-production) emissions that result from recharging comparable zero-emission battery-electric HDVs. Specifically, this white paper has demonstrated (on a preliminary basis) that near-zero-emission heavy-duty natural gas engines emit smog-forming NO_x at levels as low as, or possibly lower than, the NO_x emissions associated with generating electricity used to charge battery-electric HDVs. This is the case today even in states like California and Oregon, which have the cleanest electricity grids in the United States.

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

This does not diminish the important air quality benefits of, or the important need to commercialize and deploy, heavy-duty battery electric (or fuel cell) vehicles. All types of commercially viable near-zero-emission and zero-emission HDVs are needed to help transform America's transportation sector.

9.3. RNG Completes the Game Changing Equation

To complement the 90 percent NO_x reduction provided by landmark heavy-duty natural gas engine technology, conventional (fossil) natural gas provides significant GHG-reduction benefits. With increasing use of renewable natural gas (RNG), this engine-fuel combination can immediately begin transforming America's heavy-duty transportation sector towards sustainable ultra-low NO_x and GHG operation. RNG provides the lowest carbon intensity value of any heavy-duty transportation fuel available in the market today. According to CARB, RNG can provide "deep" GHG reductions, which are badly needed from the on-road HDV sector to combat climate change.

RNG can be produced from multiple pathways that are all highly sustainable environmentally. Some RNG pathways are rated as negative for carbon intensity, meaning that production and end use actually result in a net reduction of GHG emissions. Even if not used as a transportation fuel, RNG offers several important societal benefits that include reduction of upstream methane leakage, mitigation of catastrophic wildfire, improvements to agricultural yields, and creation of local jobs and economic development virtually anywhere in North America. However, the unique and game-changing benefits of RNG relate to its potential to fuel large numbers of near-zero-emission heavy-duty NGVs in California and nationwide, within the next decade.

While the potential is large, significant barriers must be overcome. It will require a combination of incentives, public and private investments, and new or amended regulations for America to significantly increase the use of organic waste streams and power-to-gas technologies to produce large volumes of RNG as a transportation fuel, and realize the many associated societal benefits.

9.4. Checking the Boxes of Key National, State and Local Policy Goals

This White Paper describes how the combination of heavy-duty near-zero-emission NGVs and RNG (in gradually increasing volumes with natural fossil gas) can uniquely and immediately help resolve many of America's most-pressing transportation-related environmental and energy challenges. These game-changing engines can launch California and the entire U.S. towards a transformed heavy-duty transportation sector that achieves a wide array of important energy and environmental policy goals. This engine-fuel pathway can simultaneously reduce criteria pollutants (for attainment of NAAQS) and displace petroleum with renewable fuel (to meet petroleum- and GHG-reduction requirements).²⁷⁸ It can do this simultaneously, which is essential because regulators and policymakers will not allow tradeoffs that reduce one regulated pollutant while causing another to be increased.

²⁷⁸ U.S. Environmental Protection Agency, "Working to Reduce Ozone in California," October 1, 2015, accessed online at <http://www3.epa.gov/ozonpollution/pdfs/20151001californiafs.pdf>.

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

Table 17 lists condensed versions of key national, state and local policy goals. The final column summarizes how this fuel-technology combination can “check the boxes” of each policy goal by providing major or significant associated benefits.

Table 17. Policy goals met by heavy-duty near-zero-emission NGVs + RNG

Overarching Goal / Objective(s)	Examples of Specific Policies	Pathway for Achievement with H-D Near-Zero Emission NGVs and/or RNG
Attain National Ambient Air Quality Standards (NOx, PM _{2.5})	- EPA / CARB / Air Districts: Reduce NOx emissions > 90%	<ul style="list-style-type: none"> ✓ MHDVs: 2016 start of deployments (buses, refuse trucks, and short haul trucks) with ISL-G NZ engines @ >90% lower NOx ✓ HHDTs: 2018 start of deployments (Class 8 regional and line-haul trucks) with ISX12 G NZ engines @ >90% lower NOx ✓ LHDTs: 2017 start of deployments (Class 5-6 delivery trucks) with ISB6.7 low-NOx engines @ ~50% lower NOx
Reduce petroleum use by HDVs	- Federal: Petroleum Reduction / Displacement - CA: Petroleum Reduction (goal only, to date)	✓ Immediate and growing deployments of heavy-duty NGVs in high-fuel-use HDV applications
Reduce GHG emissions from HDVs	- Federal: Phase 2 GHG Reduction - CA: AB 32, Executive Orders S-3-05 and B-30-15	✓ Immediate and growing deployments of heavy-duty NGVs in high-fuel-use HDV applications using “drop in” ultra-low CI RNG blended with low CI fossil gas
Reduce methane and black carbon emissions (SLCPs)	- Federal: New Source Rule for Methane - CA: Short-Lived Climate Pollutant (SLCP) Strategy	<ul style="list-style-type: none"> ✓ Expanded projects that capture methane gas at landfills, dairy operations, etc. to produce RNG ✓ Reduced biomass burning (including wildfire) to control BC ✓ Reduced diesel PM emissions in on and off road applications
Produce and use renewable fuels and power	- Federal: Renewable Fuel Standard - CA: Renewable Portfolio Standard	✓ Ability to produce millions to billions of RNG DGE from biomass and power to gas
Produce sustainable low carbon transportation fuels	- CA / Other States: Low Carbon Fuel Standard	✓ Continued reductions in fuel supply CI through increased RNG production using very low or negative CI pathways
Improve freight system efficiency and emissions profile	- CA: Sustainable Freight Action Plan (Executive Order B-32-15)	✓ Achieve 90% NOx reductions and lower tailpipe GHGs in HHDT applications (not yet addressable by heavy-duty BEVs / FCVs)
Reduce diesel PM / toxic air contaminant emissions (especially in disadvantaged communities with disproportional exposure)	- Federal: Diesel Emissions Reduction Act - CA: Diesel Risk Reduction Plan, Truck and Bus Regulation	✓ Opportunity to replace older in-use diesel HDVs with commercially proven NGVs that emit no diesel exhaust and provide zero-emissions-equivalent NOx levels to reduce ozone and PM _{2.5} in environmental justice areas
Maintain system interconnectivity / regional integration	- Federal, regional, state and local transportation planning organizations	✓ Continuity for high-horsepower, high torque HHDTs that can provide sufficient range for interregional goods movement
Create jobs and economic development	- Federal, regional, state and local entities	✓ Provision of new jobs in virtually any urban or rural area
Provide synergism with agriculture and farming	- Federal, regional, state and local entities	✓ Improvement of farm soil and crop yields for America’s mega-billion dollar agriculture industry

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

This presents a very important point: *today's near-zero-emission heavy-duty NGVs—fueled by conventional gas that is increasingly blended with RNG (where available)—are more than just “bridge technologies”* to America's long-term heavy-duty transportation sector. They can immediately and greatly enhance federal, state and local efforts to meet air quality standards and climate protection objectives, beginning now and into the foreseeable future. These “new-generation” heavy-duty NGVs can and should become foundations of America's long-term transportation sector. There simply is no other near-term option for wide-scale commercial deployment of ultra-clean HDVs in highly impactful and challenging heavy-heavy-duty vehicle (HHDV) applications such as regional and long-haul trucking. This does not discount the potential for heavy-duty fuel cell or battery-electric vehicles to also enter this market over the longer term. The current consensus is that it will take one to two decades before full commercialization will occur. This would likely be followed by gradual penetration into the HDV sector.

9.5. Challenges and Opportunities

This white paper describes the technical, institutional and economic challenges that must be fully addressed before America can achieve wide-scale use of near-zero-emission heavy-duty NGVs fueled by increasing percentages of RNG. On the engine and vehicle side, these challenges include the need to 1) reduce incremental subsystem costs of heavy-duty NGVs, including engines and on-board fuel storage systems; 2) expand the number of manufacturers offering near-zero-emission engine platforms; 3) further improve engine / vehicle efficiency, and 4) continue reducing direct-vehicle emissions of methane.

The major challenge to unlock the full potential of RNG as a major transportation fuel in America relates to cost. Producing RNG is significantly more expensive than conventional (fossil) natural gas. This creates market uncertainty that makes it more difficult to attract investors for RNG-production projects. It will be important to sustain the monetized value brought to RNG transactions by California's LCFS and the federal RFS. However, it will still be important to reduce the higher costs of producing RNG, which are primarily associated with relatively expensive conversion, cleanup, and transport processes compared to fossil natural gas. Specific areas for cost reduction appear to focus on biogas cleanup and pipeline interconnection. Another important challenge is to continue reducing upstream methane leakage rates, which is wasteful, costly and remains a significant source of GHG emissions.

While these challenges are significant, they are dwarfed by the very large opportunities that exist in America for expanded production and use of RNG as a transportation fuel. Major momentum is underway now to better realize considerable initial opportunities. With the current RFS and LCFS revenue streams, today RNG is an affordable ultra-clean heavy-duty transportation fuel. Hundreds of millions of DGE are currently being consumed by many heavy-duty NGV fleets 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 (refer to case studies provided elsewhere in this report). Beginning in mid-2016, some of these users will begin switching to CWI's new ultra-low NOx ISL G NZ engine (Santa Monica Big Blue Bus, CR&R, etc.).

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

Importantly, RNG can continue to gradually replace fossil gas in increasingly large percentages, in California and across the United States. The pace of this transition can occur according to regional dynamics (supply, cost, demand, regulatory drivers, etc.). There is no “blend wall” for RNG; it is a drop-in fuel for today’s existing heavy-duty natural gas engines at any mixture with conventional natural gas. That means there is opportunity to start using RNG—where the fuel is locally available and price competitive—in an estimated 65,000 in-use medium- and heavy-duty NGVs currently moving goods and people on America’s highways.

The ultimate opportunity, however, is America’s large population of heavy-duty on- and off-road vehicles that can technically be switched to heavy-duty natural gas engines using growing percentages of RNG. Studies from the U.S. Department of Energy, the State of California, the National Petroleum Council, the Union of Concerned Scientists, the American Gas Association and academia estimate there is vast potential for RNG production in the United States, with sufficient technically recoverable feedstocks to produce enough RNG to fuel large percentages of the HDVs that power America’s large goods movement sector. Continued building of success within the transportation fuel market can provide “market pull” for RNG to become a widely used substitute for fossil petroleum and natural gas in multiple uses. This can strongly help address energy, air quality and GHG-reduction goals that are specific to other key energy use sectors.

9.6. The Need for Immediate Action

The roadmap to begin transforming America’s heavy-duty transportation sector is clear. To meet daunting federal requirements for clean air—while also aggressively battling climate change—California will continue to be the key battleground in America. Consequently, many existing or new policies, issues and funding programs that help dictate deployment rates for near-zero-emissions heavy-duty NGVs and RNG will continue to be focused on California. However, it is very likely that virtually all these policies, issues and programs will, to some extent, significantly impact what happens in other states and regions. Likewise, with a very large part of California’s heavy-duty NOx and GHG emissions inventories coming from out-of-state heavy-duty trucks, State agencies like CARB are very focused on trying to expedite clean HDV technologies and fuels on the national level.

Thus, it is clear that comprehensive cooperation among local, state and national agencies and stakeholders will be required to begin systematically transforming America’s HDV transportation sector. Specific recommendations for actions are provided in Section 10.

10. 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 technical, institutional and economic challenges that need to be addressed.

On the engine and vehicle side, these challenges include the need to:

- Use strong outreach, education and communication campaigns to help ensure that heavy-duty NGV continue to have buyers, in expanding numbers
- Expand the number of manufacturers offering near-zero-emission engine platforms
- Identify and rapidly allocate major new government incentive funding to help buy down the incremental costs of near-zero-emission heavy-duty natural gas engines
- Reduce incremental subsystem costs of heavy-duty NGVs, including engines and on-board fuel storage systems
- Further improve engine / vehicle efficiency

For increased RNG production and transport to end users, these challenges include the need to:

- Expand RNG-production facilities, including in-state facilities in California (where RNG now makes up approximately half of the natural gas dispensed for transportation applications)
- Maintain and expand programs that help offset provide market certainty while helping offset the higher costs of producing RNG, through expanded monetization of its many societal benefits
- Lower the cost to the developer and improve logistics of interconnecting RNG production projects with the natural gas pipeline system
- Improve coordination with potential suppliers of RNG outside of California

The recommendations presented below generally fall within three categories:

- 1) Further study, education and outreach
- 2) New or enhanced policies, legislation and regulations
- 3) More focused and/or better-funded incentive programs

10.1. Heavy-Duty Near-Zero-Emission Natural Gas Engines and Vehicles

10.1.1. Education, Outreach and Further Study

Rapidly develop and implement focused outreach efforts to communicate benefits and encourage transition to heavy-duty near-zero-emission NGVs

It is essential that new strategies are developed and implemented 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.). Simply put, buyers are

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

required for heavy-duty near-zero-emission NGVs to succeed and help transform America's transportation sector. Potential customers include shippers, carriers, and in-house fleets, many of which actively seek to minimize emissions of criteria pollutants, TACs and GHGs from their operations. These potential customers largely lack any useful information about the emergence of near-zero-emission heavy-duty NGVs and RNG. National, state and local agencies should join with stakeholders to develop and implement focused outreach and educational efforts. This can help accelerate and maximize adoption of these vehicles, as needed nationwide to meet important targets for reducing criteria pollutants and GHG emissions. Existing curriculums and information on heavy-duty NGVs should be updated, and the information should be disseminated to target audiences through a variety of sources, including but not limited to federal programs like Clean Cities and the Alternative Fuels Database, as well as state, regional and local programs across the U.S.

Conduct further analysis on full-fuel-cycle emissions from heavy-duty ZEV and NZEV technologies

To date, most analyses of this type have focused on the LDV sector, and have not considered full-fuel-cycle emissions from HDVs. It is recommended that CARB, EPA, interested local air districts and industry stakeholders join together to conduct a rigorous, peer-reviewed comparative analysis on the full-fuel-cycle emissions of existing heavy-duty ZEV and NZEV technologies. This should include a close examination of the impacts of grid-averaged and marginal NO_x emissions and an assessment of the local air quality impacts of the various technologies.

10.1.2. Policies, Legislation and Regulations

Encourage EPA to adopt national optional low-NO_x standards

It is recommended that CARB and key stakeholders (e.g., air districts in ozone nonattainment areas) encourage EPA to immediately adopt national optional low-NO_x standards harmonized with CARB's standards. This could 1) send important market signals to heavy-duty engine and vehicle manufacturers; and 2) potentially enable adoption of important new incentive programs at the national level that focus on deployment of HDVs that meet or exceed the lowest tier of 0.02 g/bhp-hr (see below).

Establish a national template for HDV incentive programs that "leapfrog" to 0.02 g/bhp-hr NO_x

It is recommended that EPA lead efforts to establish a national template for rapid-action HDV incentive programs designed to "leapfrog" the existing 2010 heavy-duty engine emissions standards. Currently, HDV air quality incentive programs seek to deploy fuel-engine technologies that meet the existing federal heavy-duty engine standard of 0.2 g/bhp-hr. This provides surplus emission reductions when replacing older, in-use diesel HDVs. Now, new replacement HDVs are available that leapfrog past those reductions, by achieving 90 percent lower NO_x emissions than replacement HDVs that meet the current (2010) federal emission standard. EPA can help local and regional governments set up programs that reap the additional surplus emissions reductions by establishing a national template for HDV modernization programs that highly favor deployments of now-commercialized HDVs that are equipped with these near-zero-emission heavy-duty engines. To encourage maximum GHG reductions that complement the 90 percent NO_x reduction associated with near-zero-emission HDVs, EPA's template

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

should recognize and monetize the value of using any fuel that has reduced carbon intensity (relative to baseline diesel fuel), but offer higher incentives for use of renewable fuels with extremely low carbon intensity.

10.1.3. Incentives for Manufacturing and/or Deployment

Continue and expand funding to manufacturers for advanced natural gas engines, HDVs and on-board fuel systems.

It is recommended that federal, state and local government agencies increase research, development and deployment funding support to manufacturers working on heavy-duty near-zero-emission natural gas engines, NGVs and on-board fueling systems. These types of government investments have paid off (e.g. development and certification of CWI's near-zero-emission engine technology), and are needed until larger-volume production can be achieved and economies of scale can be realized to significantly reduce costs. This will help make it more attractive for engine and HDV manufacturers to expand the number of HDVs offering near-zero-emission engine platforms.

Review California's policies for HDV incentive programs to determine if adjustments can expedite awards and help ensure they are proportional to the magnitude and expediency of NOx-reduction benefits.

It is recommended that CARB, CEC and other key agencies in the State (e.g., SCAQMD, SJVAPCD and others) join together to review potential adjustments to rules and requirements of key clean HDV incentive programs. This is needed to ensure maximum funding is allocated towards deployments of commercially available near-zero-emission HDVs (with increasing use of renewable fuel) during the critical period of 2016 through 2023. Various existing HDV funding programs in California should be reviewed for potential to align statutes and requirements (e.g., old vehicle scrappage requirements) in ways that facilitate rapid HDV awards and deployments, while still meeting essential requirements for emissions reductions (surplus, quantifiable, enforceable, etc.) and fiscal accountability. Programs that are currently restricted by requirements that limit the magnitude of NOx reductions achieved should be revisited and potentially adjusted. Adoption of a single rebate program structure—similar to programs such as those used for the Clean Vehicle Rebate Program (CVRP) and Hybrid Voucher Incentive Program (HVIP)—is recommended to streamline the award process and help rapidly deploy near-zero-emission HDVs.

Devise and implement a multifaceted strategy in California that allows pooling of different incentive programs to provide major annual funding for rapid deployments.

It is recommended that CARB, CEC and other stakeholders develop a multi-faceted strategy that can pool sufficient State and other government funding to help deploy 15,000 to 20,000 heavy-duty near-zero-emission NGVs per year in California, over the next seven years. This is based on the number of near-zero-emission HDVs that CARB and SCAQMD estimate are needed in the SCAB by 2023, to deliver sufficient NOx reductions from this sector for attainment of ozone NAAQS. Including the extra cost of near-zero-emission engines, the total incremental cost for heavy-duty NGVs will range from approximately \$60,000 to \$75,000. Thus, it will require pooled funding in the billions of dollars between

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

2016 and 2023. Funding allocations that are currently being considered for this purpose are an order-of-magnitude less than what is needed to deploy these numbers.

Apply the national template to revamp and focus federal Clean HDV incentive programs

It is recommended that key national agencies, including DOE, EPA and NHSTA, join together to implement new clean HDV incentive programs in populated areas of the U.S. with high on-road diesel engine activity (e.g., seaports and urban goods movement corridors). These programs should utilize the national template designed to focus on immediate large-scale deployments that “leapfrog” the existing 2010 heavy-duty engine emissions standards. Federal agencies should consult with CARB during this process, given its expertise with such programs and the large role that out-of-state HDVs play in California’s inventories of NO_x, GHG and TAC emissions.

10.2. RNG Production and End Use

10.2.1. Education, Outreach and Further Study

Increase outreach efforts to communicate benefits of producing and using RNG to fuel NGVs

It is recommended that appropriate national, state and local agencies 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. This includes the need to reach out to municipalities through programs such as Clean Cities, to educate decision makers about the benefits of local RNG production for use as a transportation fuel. This should include lessons learned from interconnect studies in California, made available to other regions investigating plans for new RNG production facilities that will inject into the common carrier gas system. It should include dissemination of research on strategies to develop new technologies that can improve economics of RNG (e.g., making technically available RNG into economically available). These types of outreach and educational efforts can help accelerate and maximize use of RNG as an ultra-low-GHA transportation fuel.

Conduct a focused assessment in California of the supply and demand for RNG as a heavy-duty transportation fuel

It is recommended that CARB and CEC lead further study about the potential future dynamics between the supply of and demand for RNG as a transportation fuel in California. As new in-state projects come online to produce RNG, will there be sufficient numbers of heavy-duty NGVs to consume the fuel? California’s LCFS program and the federal RFS interject complex, evolving dynamics that impact these questions, and it will be important to further assess potential impacts. Lessons learned in California will likely apply to RNG supply and demand dynamics across the country, as larger national deployments are achieved.

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

10.2.2. Policies, Legislation, Regulations and Incentives

Continue policy and monetary support for use of fossil natural gas as an HDV fuel

It is recommended that air quality and energy regulatory agencies continue to recognize and support fossil natural gas as a lower-carbon-intensity transportation fuel. Fossil natural gas is essential for enabling broad deployment of near-zero-emission heavy-duty NGVs and the expanded use of ultra-low-carbon-intensity RNG as it is more widely produced and distributed. Non-renewable natural gas is a necessary intermediate step that will enable thousands of heavy-duty NGVs to continue reducing emissions of criteria pollutants, TACs and GHGs, while maintaining and expanding a well-established path for increasing volumes of RNG. All NGV fuel distribution, storage and fueling infrastructure has a direct and immediate role in the proliferation of RNG fuel supply to fleet operators. Because these investments are fully synergistic with, and complimentary to, increased use of ultra-low-carbon RNG, the risks of stranded assets are low.

Adopt new policies that encourage RNG production specifically as an NGV fuel

It is recommended that relevant federal and state agencies (especially in California) work together to establish new policies and programs that specifically support the production of RNG as a transportation fuel. Encouraging new biogas production for use in heavy-duty NGVs will require greater market certainty for RNG as a transportation fuel. To help create greater market certainty in California (and other states leading the move toward renewable transportation fuels, such as Oregon), California and the federal government should lead efforts to establish new policies and programs that encourage and incentivize RNG production for specific use as a transportation fuel. For example, new policies may be needed to remove large barriers to RNG production, such as the associated high upfront capital costs. Also, federal, state and municipal fleets equipped with NGVs could be incentivized to obtain and use increasing percentages of RNG in their natural gas fuel blend.

Improve logistics, costs and timeline of safely injecting RNG into natural gas pipelines

It is recommended that key federal and California agencies, utilities, the biogas industry and other stakeholders work together to identify and discuss remaining obstacles to injecting RNG into common carrier natural gas pipelines. For example, stakeholders can 1) explore opportunities to share interconnection, testing and monitoring costs through rate basing or tariff strategies; and 2) evaluate whether alternative standards and strategies can provide equivalent essential protections, with faster results and/or at lower costs.

Increase the federal RFS volume obligation for Advanced Cellulosic Fuels

It is recommended that EPA and other federal agencies take action to increase volume obligations for Advanced Cellulosic Fuels under the federal RFS. This can drive additional demand for RNG as a transportation fuel, thereby helping to accelerate funding and building of new RNG production facilities specifically for transportation usage.

11. Appendix 1: Details of Power Plant NO_x Equivalency Analysis

11.1. Introduction and Background

Heavy-duty battery-electric vehicles (BEVs) are designated as zero-emission vehicles (ZEVs) because they do not directly emit harmful pollutants such as NO_x. Of course, this definition neglects “upstream” pollutants emitted during generation of the electricity needed to recharge BEVs. Clearly, regulators generally prefer to control NO_x emissions from these “stationary sources” compared to “mobile sources” like HDVs; however, the upstream NO_x emissions associated with recharging BEVs can be quite significant. Importantly, the location of a battery-electric vehicle’s NO_x emissions (at a power plant, uncoupled from where it is operated) are different than those from NGVs, which occur at the tailpipe during operation. That adds further complexity to any comparison, because electricity generation plants are often located outside of air quality nonattainment areas. Some of these key nuances and issues are further discussed below.

By contrast, HDVs powered by combustion engines are not defined as ZEVs, even if they emit harmful pollutants at extremely low levels. Thus, the unofficial description for an HDV powered by an engine meeting CARB’s “optional” low-NO_x standard of 0.02 g/bhp-hr is currently a “near zero emission vehicle,” or NZEV. Recognizing that charging a heavy-duty BEV results in upstream NO_x emissions, it is reasonable to ask how heavy-duty NZEV technology compares on a full-fuel-cycle (aka well-to-wheels, or W2W) basis for NO_x emissions, relative to heavy-duty BEV technology.

Quantifying these upstream emissions is challenging due to the complexity and size of the U.S. electrical grid. The electrical grid is composed of more than 7,200 electrical generators, including combustion-based systems such as coal, natural gas, fuel oil, and biomass; as well as non-combustion systems including wind, solar, nuclear, and hydro. These generators are dispatched to the grid under the direction of authorities responsible for balancing power generation and demand over a particular service area. The service areas have developed over time based on the needs of customers and the particulars of the electrical grid in a given area. Consequently, these regions have very little relation to governmental boundaries such as counties or states. Further, a great deal of electrical power exchange occurs between balancing authorities, making it difficult or impossible to ascertain exactly how much power supplied to a particular customer is coming from a particular generator, or mix of generators. Therefore, when estimating the mix of generation supplying a geographic area, generators are typically grouped into regions that are defined with the goal of minimizing the net import or export of power in the region. This creates regions that are somewhat self-contained in terms of power generation and demand.

11.2. Electrical Grid Sub Regions

The U.S. EPA’s Emissions & Generation Resource Integrated Database (eGRID) provides emissions, net generation, and physical location data for most electric generators in the U.S. Additionally, eGRID defines 26 sub-regions in the U.S., developed to group generators based on the companies that control them. This produces an approximate geographic grouping of generators, but it is not geographically precise or aligned with governmental boundaries.

In an effort to create a structured set of geographic regions, EPRI recently proposed 15 sub-regions based on its new Regional Economy, Greenhouse Gas, and Energy (REGEN) model ²⁷⁹. These sub-regions represent groupings of states (see Table 18) intended to approximately match load and generation demands amongst power

balancing authorities while retaining relevance to political boundaries and market behaviors. Because the REGEN regions offer both a good balance of load/demand matching and follow familiar state boundaries, the following analysis adopts the REGEN region definitions to calculate regional NOx emissions associated with electrical loads such as EV charging.

11.3. Determining a Vehicle-Equivalent NOx Emission Rate

Heavy-duty on-road engines are certified to emissions standards while being operated on an engine dynamometer over a test cycle known as the Federal Test Procedure (FTP). The FTP incorporates a range of transient and steady-state engine conditions, as well as cold-start and hot-start events. The emissions standard is given in units of grams per brake horsepower-hour (g/bhp-hr) of NOx, and is measured at the engine flywheel. However, when the engine is put in a vehicle and used to deliver power to the vehicle’s wheels, there is a loss of efficiency due to the transmission and other drivetrain components. Assuming a driveline efficiency loss of 6 percent,²⁸⁰ the emissions rate with respect to energy delivered to the wheels is 0.021 g/hp-hr. Note that the unit has changed to “g/hp-hr”, dropping the “brake” abbreviation to indicate emissions based on energy measured at the wheels of the vehicle.

Table 18. 15 EPRI REGEN sub-regions and their states

REGEN Region	Associated States
California	CA
Florida	FL
Mid Atlantic	DC, DE, MD, NJ, PA
Mountain North	CO, ID, MT, WY
Mountain South	AZ, NM, NV, UT
New England	CT, MA, ME, NH, RI, VT
New York	NY
Northeast Central C	IL, MI, OH
Northeast Central R	IN, WI, WV
Northwest Central	IA, KS, MN, MO, ND, NE, SD
Pacific	OR, WA
South Atlantic	NC, SC, VA
Southeast Central	AL, GA, KY, MS, TN
Southwest Central	AR, LA, OK
Texas	TX

²⁷⁹ Alexander M., “Environmental Assessment of a Full Electric Transportation Portfolio” 2015

²⁸⁰ National Research Council, “Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles”, 2010. Table 5-4.

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

Determining the power plant NOx emissions associated with charging a heavy-duty BEV requires accounting for driveline losses and several factors that include grid-to-battery charging efficiency, battery-to-wheels efficiency, and enhancements to overall vehicle efficiency from regenerative braking. Further, because the eGRID emissions and net electricity generation data are measured at the generator, a grid transmission and distribution loss must be included when calculating the load demand at the generator. Much of the efficiency loss associated with charging and battery-to-wheels efficiency is offset by the energy recovered through regenerative braking. The estimated gain in BEV efficiency of 25 percent is based on reported energy recovery for a Class 8 battery-electric semi-tractor tested over the Urban Dynamometer Driving Schedule (UDDS), which simulates the vehicle drive cycle that would result from an engine running the FTP engine test cycle. Consequently, vehicle efficiencies measured on the UDDS should be comparable to engine efficiencies measured under the FTP after adjustment for driveline losses.

As shown in Table 19, when accounting for each of these process efficiencies, the net plant-to-wheels efficiency is estimated at 88 percent. When calculating power plant-related EV emissions, eGrid

Table 19. Typical electrical efficiencies / losses for a Class 8 battery-electric truck

Efficiency Parameter	Electrical Efficiency / Loss
Grid Transmission and Distribution Loss	-8.3 percent (national average) ¹
EVSE + Charging Efficiency Loss	-15 percent ²
Battery-to-Wheels Efficiency Loss	-15 percent ³
BEV Efficiency without Regenerative Braking	66 percent
Regenerative Braking Energy Gain	+25 percent (UDDS duty cycle) ⁴
Net Plant-to-Wheels Efficiency	88 percent

¹US EPA, eGRID 2012

²Reported ranges are typically 80-90%, depending on charge rate and protocol per the following sources:

- 1) Francort J, "INL Efficiency and Security Testing of EVSE, DC Fast Chargers, and Wireless Charging Systems", 2013;
- 2) Forward E, et al., "An Assessment of Level 1 and Level 2 Electric Vehicle Charging Efficiency", 2013;
- 3) Russel R, et al., "Assessment of the Performance of a Class 5 Battery Electric Commercial Truck", 2013

³Russel R, et al., "Assessment of the Performance of a Class 5 Battery Electric Commercial Truck", 2013

⁴Johnson K, et al., "Performance Evaluation of TransPower All-Electric Class 8 On-Road Truck", 2015

emissions rates are increased by 13.6 percent to reflect the plant-to-wheels efficiency of 88 percent. The resulting emissions can then be compared to the 0.021g/hp-hr effective vehicle emissions rate calculated for a vehicle equipped with an engine certified to the 0.02g NOx/bhp-hr engine standard.

11.4. Regional Power Plant Emissions Equated to Heavy-Duty Engine Standards

Regional power plant NOx emission rates were calculated using the REGEN region definitions described previously and EPA’s eGRID 2012 database. This database reports total NOx emissions and net generation for most electrical generators in the U.S. for calendar year 2012. Emissions are reported in tons per year, and net generation is reported in megawatt-hours per year. Regional emissions and net generation for each REGEN region are determined by summing the emissions and generation for each

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

power plant based on the physical location of the power plant. Once total emissions and net generation are determined for a region, the annual average emissions rate is calculated by dividing total emissions by net generation. The resulting emissions rate (in tons/MWh) is converted to a g/hp-hr basis using standard unit conversions and then divided by the 88 percent plant-to-wheels efficiency for BEVs, described previously.

As noted in Section 6.4, the key finding from these calculations is that in all regions, the current average grid mix results in a heavy-duty BEV indirectly emitting more NO_x per hp-hr (equivalent) than the tailpipe NO_x emissions of a heavy-duty NGV powered with a 0.02 g/bhp-hr engine.

The “California” and “Pacific” grid subregions are the cleanest in the U.S. with respect to average power plant NO_x emissions. This results from a combination of 1) high percentages of zero emission renewables (solar, wind, and hydro) that generate electricity in these subregions, and 2) stringent NO_x emissions standards implemented on power plants in California. Despite these exceptionally clean grids, the average NO_x emissions rates associated with charging heavy-duty BEVs are 2.5 to 3.5 times greater than a comparable heavy-duty NGV operating with the newly certified engine meeting the 0.02g NO_x/bhp-hr standard. In large swaths of the country, including the Mountain and Central regions, average grid NO_x emissions from power plants are approximately thirty times higher than the 0.02g engine standard. Consequently, in mid-2016 when heavy-duty NGVs using low-NO_x engines are rolled out, they will offer significant NO_x-reduction benefits even when compared to similar heavy-duty BEVs, especially if the BEVs are recharged in regions that have the highest-NO_x electricity grids.

11.5. Marginal vs Average NO_x Emissions

When calculating grid emissions rates, the question arises as to whether to use average or marginal emissions rates. Average emissions rates, like those used in this analysis, are calculated by dividing total emissions by total generation. All loads placed on the grid are assumed to generate emissions at the same rate.

By contrast, a marginal emissions rate calculation attempts to estimate the incremental emissions that would be produced to serve the incremental load. Specifically, marginal emissions calculations reflect the fact that an incremental load does not incrementally increase the demand on all operating generators. Instead, the incremental load is served by the lowest cost generator with available capacity.

In both cases, the best estimates of emissions impacts require the use of a “dispatch model” that attempts to replicate the decision making process used by grid operators to select the least-cost generating mix that meets the many operational and environmental constraints that power plants are subject to in the various regions around the country. The use of dispatch modeling is less critical when looking at incremental loads that are a relatively small fraction of the overall grid generation as these load changes are less likely to significantly affect the dispatch decisions of grid operators.

While marginal emissions rates are a useful approach to compare total emissions under different policy scenarios, there is still significant academic debate as to how to calculate marginal rates and when they

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

should be used. For example, the Union of Concerned Scientists notes in its report “State of Charge” that:

“While a marginal emissions analysis of EV charging is important for forward-looking studies of the policy implications of large-scale EV adoption, our goal in this analysis is to give consumers an idea of what the typical global warming emissions of the electricity used to charge their EV will be on today’s electricity grid. Therefore, we use the average emissions intensity of the electricity...”²⁸¹

Alternatively, researchers at the University of California, Davis argue in their report, “From Cradle to Junkyard: Assessing the Lifecycle Greenhouse Gas Benefits of Electric Vehicles” that analyses of future grid emissions require the use of average emissions rates, because:

“...there is no credible way to estimate the dispatch order of an electric system that does not yet exist. Again, the “average” approach may be justified if a large fraction of electricity demand is derived from EVs.”²⁸²

Given this paper’s focus on the immediate NO_x-emission-reduction benefits of deploying near-zero-emission heavy-duty NGVs into the transportation sector, and given the ongoing debate around how and when to use marginal emissions rates, the current analysis relies on average grid emissions and assumes all loads connected to the grid are treated equally from an emissions perspective. Readers interested in alternative analyses relying on marginal emissions rates are encouraged to review the Electric Power Research Institute (EPRI) 2015 report entitled Environmental Assessment of a Full Electric Transportation Portfolio.²⁸³

11.6. Future NO_x Emissions Scenarios as the U.S. Grid Gets Cleaner

Over the long term, it is important to recognize that regulations such as revised Stationary Source Performance Standards and the Clean Power Plan are expected to force some power plants to modernize or close down, leading to an overall cleaner grid. It is not possible to predict the exact effects these policies will have on individual power plants across the U.S. Below, several scenarios were considered in the 2030 timeframe under which the national grid may develop progressively lower NO_x emissions.

Generator emissions capped at 0.11 lbs NO_x/MMBTU – this scenario assumes that all generators in the U.S. reduce their emissions to no more than 0.11 lb NO_x/MMBTU based on current emissions limits for retrofitted power plants. While existing power plants are not required to reduce their emissions to this

²⁸¹ Union of Concerned Scientists, “State of Charge Technical Appendix,” section on “Average vs. Marginal Emissions,” May 2012, http://www.ucsusa.org/sites/default/files/legacy/assets/documents/clean_vehicles/electric-car-global-warming-emissions-appendix.pdf.

²⁸² University of California; Davis, James Archsmith, Alissa Kendall and David Rapson; “From Cradle to Junkyard: Assessing the Life Cycle Greenhouse Gas Benefits of Electric Vehicles; September 2015, http://faculty.econ.ucdavis.edu/faculty/dsrapson/EV_vs_ICE_AKR.pdf.

²⁸³ Electric Power Research Institute, “Environmental Assessment of a Full Electric Transportation Portfolio,” September 2015, http://www.eenews.net/assets/2015/09/18/document_cw_01.pdf.

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

level unless they undergo significant retrofitting or modification, it is possible that many large generators will have to be retrofitted to comply with the Clean Power Plan’s limits on GHG emissions. Consequently, this scenario makes the optimistic assumption that all generators emitting above the 0.11 lb/MMBTU standard reduce their emissions to meet the standard.

EPRI 2030 Average Grid Mix – this scenario is derived from EPRI’s estimated national average grid emissions rate in its 2030 electrification scenario. While the authors report regional data, the information is not sufficient to calculate emissions for each REGEN region so only the national average emissions rate is compared under this scenario.

California Standard – this scenario assumes electricity is derived only from power plants meeting California’s stringent standard of 0.07 lbs NOx/MWh.

As shown in Table 20, under all of these potential future scenarios, a heavy-duty NGV powered by a near-zero-emissions CWI ISL G NZ engine (or any other engine that eventually meets the 0.02g NOx standard) will still produce comparable or less total NOx emissions than a comparable heavy-duty BEV charging from the grid. Increasing the renewables in the electricity mix (e.g., 50 percent by 2030 per California’s goal) brings the heavy-duty BEV NOx closer to parity with the heavy-duty NZEV, when the mix is already exceptionally clean (California and Pacific sub-regions). Using a grid mix of 50 percent zero-emission renewable energy (e.g., solar, wind, hydro) and 50 percent natural gas combined cycle generation (at the low NOx level of 0.07 lbs per mW-hr) results in the heavy-duty BEV having NOx emissions associated with electricity generation that would be comparable to the tailpipe NOx emissions

Table 20. Vehicle-equivalent NOx emission rates under future “cleaner-grid” scenarios

REGEN Region	Estimated Vehicle-Equivalent NOx Emissions (g/hp-hr)			CA Standard 0.07 lb NOx/MWh
	eGRID 2012	Generator Emissions capped at 0.11 lb NOx/MMBTU	EPRI 2030 Average Grid Mix	
Pacific	0.05	0.03	0.03	0.03
California	0.07	0.06	0.01	
New York	0.13	0.09	0.01	
New England	0.16	0.08	0.03	
Florida	0.25	0.17	0.07	
South Atlantic	0.26	0.15	0.10	
Texas	0.27	0.19	0.13	
Southeast Central	0.33	0.20	0.13	
Mid Atlantic	0.37	0.16	0.10	
Northeast Central C	0.38	0.23	0.14	
Southwest Central	0.51	0.26	0.13	
Northeast Central R	0.56	0.31	0.24	
Mountain South	0.59	0.23	0.17	
Northwest Central	0.61	0.29	0.21	
Mountain North	0.63	0.30	0.24	
Continental U.S.	0.36	0.20	0.12	

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

from a heavy-duty engine certified at 0.01 to 0.02 g/bhp-hr. Based on this analysis, it is concluded that well into the future, near-zero-emission heavy-duty NGVs will continue to offer *among the lowest equivalent NOx emissions* of any HDV fuel-technology pathway—even as the U.S. electrical grid modernizes and NOx emissions are reduced significantly below levels emitted by today’s grid.

11.7. A Note Regarding “Off-Cycle” Emissions

It should be noted that the comparisons presented here reflect emissions performance over the FTP and UDDS cycles. The W2W emissions and efficiencies of both heavy-duty low-NOx engine vehicles and BEVs can, and do, deviate from these certification test cycles. Referred to as “off-cycle” operation, real world vehicle operations do not perfectly match certification test cycles. In some applications, these deviations can be very significant. Recent tests of EPA 2010-compliant heavy-duty NGVs have shown good emissions performance in off-cycle operations.²⁸⁴ By contrast, diesel vehicles have shown dramatic increases in NOx emissions during low-load low-speed operation, when exhaust temperatures are too low to fully activate the aftertreatment system’s SCR catalysts. The off-cycle emissions performance of low-NOx engines has not yet been quantified, but experience from in-use testing of current-generation heavy-duty NGVs is promising (as acknowledged by CARB; refer back to Table 8 on page 69). Moreover, in many U.S. regions, tailpipe NOx emissions from heavy-duty NGVs certified to 0.02 g/bhp-hr will be so low compared to those of heavy-duty BEVs that any off-cycle NOx emission impacts would need to increase average NOx emissions by *more than an order of magnitude*, before the heavy-duty NGVs would lose their equivalent NOx-reduction advantage over comparable BEVs.

²⁸⁴ See CARB “Draft Technology Assessment: Low Emission Natural Gas and Other Alternative Fuel Heavy-Duty Engines,” September 2015, Figure VI-1, http://www.arb.ca.gov/msprog/tech/techreport/ng_tech_report.pdf

12. Appendix 2: Assumptions for Section 6 Cost-Effectiveness

Table 21. Assumptions used to derive graphs in Section 6.9 (see page 106)

Duty Cycle, Life, EER and Baseline Emissions							Baseline Diesel and NG		
Vocation	VMT (mi/year)	Fuel Economy (mi/DGE)	Typical Retention Period (years)	CNG EER	EV EER	FCEV EER	NOx (g/mi)	PM (g/mi)	ROG (g/mi)
Regional Haul Tractor	52,119	6.56	5	0.9	2.7	1.9	1.08	0.0031	0.054
Short Haul Tractor	14,417	6.58	7				1.27	0.0030	0.057
Refuse	14,417	2.90	12				1.01	0.0039	0.053
Transit	44,670	5.20	12				0.81	0.0032	0.023
Source	1	1	2,3	4	4	4	1	1	1

Sources:

- California EMFAC 2014 heavy duty emissions model results for Model Year 2015 diesel trucks and Calendar Year 2015
- TIAX, "US and Canadian Natural Gas Vehicle Market Analysis: Market Segmentation" Prepared for America's Natural Gas Alliance, 2012
- North American Dealers Association, "Daycab vs Sleeper Retail Pricing" September 2015
- California Low Carbon Fuel Standard Regulation

Emissions, Activity, and Fuel Economy Assumptions									
Technology	Vocation	VMT (mi/year)	Fuel Economy (mi/DGE)	Typical Retention Period (years)	EER	NOx (g/mi)	PM (g/mi)	ROG (g/mi)	Weighted Emissions (g/mi)
2015 Diesel	Regional Haul Tractor	52,119	6.6	5	1	1.08	0.0031	0.0544	1.192
	Short Haul Tractor	14,417	6.6	7	1	1.27	0.0030	0.0572	1.391
	Refuse	14,417	2.9	12	1	1.01	0.0039	0.0528	1.138
	Transit	44,670	5.2	12	1	0.81	0.0032	0.0228	0.899
2015 NG	Regional Haul Tractor	52,119	5.9	5	0.9	1.08	0.0031	0.0544	1.192
	Short Haul Tractor	14,417	5.9	7	0.9	1.27	0.0030	0.0572	1.391
	Refuse	14,417	2.6	12	0.9	1.01	0.0039	0.0528	1.138
	Transit	44,670	4.7	12	0.9	0.81	0.0032	0.0228	0.899
2015 NZ NG	Regional Haul Tractor	52,119	5.9	5	0.9	0.11	0.0031	0.0544	0.224
	Short Haul Tractor	14,417	5.9	7	0.9	0.13	0.0030	0.0572	0.245
	Refuse	14,417	2.6	12	0.9	0.10	0.0039	0.0528	0.232
	Transit	44,670	4.7	12	0.9	0.08	0.0032	0.0228	0.168
2015 BEV	Regional Haul Tractor	52,119	17.7	5	2.7	0	0	0	0
	Short Haul Tractor	14,417	17.8	7	2.7	0	0	0	0
	Refuse	14,417	7.8	12	2.7	0	0	0	0
	Transit	44,670	21.8	12	4.2	0	0	0	0
2015 FCV	Regional Haul Tractor	52,119	12.5	5	1.9	0	0	0	0
	Short Haul Tractor	14,417	12.5	7	1.9	0	0	0	0
	Refuse	14,417	5.5	12	1.9	0	0	0	0
	Transit	44,670	9.9	12	1.9	0	0	0	0
Data Source		1	1	2,3	4	1	1	1	1,5

Sources:

- California EMFAC 2014 heavy duty emissions model results for Model Year 2015 diesel trucks and Calendar Year 2015. NZ engine NOx emissions assumed to be 90% below baseline.
- TIAX, "US and Canadian Natural Gas Vehicle Market Analysis: Market Segmentation" Prepared for America's Natural Gas Alliance, 2012
- North American Dealers Association, "Daycab vs Sleeper Retail Pricing" September 2015
- California Low Carbon Fuel Standard Regulation
- Weighted emissions are calculated using the Carl Moyer Air Quality Standards Attainment Program formula: Weighted Emissions = NOx + ROG + 20*PM

Fuel Pathway Carbon Intensity Assumptions and Sources								
Vehicle Technology	Diesel	CNG	CNG	NZ CNG	NZ CNG	EV	FCV	FCV4
Representative LCFS Pathway	ULSD001	CNG002	LFG-CNG ^a	CNG002 ^b	LFG-CNG ^{a,b}	ELC001	HYGN001	HYGN005
Carbon Intensity (gCO ₂ e/MJ)	102.01	78.36	18.11	77.36	17.11	105.16	151.01	88.33

Source: California Air Resources Board "LCFS Illustrative Fuel Pathway Carbon Intensity" Prepared for the Assessment of Critical Barriers and Opportunities to Accelerate Biofuels and Biomethane as Transportation Fuels in California event at UC Davis September 17, 2015

^aNew illustrative pathway reported by ARB Staff. No existing pathway identifier reported

^bAssumed reduction of 4.1 gCO₂e/MJ for Near-Zero NG engines based on reduced methane slip associated with closed crankcase technology

Incremental Cost Assumptions by Technology and Vocation					
Vocation	CNG	CNG NZ	EV	FCV	Assumptions
Regional Haul Tractor	\$72,500	\$80,500	\$434,000	\$525,000	EV: two 350 kWh battery packs required
Short Haul Tractor	\$52,500	\$60,500	\$224,000	\$525,000	EV: one 350 kWh battery pack required
Refuse	\$35,000	\$43,000	\$146,000	\$525,000	EV: 1.6 350 kWh battery packs required
Transit	\$45,000	\$53,000	\$335,000	\$815,000	EV: Based on reported incremental costs for transit projects

Additional Assumptions

CNG NZ: \$8,000 cost adder over baseline CNG vehicles

EV: \$210,000 per 350 kWh battery pack

FCVs: \$450,000 for fuel cell system and \$75,000 for fuel storage based on 2016 US DOE performance targets

13. Appendix 3: Control of Upstream Methane Emissions

Methane—a potent GHG and the dominant constituent of natural gas—can be emitted during “upstream” production, processing, and delivery segments of the natural gas supply chain. Methane accounted for about 10 percent of total U.S. GHG emissions in 2013, according to EPA’s latest inventory. Beyond being a GHG, methane is considered a “short-lived climate pollutant” (SLCP). These types of gases remain in the atmosphere for a much shorter period of time than longer-lived climate pollutants (e.g., CO₂); but their impacts on heating the atmosphere can be far greater than CO₂. This higher relative GHG potency compared to longer-lived climate pollutants makes methane an especially urgent target for effective controls.²⁸⁵

Agricultural sources in livestock and farming operations are the largest U.S. emitters of methane. For example, approximately 55 percent of the annual methane emissions in California result from livestock (mostly beef and dairy cows) manure and enteric fermentation (i.e. “burps”). California’s oil and gas industry accounts for six percent of the State’s annual methane inventory²⁸⁶. On a national basis, livestock account for approximately 36 percent of methane emissions, while natural gas systems account for approximately 25 percent.²⁸⁷

For natural gas to become a full-scale replacement for diesel in America’s heavy-duty transportation sector, it will be important to reduce its “upstream” release into the atmosphere wherever possible. These types of efforts are well underway by the natural gas industry; further discussion is provided below.

13.1. Industry Efforts to Reduce Methane Leakage

There are many sources of methane emissions across the entire oil and gas supply chain. These emissions are characterized as either:

- Fugitive emissions – methane that “leaks” unintentionally from equipment (e.g., flanges, valves, pumps, compressors, etc.)
- Vented emissions – methane that is released due to equipment design or operational procedures, such as from pneumatic device bleeds, blowdowns, incomplete combustion, or equipment venting
- Un-combusted emissions – methane in the exhaust of natural gas combustion equipment, used in production and transmission segments

²⁸⁵ U.S. EPA Inventory of U.S. Greenhouse Gas Emission and Sinks: 1990-2013

<http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf>.

²⁸⁶ California Air Resources Board, “Draft Short-Lived Climate Pollutant Reduction Strategy,” September 2015, accessed online at <http://www.arb.ca.gov/cc/shortlived/2015draft.pdf>.

²⁸⁷ U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2013, April 15, 2015, <http://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf>.

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

Over the last five years, increased interest in methane emissions from the natural gas value chain has resulted in a surge of research and analysis.²⁸⁸ Numerous studies are underway to examine all areas that make up the natural gas supply chain: production; gathering lines and processing facilities; long-distance pipelines, storage, and local distribution; as well as some end users using natural gas, commercial trucks and refueling stations.

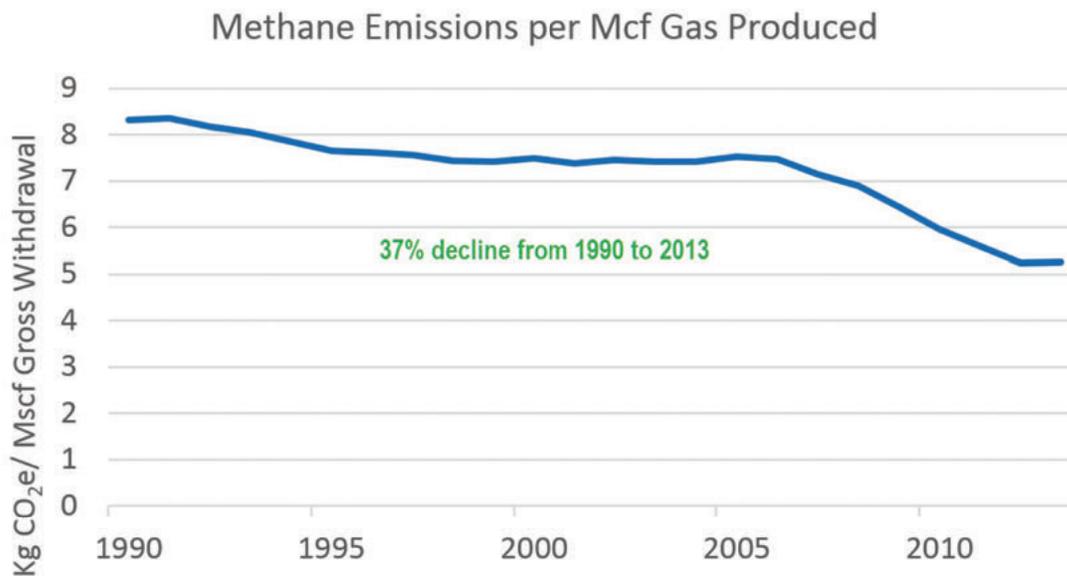


Figure 40. Methane emitted per natural gas produced in the U.S. (EPA, 2015 inventory)

Many of these studies are very technical and some are contradictory; others won't be released until well into 2016. What is clear is that the natural gas industry has taken aggressive action to reduce upstream methane emissions. Methane emissions per volume of gas production (Mcf) declined about 37 percent during the period from 1990 to 2013 (see Figure 40). EPA reports that total methane emissions from the "energy" sector (including natural gas and petroleum systems) declined by 20 percent over this same period. This has occurred during one of the most-prolific periods ever for production by the U.S. oil and gas sector.

²⁸⁸ Perhaps the most extensive recent work on direct methane measurement is a series of 16 studies organized by the Environmental Defense Fund (EDF) with a variety of researchers, including several universities, and published in peer-reviewed journals. See <https://www.edf.org/climate/methane-studies>.

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

In March 2016, 41 private companies joined with EPA to initiate a new voluntary federal program to reduce methane emissions from the oil and gas sector. This Natural Gas STAR Methane Challenge Program builds upon past efforts between EPA and the U.S. oil and natural gas industry that focuses on achieving cost-effective methane emission reductions from natural gas operations. Under this program, these 41 companies commit to using best management practices such as replacing old pipelines and reducing leaks. They will report their progress annually to EPA, and the agency will post information on the companies on a public website. The program is expected to further the nation's efforts to reducing methane from the oil and gas sector. At the same time, EPA is continuing to shape new regulatory action on existing oil and gas operations.²⁸⁹

13.2. Rare Events Causing Large Methane Leakage

Underground storage of natural gas is an integral, essential component of America's energy system (see box, based on information from the American Gas Association²⁹⁰). In late October 2015, a major gas leak was discovered at a large natural gas storage facility within a California utility's natural gas system. Initial leak rates were very high, although the leak rate was significantly reduced within weeks. In mid-February 2016, the leak was plugged. According to CARB, a robust quantification of the overall leak volume will not be available for several months.²⁹¹

Natural gas leaks of this magnitude at storage facilities are extremely rare. Industrial accidents of this kind pose public safety issues that cannot be diminished, but it is important to maintain perspective. For many decades, underground natural gas storage facilities have provided essential, safe and cost-effective ways to help meet America's vast energy needs. Natural gas storage is vital for gas utilities

The Importance of Natural Gas Storage

Underground storage of natural gas is an integral component of the nation's energy system. Natural gas storage adds flexibility to the gas transportation network, and has many uses, including for seasonal management of gas transmission. During summer months, when U.S. customers use less gas and there is excess supply, utilities purchase natural gas and store it for distribution in the colder months when there is peak demand. Underground storage provides a physical location to hold supplies not being consumed. It is also used to maintain system integrity and provide necessary positive pressure on pipelines; this helps maintain efficient operation.

There are approximately 400 active storage facilities in 30 states, these are owned and operated by various companies. Approximately 20 percent of all natural gas consumed annually in the U.S. during the five-month winter heating season is supplied by underground storage.

Source: American Gas Association

²⁸⁹ U.S. Environmental Protection Agency, "EPA Launches New Voluntary Methane Challenge Program to Reduce Emissions from the Oil and Gas Sector, press release, March 30, 2016, <https://yosemite.epa.gov/opa/admpress.nsf/0/d18d3f2c205f996285257f860052b06b?OpenDocument>.

²⁹⁰ American Gas Association, "The Role of Natural Gas Storage," https://www.aga.org/sites/default/files/the_role_of_natural_gas_storage_fact_sheet_final.pdf.

²⁹¹ California Air Resources Board Aliso Canyon Leak update, February 2016.

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

to provide reliable, reasonably-priced natural gas service to both residential and business customers; it is used to heat homes and water, cook food and generate clean electricity. Storing large amounts of energy entails inherent risks and challenges in any form, regardless of whether it's petroleum, natural gas, hydrogen, or water in hydroelectric dams.

It also important to note that these types of storage facilities are likely to play an important long-term role to store large volumes of very low-carbon RNG. America will need to store RNG for use in many critical applications, including to generate renewable electricity or hydrogen that will be used to power heavy-duty ZEV technologies. Another vision involves storing RNG that has been produced using "power-to-gas" technology that can help "decarbonize" America's natural gas pipeline system.

14. Appendix 4: Potential Role of Renewable Diesel Fuel

This section provides a brief overview on the potential for, and challenges of, renewable diesel becoming a major HDV fuel to help transform America's heavy-duty transportation sector. A thorough review of renewable diesel is beyond this report's scope. For comprehensive treatment, see California EPA's "Multimedia Evaluation of Renewable Diesel" accessible at: http://www.arb.ca.gov/fuels/multimedia/meetings/renewabledieselstaffreport_nov2013.pdf.

14.1. Introduction

Renewable diesel (RD) is an emerging "drop-in" HDV transportation fuel that is chemically and structurally "almost identical" to conventional diesel fuel. Transportation fuels in the U.S. must meet motor vehicle fuel specifications set by agencies like CARB and EPA. RD meets the same standards and specifications as conventional diesel for aromatics, sulfur, lubricity, and other key chemical or physical properties encumbered under ASTM²⁹² International Standard D975-12a.²⁹³ This means that RD can be blended with conventional diesel "in any amount and used with existing infrastructure and diesel engines." As stated by CARB, RD "should be treated no differently" than conventional diesel that is legally sold in California.²⁹⁴ EPA, which generally refers to "biomass-based diesel," has also approved RD as a replacement for conventional diesel.

It is important to note that RD is not biodiesel. RD uses similar feedstocks, but has different processing methods from biodiesel, and includes different chemical components. For example, RD is free of the ester compounds found in fatty acid methyl ester (FAME) biodiesel, and it has a much lower aromatic content.²⁹⁵ High-level blends of RD, including 100 percent (RD100), can be used in existing heavy-duty diesel engines without modification. By comparison, heavy-duty engine manufacturers limit the blend percentage of biodiesel that can be used in their engines. Biodiesel blends up to B20 have been sanctioned by most heavy-duty engine OEMs; this was enabled by adoption of ASTM standard D7467.²⁹⁶ Typically, OEMs impose restrictions on biodiesel blends over this percentage by voiding the customer's new engine warranty, if it can be demonstrated that damage occurred due to a higher-level biodiesel blend.

14.2. Advantages and Uses

RD offers advantages compared to both conventional diesel and biodiesel fuel. As noted, it is directly usable in existing diesel-powered vehicles, with no engine modifications required even for RD100. RD has a high

²⁹² ASTM, formerly the American Society for Testing and Materials, develops international standards for materials, products, systems, and services used in construction, manufacturing, and transportation.

²⁹³ California Environmental Protection Agency, "Staff Report: Multimedia Evaluation of Renewable Diesel," prepared by the Multimedia Working Group, May 2015, http://www.arb.ca.gov/fuels/diesel/altdiesel/20150521RD_StaffReport.pdf.

²⁹⁴ California Air Resources Board and State Water Resources Control Board, "Renewable Diesel Should Be Treated the Same as Conventional Diesel," joint letter to various industry "stakeholders," July 31, 2013.

²⁹⁵ California Environmental Protection Agency, "Staff Report: Multimedia Evaluation of Renewable Diesel," prepared by the Multimedia Working Group, May 2015, http://www.arb.ca.gov/fuels/diesel/altdiesel/20150521RD_StaffReport.pdf.

²⁹⁶ DieselNet.com, "Compatibility of Biodiesel with Petroleum Engines," accessed online at https://www.dieselnet.com/tech/fuel_biodiesel_comp.php.

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

cetane number²⁹⁷ and other good qualities for compression-ignition engines, which enable it to provide similar or better vehicle performance compared to conventional ultra-low sulfur diesel (ULSD). It is a low-carbon-intensity fuel that can help reduce “engine-out” emissions of criteria pollutants and GHGs (see below). Moreover, RD’s nearly zero sulfur content enables the use of advanced emission control devices. It can be produced using existing oil refinery capacity; thus, extensive new production facilities will not be required for expanded RD use.

14.3. Acceptance by Heavy-Duty Engine and Vehicle Manufacturers

The fact that pure (100%) RD is a drop-in, market-ready replacement for petroleum-based diesel has been corroborated by at least one major manufacturer of heavy-duty engines and trucks. Volvo Trucks North America conducted truck and engine testing on RD, and announced in 2015 that it has approved use of RD in all of its proprietary engines. Volvo indicated there is “no risk” that end users will lose their warranty coverage on any of their heavy-duty truck and engine combinations as the result of using RD.²⁹⁸

14.4. Production, Feedstock and Supply

Various biomass-to-liquid processes are used to produce RD. The most common process is to upgrade conventional biodiesel (or fatty acid methyl esters, FAME) via hydrogenation, using existing hydro-treatment processing equipment. The resulting fuel contains pure hydrocarbons and paraffinic compounds, with very low aromatics.

Neste (formerly Neste Oil) is one of the world’s largest RD producers. Neste’s NExBTL process is capable of using multiple feedstock that include palm oil, palm fatty acid distillate (PFAD; a byproduct from the physical refining of palm oil), tallow (i.e., rendered animal fat), and used cooking oil. In 2012, Neste invested billions of dollars to build RD production plants and facilities in Singapore, Rotterdam and Finland, and these facilities are all operational today. Worldwide RD capacity for Neste’s facilities totals approximately 700 million gallons per year (MGPY).

Approximately 325 to 400 million gallons of RD were supplied to U.S. markets in 2014, most of which was imported by Neste.^{299,300} Currently, the greatest U.S. demand for RD is in California, which has received about one third of the U.S. supply (imported and domestic). Neste’s Singapore plant is particularly well situated to deliver RD to California and other west coast markets of the U.S. In recent years, Neste has delivered more

²⁹⁷ Cetane number refers to the relative ranking of a fuel’s auto-ignition characteristics for use in compression ignition (diesel) engines. Fuels with a high cetane number readily auto-ignite; this is essential for diesel engines.

²⁹⁸ Volvo Trucks North America, “Volvo Trucks Approves Renewable Diesel Fuel for Proprietary Engines,” press release, December 9, 2015.

²⁹⁹ CARB, Low Carbon Fuel Standard, “Appendix B, Development of Illustrative Compliance Scenarios and Evaluation of Potential Compliance Scenarios,” 2015.

³⁰⁰ U.S. EPA, Renewable Fuel Standard Program: Standards for 2014, 2015 and 2016 and Biomass-Based Diesel Volume for 2017; Proposed Rule; 40 CFR Part 80 No. 111, June 10, 2015.

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

than 100 MGPY of RD to California end users. Currently, most RD sold in California (by any source) is derived from tallow³⁰¹ feedstock.

There are at least two facilities that currently produce RD within the U.S. These are: 1) Diamond Green in Norco, Louisiana with a capacity of 137 MGPY, and 2) REG Synthetic Fuels in Geismar, Louisiana with a capacity of 75 MGPY. The Diamond Green facility has registered fuel pathway documents with CARB for the LCFS program; however, there are no known RD shipments to California from these plants. The additional benefit of the credits under the LCFS program apparently do not warrant the additional cost of transporting the fuel via railcar. This, it's currently uncertain if these facilities will choose to deliver product to the California market.

14.5. Expanding End Users

As noted, California currently leads the U.S. in the use of RD as a HDV transportation fuel. In 2014, 113 million gallons of RD were used to generate credits in the California LCFS program. This constituted roughly 15 percent of all 2014 credits under the LCFS. This is expected to grow in California and other states, as increasing numbers of HDVs are being fueled with RD.

Examples of significant recent developments for RD use include the following:

- In July 2015, United Parcel Services (UPS) UPS announced that it will buy as much as 46 million gallons of RD over the next three years. UPS has set a goal to displace 12 percent of its petroleum-based fuels in its ground fleet by 2017. The renewable fuels will be purchased from Neste (tallow), Renewable Energy Group (other oils / fats), and Solazyme (algae-derived oil). UPS executives indicate that performance will be “as good or even better” than traditional diesel.³⁰²
- In mid-2015, the City of San Francisco announced that its municipal HDV fleet will switch from petroleum diesel to RD by early 2016. Reportedly, all 53 diesel fueling sites are switching to 99 percent RD (RD99), with the intent for nearly 2,000 HDVs to operate on it. This will require an estimated 4.9 million gallons of RD per year.³⁰³
- The northern California cities of Walnut Creek and Oakland have also made similar announcements about switching their City-owned HDVs over to RD. Oakland’s HDV fleet of 250 diesel vehicles will use a reported 230,000 gallons of RD each year.³⁰⁴
- In December 2015, the California Department of General Services issued a memo stipulating that California agencies “shall purchase state-contracted renewable diesel fuel, in lieu of conventional

³⁰¹ Tallow is animal fat derived from waste at a meat processing plant. Rendering produces two types: edible and inedible tallow. Edible tallow is used by the food industry and most of the inedible tallow is currently used as a supplement in animal feed, but can also be a feedstock for RD.

³⁰² New York Times, “UPS Agrees to Buy 46 Million Gallons of Renewable Diesel,” July 29, 2015, accessed online at http://www.nytimes.com/2015/07/30/business/ups-agrees-to-buy-46-million-gallons-of-renewable-diesel.html?_r=0.

³⁰³ San Francisco Examiner, “City fleet to adopt use of renewable diesel fuel,” July 21, 2015.

³⁰⁴ Government Fleet, “Oakland Moves to Renewable Diesel for City Fleet,” October 2016, <http://www.government-fleet.com/news/story/2015/10/third-calif-fleet-switches-to-renewable-diesel.aspx>

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

diesel and biodiesel fuels, when making bulk purchases of fuel for diesel powered vehicles and/or equipment.” Reportedly, at least 80 percent of the RD will be “NexDiesel” supplied by Golden State Petroleum, which uses Neste as its bulk supplier.³⁰⁵

- In early 2015, Propel Fuels began selling RD at 18 fueling stations in California. Propel is California’s self-proclaimed “largest retailer of low-carbon fuels. As of late 2015, Propel is selling its “Diesel HPR” (*High Performance Renewable*) at 31 stations in northern and southern California. Propel’s “Diesel HPR” (*High Performance Renewable*) fuel consists of 98 percent RD (supplied by Neste, from the NEXBTL process) blended with 2 percent CARB diesel.
- The California Energy Commission has just awarded \$11.2 million in funds from the Alternative and Renewable Fuel and Vehicle Technology Program (ARFVTP) to add approximately 27 MGPY of additional RD production capacity.³⁰⁶
- The Oregon Department of Energy is working with “public entities across the state” to “tap into the emerging renewable diesel market.” One such entity, the Eugene Water & Electric Board, has switched its fleet to RD from biodiesel, and now uses about 6,100 gallons of RD per month. Fleet managers note that the use of RD has resulted in less-frequent need to undergo regeneration (by manual cleaning) of the diesel particulate filters on their HDV fleet.³⁰⁷

14.6. Cost and Price

According to Propel Fuels, it is selling RD at its 31 stations in California at a “cost competitive” price, which translates to a Diesel HPR price per gallon that is “slightly less than conventional diesel.” For example, Propel’s RD price was \$2.89 per gallon in Sacramento in March 2015, compared to \$3.09 per gallon for traditional diesel.³⁰⁸ It is unclear if Propel is setting its RD pricing according to cost plus margin, or if it currently sells RD as a “loss leader” to attract broader interest and acceptance.

14.7. Constraints and Challenges

Use of RD entails modest limitations on blending, as a result of pump labeling issues. These do not appear to be a significant impediment to wider use. As with other renewable fuels (including RNG), supply availability is the most-significant constraint for expanding RD use into HDV transportation markets. This will be linked to feedstock issues and competition from other markets. Unlike biodiesel, the RD refining process can be controlled to produce different renewable products; these include jet fuel and bio-based chemicals such as naphtha. This makes it more likely that there will be competition from biofuel markets other than on-road HDVs, some of which may be more profitable. Further, in the

³⁰⁵ Fleets and Fuels, “Cal DGS Requires Renewable Diesel,” December 11, 2015.

³⁰⁶ California Energy Commission, Alternative and Renewable Fuel and Vehicle Technology Program Project Funding Summary through April 15, 2015, accessed online, <http://steps.ucdavis.edu/files/09-11-2015-Compendium-Narrative-updated-4.15.15.pdf>.

³⁰⁷ NGTNews, “Eugene Water & Electric Board Touts Switch to Renewable Diesel,” January 18, 2016, http://ngtnews.com/eugene-water-electric-board-touts-switch-to-renewable-diesel/?utm_medium=email&utm_source=LNH+01-19-2016&utm_campaign=NGT+Latest+News+Headlines.

³⁰⁸ From Propel Fuels website, and a personal communication to GNA after calling the Propel Fuels Customer Service hotline.

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

event that other regions (states or nations) adopt aggressive programs to incentivize low carbon fuels, the ability to deliver RD into these markets may significantly change its supply chain dynamics.

As noted, tallow is currently the feedstock for most RD used in the U.S. According to CARB, “additional availability of tallow feedstocks are not certain, as most of the U.S. supply of tallow may not be available to RD production, and international tallow is already being drawn to the U.S. in large amounts.” However, CARB notes that “RD can be produced from any fatty acid feedstock.”³⁰⁹

14.8. Criteria Pollutant Emissions

CARB has performed in-house testing and also contracted with the University of California, Riverside to evaluate tailpipe emissions of HDVs using RD. This program included chassis dynamometer testing of on-road HDVs, as well as engine dynamometer testing of on- and off-road engines. Various test engines, vehicles, cycles and RD blends were used in these evaluations. CARB concluded the following:

“In general, this study found that most emissions from renewable diesel are reduced (relative to diesel fuel meeting ARB motor vehicle fuel specifications (CARB diesel), including particulate matter (PM), oxides of nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO₂), total hydrocarbons (THC), and most toxic species.”

NOx is the key criteria pollutant that must be dramatically reduced to attain NAAQS in “extreme” ozone areas like California’s SCAB and SJVAB. CARB found that 100 percent RD “generally” decreases NOx by roughly 10 percent, and thus it “could be expected to improve ground level ozone” compared to baseline CARB diesel fuel. CARB also noted that RD reduces PM emissions by about 30 percent (including carcinogenic diesel PM). However, when used in newer engines/vehicles (e.g., 2010 compliant diesel engines) with state-of-the-art emissions controls, these benefits are likely to be reduced significantly.³¹⁰

14.9. GHG Emissions and Carbon Intensity

When used to displace conventional diesel as an HDV fuel, RD has good GHG-reduction potential. CARB has applied its latest “CA-GREET” model to calculate preliminary full fuel cycle carbon intensity (CI) scores for “representative” RD fuel pathways (i.e., they are not based on any individual producer’s parameters). CARB’s analysis indicates that five different RD fuel pathways have CI scores that range from 51 to 83 percent lower (i.e., less carbon intense) than the baseline CARB diesel fuel. Currently, tallow is the feedstock for most RD used in California; it has a preliminary CI score under the new model that is 72 percent lower than CARB diesel.³¹¹

³⁰⁹ CARB Staff Report, Multimedia Evaluation of Renewable Diesel, Prepared by Multimedia Working Group, November 2013. Available online: http://www.arb.ca.gov/fuels/multimedia/meetings/renewabledieselstaffreport_nov2013.pdf

³¹⁰ CARB Staff Report, Multimedia Evaluation of Renewable Diesel, Prepared by Multimedia Working Group, November 2013. Available online: http://www.arb.ca.gov/fuels/multimedia/meetings/renewabledieselstaffreport_nov2013.pdf

³¹¹ CARB, “LCFS Illustrative Fuel Pathway Carbon Intensity Determined Using CA-GREET 2.0,” 9/17/2015, online at http://steps.ucdavis.edu/files/09-17-2015-Table-for-UCDavis_LCFS-Illustrative-CIs_FINAL.pdf. Total CI scores include direct and indirect contributions.

14.10. Potential for Expansion of U.S. RD Production Capacity

Regulators and market observers—especially in California—are increasingly optimistic about RD’s potential to become a mainstream replacement for conventional diesel fuel. CARB has developed an illustrative compliance scenario estimating low-, mid-, and high-growth projections for total U.S. RD production capacity. As shown in Table 22, projections for total U.S. capacity range from 690 to 1,290 million gallons per year (MGPY).³¹² Adding in another 240 MGPY of RD from international producers (e.g., Neste), CARB has projected that 929 MGPY to 1.529 BGPY could be available by 2020. In each scenario, CARB assumes that tallow will be the largest feedstock, with additional feedstock being corn oil, soy oil, and used cooking oil. CARB assumes that 400 MGPY of this national RD production in 2020 will be available for use in California.

Table 22. Projected U.S. renewable diesel production capacity in 2020 (CARB, 2015)

Current Capacity (MGPY)	Announced Capacity (MGPY)	CARB Growth Scenarios	By 2020 (MGPY)	
			Projected Additional Capacity	Total
212	277	Low Growth	200	689
		Mid Growth	400	889
		High Growth	800	1,289

Lux Research recently prepared a report³¹³ assessing the outlook for RD and other biofuels for the 2018 timeframe. The report cites the U.S. and Brazil as being the “biggest emerging production center for biofuels” such as RD. China, Indonesia, Thailand, Columbia, Argentina, Portugal, Poland and France are also emerging leaders. Lux Research estimated that RD will make up 18 percent (nearly 11 billion gallons per year) of the world’s total biofuel production in 2018.

Using its database of more than 1,800 global biofuel production facilities, Lux projected capacity expansion for RD in the U.S. over the next three years to be 279 MGPY. An additional 69 MGPY of new added renewable diesel capacity is expected for Canada. This makes the total projected added RD capacity in North America to be about 348 MGPY. These figures do not reflect the existing RD in the U.S. and Canada.³¹⁴

14.11. Summary: RD as a Pathway to Near-Zero NOx and Low GHG Emissions

California intends to “implement statewide strategies that employ lower NOX combustion engines coupled with the use of renewable fuels.”³¹⁵ This includes very significant plans to increase the volume

³¹² CARB, Appendix B, Development of Illustrative Compliance Scenarios and Evaluation of Potential Compliance Scenarios, 2015.

³¹³ Lux Research, “Biofuels Outlook 2018: Highlighting Emerging Producers and Next-Generation Biofuels,” press release, <http://www.luxresearchinc.com/news-and-events/press-releases/read/biofuels-capacity-grow-61-bgy-2018>.

³¹⁵ CARB, Draft Technology Assessment: Lower-NOx Heavy-Duty Diesel Engines,” http://www.arb.ca.gov/msprog/tech/techreport/diesel_tech_report.pdf, September 2015.

³¹⁴ Victor Oh, Lux Research, personal communication to Jon Leonard of GNA, December 15, 2015.

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

of RD used in diesel engines, which by itself can provide significant reductions in criteria pollutants (including NO_x) while delivering major GHG reductions. As heavy-duty engines with progressively lower NO_x levels are commercialized, the combination of such engines and RD substituted for conventional diesel will offer compelling NO_x and GHG benefits.

However, to achieve California's NO_x-reduction goals—as necessary to attain ozone NAAQS in 2023 and 2032)—it will be necessary to rapidly phase-in very large numbers of HDVs that emit NO_x at *near-zero* or *zero* levels. At a minimum, such HDVs will need to emit at or below CARB's bottom-tier Optional Low-NO_x Standard of 0.02 g/bhp-hr. No heavy-duty diesel engine (using conventional or renewable diesel) has yet been certified below the existing NO_x standard of 0.2 g/bhp-hr. Engine manufacturers have noted that challenging "NO_x-GHG" tradeoff issues must be resolved before heavy-duty diesel engines can be certified to the 0.02 g/bhp-hr NO_x level already achieved by CWI's ISL G NZ natural gas engine.

Heavy-duty diesel engines appear to be on the pathway to achieve these low NO_x levels, but there is significant uncertainty about the timeframe for this, and how it will impact California's goal to achieve major GHG reductions. Surprisingly, none of CARB's draft Technology Assessment documents specifically discuss the technological and commercial potential for advanced diesel engines using RD to help simultaneously meet the state's low NO_x and GHG goals. However, California's draft Mobile Source Strategy makes it clear that CARB expects approximately 500,000 low-NO_x trucks using RD to be deployed in the state over the next two decades (refer back to Section 4.6).

One thing is well established: heavy-duty diesel engines are the incumbent technology for goods movement applications, all across America. Whether they are fueled in the future by diesel or renewable diesel, this pathway "enjoys" all the associated advantages of incumbency. Among the four NZEV and ZEV pathways with the best potential to help transform America's transportation sector (refer back to Table 4 on page 60), it is the least likely to need further advocacy and support.



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