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# HEAVY-DUTY TRUCK AND BUS NATURAL GAS VEHICLE TECHNOLOGY ROADMAP



FINAL REPORT



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## **Acknowledgments**

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## **Preface**

This Roadmap was produced on behalf of the Southern California Gas Company, the nation's largest natural gas utility company and a leader in the development of new, advanced technologies which maximize the cleaner-burning characteristics of natural gas in residential, commercial, industrial and transportation applications. The Southern California Gas Company supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

## **Abstract**

The California Hybrid, Efficient and Advanced Truck Research Center (CalHEAT) was established by the California Energy Commission in 2010. It is operated by CALSTART to perform research into planning, commercializing, and demonstrating truck technologies for more fuel-efficient medium- and heavy-duty vehicles and to reduce emissions. The role of the research center is to facilitate and understand key commercialization pathways in order to help the state of California meet its environmental goals as they relate to medium and heavy duty trucks. The focus of this Roadmap was to identify key technologies, policy drivers and infrastructure to support pending anticipated growth in the use of natural gas as a fuel in the Class 8 Truck and bus market.

## Table of Contents

Acknowledgments .....	i
Roadmap Advisory Council.....	ii
Preface .....	iii
Abstract.....	iv
Table of Contents.....	v
List of Figures.....	vii
Executive Summary.....	1
Chapter 1: Background.....	4
1.1 Purpose .....	4
1.2 Key Findings.....	5
1.3 Priority Recommendations.....	5
1.3.1 Technology Recommendations.....	6
1.3.2 Policy Recommendations .....	6
1.4 Market Forecast.....	7
1.5 Drivers of Change.....	10
1.5.1 Continuation of low natural gas prices.....	11
1.5.2 Increasing regulatory pressure on lowering NOx Emissions .....	12
1.5.3 Increasing regulatory pressure on greenhouse gases and truck efficiency .....	15
Chapter 2: Pathways .....	20
2.1 Natural Gas Engine Technology .....	21
2.1.1 Overview .....	21
2.1.2 Recommendations for Engines .....	22
2.2 Fuels, Storage & Infrastructure .....	24
2.2.1 Fuels Trend Overview.....	24
2.2.2 Recommendations for Fuels .....	25
2.2.3 Onboard Gas Vehicle Storage Overview.....	26
2.2.4 Recommendations for Gas Storage.....	27
2.2.5 Infrastructure Trend Overview .....	28
2.2.6 Recommendations for Infrastructure.....	29
2.2.7 Electrification & Hybridization Overview .....	29
2.2.7.1 Range Extension and Electrification.....	29
2.2.7.2 Recommendations for Range-Extended Electric Using Alternative Power Plants.....	31

2.2.7.3	Natural Gas Hybrids .....	32
2.2.7.4	Recommendations for Natural Gas Hybrids (includes Hydraulic Hybrids).....	33
2.3	Policy.....	
2.3.1	Overview .....	34
2.3.2	Recommendations for Policy .....	35
2.4	Pathways by Vehicle Application .....	36
2.4.1	Overview .....	36
2.4.2	Recommendations by Application .....	37
2.4.2.1	Transit Buses .....	37
2.4.2.2	Refuse Collection .....	38
2.4.2.3	Port Drayage.....	38
2.4.2.4	Regional and Local Delivery Class 8 Trucks .....	39
2.4.2.5	Over the Road Trucks .....	39
Appendix	.....	40
	Detailed engine/driveline technology descriptions and an assessment of their potential emissions & CO <sub>2</sub> improvements	



## List of Figures

Figure 1:	Baseline Inventory of Natural Gas Trucks and Buses in SoCal Gas Territory.....	5
Figure 2:	Baseline Inventory of Natural Gas Trucks and Buses in SoCal Gas Territory (continued)...	6
Figure 3:	Potential Market Growth Scenario Using ACT and CalHEAT Inventory.....	7
Figure 4:	Historical Oil and NG Fuel Prices.....	8
Figure 5:	Natural Gas Pump Price – Low Price Volatility.....	8
Figure 6:	Major NOx Emission Sources in South Coast Air Basin.....	10
Figure 7:	Major NOx Emission Sources in San Joaquin Valley.....	11
Figure 8:	SoCal Gas Territory in relation to SCAQMD and SJVAPCD Air Districts.....	11
Figure 9:	Top 15 NOx Source Categories (SCAQMD and SJVAPCD).....	12
Figure 10:	CARB’s 2050 GHG Target – AB 32 Climate Change Scoping Plan.....	13
Figure 11:	Broader Approach Needed to Reach State and Regional Targets.....	14
Figure 12:	CO2 Reduction from CalHEAT Roadmap.....	15
Figure 13:	EPA and NHTSA Phase 1 Standards for M-HD Vehicles.....	16
Figure 14:	Roadmap Pathways Overview.....	17
Figure 15:	Select NG Engine and Vehicle Technology Advancement Potentials for Lower NOx & CO2 Emissions.....	20
Figure 16:	CNG Tanks Mounted Behind the Cab.....	22
Figure 17:	Typical LNG framerail tank placement.....	22

## Executive Summary

The California Hybrid, Efficient and Advanced Truck Research Center (CalHEAT) was established by the California Energy Commission in 2010. It is operated by CALSTART to perform research into planning, commercializing, and demonstrating truck technologies for more fuel-efficient medium- and heavy-duty vehicles and to reduce emissions. The role of the research center is to facilitate and understand key commercialization pathways in order to help the state of California meet its environmental goals as they relate to medium and heavy duty trucks.

This Roadmap was produced on behalf of the Southern California Gas Company. The focus of this Roadmap was to identify key technologies, policy drivers and infrastructure to support pending anticipated growth in the use of natural gas as a fuel in the Class 8 truck and bus market with a focus on Refuse Collection, Transit Bus, Drayage Trucks, Regional /Beverage Delivery Trucks and Line Haul (often referred to as Over the Road) Trucks.

The recent increase in supply of natural gas in the United States along with a highly attractive price point, nearly half that of diesel fuel, have created the opportunity for a significant market growth of Class 8 trucks to occur. In addition, policy drivers in California pressing for near zero and zero emissions combined with the need for significant reductions in greenhouse gases (GHGs) have created a compelling scenario for market growth should Class 8 Truck manufacturers offer drivetrain solutions with the performance, efficiencies, and reliability and cost of ownership to meet the needs of the Class 8 truck and bus fleets.

The purpose of this Technology Roadmap is to identify the various pathways that will impact the penetration and deployment of Heavy Duty Natural Gas Vehicles to reduce greenhouse gas emissions and achieve near zero emissions (NZE) of criteria pollutants and improve engine fuel efficiency. The target for NZE for criteria pollutant is defined as <0.02 g/bh-hr for NO<sub>x</sub>, <0.06 g/bh-hr for Non-Methane Hydrocarbons (NMHC), <10 g/bh-hr for CO, and < 0.002 g/bh-hr for PM by 2023 and beyond. For natural gas vehicles to remain viable in the time period of 2014 to 2032, they must be technologically able to address the next generation of criteria and greenhouse gas emission standards. Natural gas vehicles are already inherently cleaner than those running on petroleum fuels, but that advantage may be diminished in the 2020's as newer technologies and fuels emerge driven by pending voluntary lower NO<sub>x</sub> emission standards. By identifying the future technology barriers and gaps now, regulators and other technology stakeholders will be able to ensure that natural gas will continue to grow as a petroleum reduction strategy along with a tool for addressing NO<sub>x</sub> and greenhouse gases.

In order to identify and document the technology pathways that will facilitate the development of heavy-duty natural gas vehicles that are cleaner and more efficient, CALSTART and the CalHEAT Truck Research Center developed steps and pathways that can guide new investments and policies by Southern California Gas Company and regional/state regulators. This Roadmap concentrates on the following areas:

- ✓ *Vehicle technologies* – including emission reductions ,combustion efficiencies, external natural gas-hybrid advancements, advanced combustion and power plants
- ✓ *Gas storage* – including lower compression pressures and lighter weight and lower cylinder costs
- ✓ *Fuel* - including cost, availability, new sources, and issues related to gas quality, and the greater potential of renewable natural gas
- ✓ *Infrastructure* – including station size options for CNG and LNG and modular stations

In each of these areas, the authors took an approach that first identifies the following:

- ✓ Current state of the technology
- ✓ Its potential contribution to lower NOx emissions and greater overall energy efficiency
- ✓ Gaps and barriers that will need to be lowered for new technologies to be successfully implemented
- ✓ Strategies and technologies that will be required to be implemented in that area
- ✓ Other non-technology barriers that need to be addressed
- ✓ Timeframes for feasible and successful adoption of new technologies
- ✓ The end-value/benefit of each of the strategies and technologies identified

The results of the initial investigation were then integrated into application-based pathways. The applications include *drayage, long haul, local and regional delivery, refuse and transit*.

Based on our investigations and analysis, the following **key** findings were made:

- ✓ The market for heavy-duty natural gas trucks in the Southern California Gas Company service territory may grow four-fold by 2020 and ten-fold by 2030, reaching 73,000 trucks by 2030 – the recent release of the 11.9-liter natural gas engine is identified as a key enabler
- ✓ Regional/local delivery and line haul applications are forecasted to be the key growth markets
- ✓ Natural gas will have or maintain majority market share in transit and refuse applications by 2030
- ✓ New federal fuel economy and greenhouse gas regulations for trucks will be enacted for 2019 and beyond that will drive technology development of advanced drivetrains – this is seen as a positive impact for NG

The following priority technology recommendations were developed:

- ✓ Southern California Gas Company should work with the Los Angeles Metropolitan Transit Agency and others to become early adopters of low-NOx natural gas engines

currently in development in order to secure early beachhead markets for low NOx engine makers (*see Engines section*)

- ✓ Deploy 65-100 new stations strategically in the service territory to support long-haul markets – this enables the greater use of CNG in this application (*see Infrastructure section*)
- ✓ Demonstrate and validate the performance of “NG in a box” modular stations to allow greater usage of localized natural gas for LNG & CNG (*see infrastructure section*)
- ✓ Help to secure the best possible outcome for natural gas range extenders in drayage applications to meet the needs of Zero Emissions Corridor and Zones to be implemented around 2020 (I-710 and POLB/POLA) (*see Port Drayage section*)
  - Participate in the California Energy Commission’s Medium- and Heavy Duty technology demonstration activity as it relates to natural gas range extenders
  - Work with the California Energy Commission’s PIER Program
- ✓ Build partnerships and encourage the development of natural gas-turbine range extender electrified drivelines to provide natural gas options for the California Zero Emission Bus regulations (*see Transit section*)

The following policy recommendations were developed:

- ✓ Support the use of California cap-and-trade funds for natural gas Class 8 vehicle purchases and infrastructure development (*see Policy section*)
- ✓ Work to encourage the California Energy Commission to make natural gas truck incentives more transparent by adopting voucher structures similar to the California HVIP program (*see Policy section*)
- ✓ Weigh in with the National Highway Traffic Safety Administration and the Environmental Protection Agency on Phase 2 fuel economy standards to insure fair recognition of natural gas (*see Engines section*)
- ✓ Track and weigh in on state and federal low-carbon fuel standards and renewable fuel standards proceedings in encourage the greater use of renewable feedstocks (*see Fuels section*)

## Chapter 1: Background

The CalHEAT Truck Research Center published its Research and Market Transformation Roadmap for Medium and Heavy Duty Trucks in 2013. The Roadmap provides pathways and stepping stones through the year 2020 that will be required to develop and deploy zero- and near-zero emission medium and heavy duty truck drivetrain technologies and facilitate California in meeting its environmental goals. This original research published on April 4, 2013 included natural gas as a key in the area of alternatively fueled hybrids, advanced powerplants, combustion cycles, and optimized alternatively fueled engines.

This report is a deeper and more focused review of heavy-duty natural gas vehicles and their drivetrain and infrastructure options, resulting in a Roadmap or series of pathways towards commercial product offerings in the year 2023 and beyond, specifically for regions served by the Southern California Gas Company. In particular, it investigates the pathways that heavy-duty natural gas vehicles should follow in order to play a significant role in the overall strategy to provide near-zero emission transportation options to meet state and regional regulations. Natural gas is already a strong component of the clean transportation strategies of Southern California regions, and is a significant driver for California and the SoCal Gas region to enable a reduction in the use of petroleum as well as criteria emissions in heavy duty vehicles; yet, little has been done to forecast or provide pathways of the future technology needs for natural gas vehicles, especially in the heavy-duty classes (7 to 8). The significant price advantage and abundant supplies of natural gas reinforce the notion that it will remain and grow as a major part of the clean transportation portfolio for at least the next fifteen to twenty-five years.

### 1.1. Purpose

The specific purpose of this Technology Roadmap is to develop a series of stepping stones towards commercial product offerings in the year 2023 for regions serviced by SoCal Gas. To that end, the Roadmap identifies the various pathways that impact the penetration and deployment of heavy duty natural gas vehicles (Class 7/8) to reduce greenhouse gas (GHG) emissions by 20%, achieve near zero emissions (\*NZE) of criteria pollutants, and improve engine fuel efficiency to 50% in the SoCal Gas territory. New National Ambient Air Quality Standards (NAAQS), 24-hour fine particulates (PM<sub>2.5</sub>), and 8-hour surface level ozone standards are more stringent than previous standards. The 2012 South Coast Air Quality Management District (SCAQMD) Air Quality Management Plan (AQMP) attempts to achieve attainment of the federal 24-hour PM<sub>2.5</sub> of 35 ug/m<sup>3</sup> by 2014 and attempts to show major progress toward achieving the 8-hour ozone standard of 80 ppb by 2023 and 75 ppb by 2032.

To achieve these standards, the SCAQMD needs to accelerate retrofits or replacement of existing vehicles or equipment, acceleration of vehicle turnover through voluntary vehicle retirement programs, and greater use of cleaner fuels in the near-term. In the longer-term, in

order to attain the federal ozone ambient air quality standard, there is a need to increase the penetration and deployment of near-zero and zero-emission vehicles using new lower NOx natural gas engines, greater electrification of the driveline and cleaner nonvehicle power plants such as NG based turbines and fuel cell. For natural gas vehicles to remain viable in this time period, they must be technologically able to address the next generation of criteria and greenhouse gas emissions standards. Natural gas vehicles are already inherently cleaner than those running on petroleum fuels, but that advantage may be less so in the 2020's as newer technologies and fuels emerge driven by pending voluntary lower NOx emission standards. By identifying the future technology barriers and gaps now, regulators and other technology stakeholders will be able to ensure that natural gas will continue to grow as a petroleum reduction strategy along with a tool for addressing NOx and greenhouse gases.

## **1.2. Key Findings**

This Roadmap evaluates several strategies to further support the successful deployment of NG technologies. To that end, the CalHEAT team analyzed the necessary market and technological gaps that should be addressed to speed the implementation of needed changes. The key findings listed below identify a series of achievable actions to develop and adopt successive next steps across multiple categories.

- ✓ Market for heavy-duty natural gas trucks in So Cal Gas territory expected to grow 4X by 2020 and 10X by 2030, reaching 73,000 trucks by 2030 – recent release of 11.9L NG engine is a key enabler
- ✓ Regional/local delivery and line haul are forecasted to be the key growth markets
- ✓ Natural gas will have a majority market share in transit and refuse applications
- ✓ New federal fuel economy and greenhouse gas regulations for trucks will be enacted for 2019 and beyond that will drive technology development of advanced drivetrains – positive impact for NG

## **1.3. Priority Recommendations**

A NGV research literature review, RDD&D gap analysis, and stakeholder interviews combine to suggest that the following top-level recommendations would provide the greatest acceleration of NGV market penetration toward their full market potential.

These priority recommendations are those identified by the CalHEAT team as the most feasible ways to accelerate NG commercial product offerings in terms of Technology and Policy strategies (described in more detail in Chapter 2, Sections 2.1 and 2.3, respectively). The recommendations for the other strategies are also important and will contribute to further deployment of NG vehicles, but are only identified and discussed in Chapter 2.

### **1.3.1. Technology Recommendations**

- ✓ Work with LA Metro and other transit agencies to become early adopter of low-NOx NG engines to secure early beachhead market for low NOx engine makers (see Engines section)
- ✓ Deploy 65-100 new stations strategically in service area to support long-haul markets – enables greater use of CNG in this application (see Infrastructure section)
- ✓ Demonstrate and validate the performance of “LNG in a box” modular stations to allow greater usage of localized natural gas for LNG (see infrastructure section)
- ✓ Help to secure best possible outcome for NG range extenders in drayage applications to meet needs of Zero Emissions Corridor and Zones to be implemented around 2020 (I-710 and POLB/POLA) (see Port Drayage section)
- ✓ Participate in CEC M-HD demo activity as it relates to NG range extenders demonstrations
- ✓ Work with the California Energy Commission-Public Interest Energy Research (CEC-PIER) Program to pursue funding
- ✓ Build partnerships and encourage development of NG-turbine range extender electrified drivelines to provide NG option for California Zero Emission Bus regulations (see Transit section)

### **1.3.2. Policy Recommendations**

- ✓ Support use of CA cap-and-trade funds for vehicle purchases & infrastructure development (see Policy section)
- ✓ Work to encourage CEC to make NG truck incentives more transparent by adopting HVIP-like voucher structure (see Policy section)
- ✓ Weigh in with NHTSA/EPA on Phase 2 fuel economy standards to insure fair recognition of natural gas (see Engines section)
- ✓ Track and weigh in on state & federal LCFS/RIN (RFS renewable identification number) proceedings (see Fuels section)

## 1.4. Market Forecast

In preparing this Market Forecast, the CalHEAT team evaluated a wide range of trends and issues that could have major implications for the U.S. natural gas market. Because of the uncertainties inherent in any energy market projection, this projection should not be viewed in isolation. Readers are encouraged to review alternative cases to gain perspective on how variations in key assumptions can lead to different outlooks.

The table below<sup>1</sup> was derived by breaking out the zip codes that align with the SoCal gas service territory utilizing the CalHEAT Inventory analysis. It focuses on class 8 Trucks and buses which include the following vocations: refuse collection, transit buses, drayage trucks, regionals delivery trucks, and over the road coaches (often referred to as line haul). These trucks, while representing only 20% of all medium and heavy duty trucks in the region, also represent more than 60% of the NOx, greenhouse gases, and fuel use of all classes of medium and heavy duty trucks.<sup>2</sup> Thus they represent the best target for the introduction and growth of the use of natural gas as an enabler to reduce NOx, GHG's and the cost of fuel. HDV refuse trucks and transit buses, with some drayage trucks and other goods movement vehicles, will continue to be the dominant near-term classes for NGV applications. Line-haul trucks (typically the largest and heaviest class of HDVs) are considered to be a longer-term NGV application, while return-to-base truck and bus operations are more practical near-term applications due to their use of centralized refueling infrastructure. Compressed natural gas (CNG) technology is broadly applicable to many urban-area heavy-duty and medium-duty uses, while liquefied natural gas (LNG) is likely to be focused primarily on heavy-duty long-haul intercity trucks and others with very high daily mileage due to fuel tank volume constraints.

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<sup>1</sup> Inventory data derived from CalHEAT report. Silver, Fred, and Brotherton, Tom. (CalHEAT). "Research and Market Transformation Roadmap to 2020 for Medium- and Heavy-Duty Trucks." California Energy Commission. Draft Rev # 7 Dated 6-14-2013.

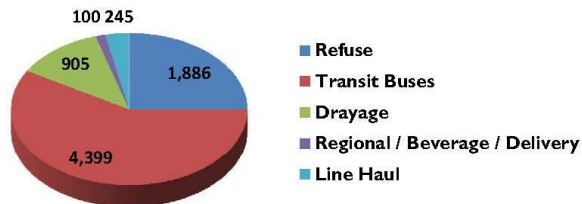
<sup>2</sup> Id.



## Baseline Inventory of Natural Gas Trucks and Buses In SoCalGas Territory



	Refuse	Transit Buses	Drayage	Regional Beverage Delivery	Line-Haul	Grand Totals
LNG	1,070	333	900	100	245	2,648
CNG	816	4,066	5	-	-	4,887
Subtotals	1,886	4,399	905	100	245	7,535
Truck / Bus Life	12 years	12 years	10 years	12 years	6-7 years	-
Addressable Market	6,732	6,396	13,080	51,392	112,501	190,101
NG Market Share	28.8%	68.8%	6.9%	0.2%	0.2%	4.0%

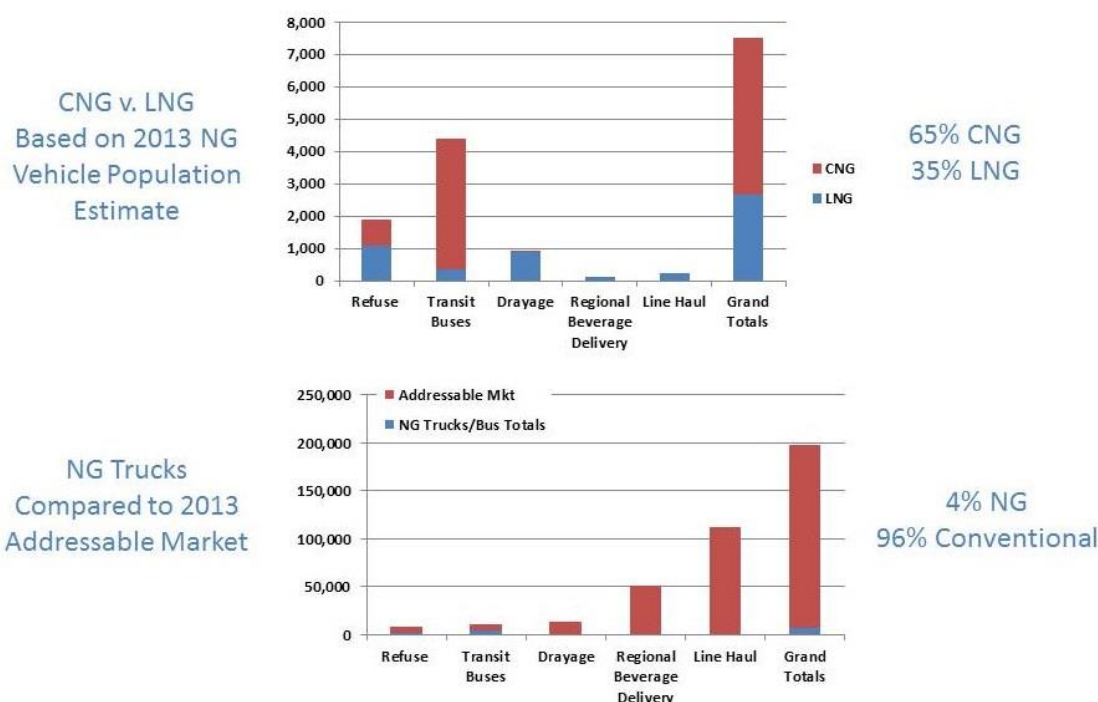


**Figure 1 : (Source: CalHEAT Research and Market Transformation Roadmap to 2020 for Medium- and Heavy-Duty Trucks)**

Specifically within the SoCal Gas territory, the dominant classes for NG truck and bus applications also include refuse and transit, with 65% using CNG and 35% using LNG (see Figure 2 below)<sup>3</sup>. Overall, NG Heavy Duty vehicles make up 4% of the total 2013 addressable market in the Southern California Gas operating region.

<sup>3</sup> Inventory data derived from CalHEAT report. Silver, Fred, and Brotherton, Tom. (CalHEAT). "Research and Market Transformation Roadmap to 2020 for Medium- and Heavy-Duty Trucks." California Energy Commission. Draft Rev # 7 Dated 6-14-2013.

## Baseline Inventory of Natural Gas Trucks and Buses In SoCalGas Territory (Continued)



**Figure 2: (Source: CalHEAT Research and Market Transformation Roadmap to 2020 for Medium- and Heavy-Duty Trucks)**

In preparation of this market forecast for NG vehicles in California, the CalHEAT team referenced the California Truck Inventory Study that was performed in the development of the CalHEAT Roadmap. That study was developed to better understand the various types of trucks used in California, their relative populations, and how they are used. The analysis included nearly 1.5 million commercial medium- and heavy-duty trucks, grouped by weight and application, to establish a baseline inventory and determine fuel use and potential for efficiency and emissions improvements.

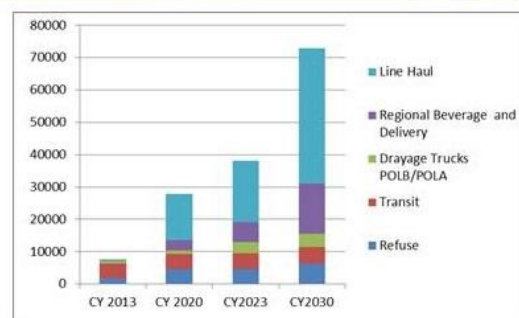
The table below illustrates a potential market growth scenario using the CalHEAT Truck Inventory, and the ACT inventory.<sup>4</sup> The data shows total truck population growth according to State EMFAC projections used on the addressable market. ACT growth rates were used for refuse trucks and the market share was maintained for transit buses. The ACT Average Growth rate was used for TL-LTL-Expedited and owner operated on Port. The Drayage segment maintained its present share for four years due to regulations forcing Large buy of 2007/2010 trucks. The ACT Average growth rate was used for regional beverage delivery and however it

<sup>4</sup> America's Commercial Transportation Research Co. (ACT). "Natural Gas Vehicle Penetration Forecasts and Calculators." August 2012.

was cut in half for Line haul trucks given the need for even larger engines, 13 and 15 liters, the obstacles associated with growing the refueling network on a national basis and the potential risk adversity we project on fleets in terms of adopting new fuels and technologies.

### Potential Market Growth Scenario Using ACT and CalHEAT Inventory

	CY 2013	CY 2020	CY2023	CY2030
Refuse	1886	4594	4704	6411
Transit	4399	4620	4760	5050
Drayage Trucks POLB / POLA	905	1075	3525	4077
Regional / Beverage / Delivery	100	3265	6087	15518
Line Haul	245	14313	19133	41798
<b>Total NG</b>	<b>7535</b>	<b>27868</b>	<b>38210</b>	<b>72853</b>



Market Share Scenarios	CY2013	CY2020	CY2023	CY2030
Refuse	28.0%	55.5%	53.2%	62.4%
Transit	68.8%	68.8%	68.8%	68.8%
Drayage POLA / POLB	6.9%	6.9%	21.5%	22.1%
Regional / Beverage / Delivery	0.2%	5.5%	10.5%	24.5%
Line Haul	0.2%	8.7%	11.1%	21.3%
<b>Total</b>	<b>4.0%</b>	<b>10.9%</b>	<b>14.5%</b>	<b>24.6%</b>

NG as a Percentage of the Total or Addressable market

Note: market forecast figures are currently undergoing final revisions in conjunction with other parties

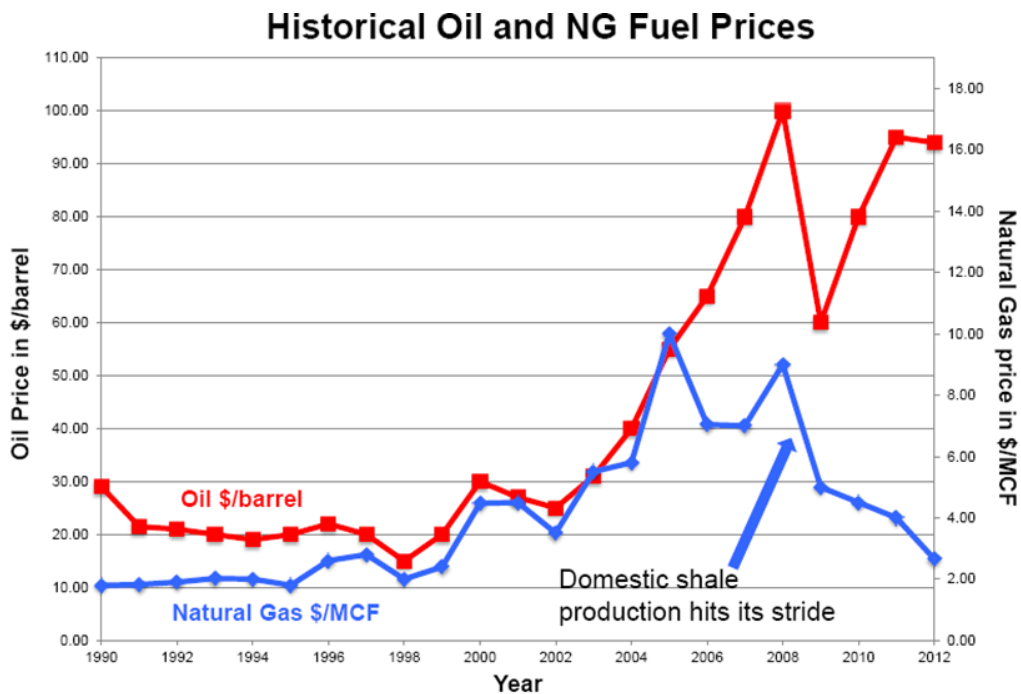
**Figure 3: (Source: CalHEAT Research and Market Transformation Roadmap to 2020 for Medium- and Heavy-Duty Trucks)**

## 1.5. Drivers of Change

The following section addresses the primary drivers of change from now through 2023. Natural gas is a compelling long term fuel for vehicles for the following reasons: (1) new fracturing technology allows economical access to natural gas; (2) current and future production is projected to outstrip demand; (3) the U.S. has some of the largest NG reserves in the world; (4) both Frost and Sullivan and ACT are projecting significant adoption in the heavy duty vehicle market; and (5) fleets seek price certainty & stability.

### 1.5.1. Continuation of low natural gas prices

As the tables below indicate, the “pump price” of natural gas is less subject to changes in market prices for energy. A doubling of the price of natural gas results in an increase of prices at the pump only 50 cents per gasoline gallon equivalent (GGE). The key factor limiting the potential increase in the natural gas price at the pump is that the NG commodity prices are only a small fraction of the fuel cost at the pump



*Figure 4: Kennon Guglielmo, Ph.D. President, EControls CTO, Enovation Controls. “Domestic Heavy-Duty Mobile Natural Gas History, Technology, and Outlook.” Presented at NAFA Institute & Exposition, Atlantic City. April 25, 2013.*

## Natural Gas Pump Price Low Price Volatility

Natural Gas @ \$4.00 per MCF		Natural Gas @ \$8.00 per MCF	
INPUT	COST	INPUT	COST
Natural Gas (divide by 8)	\$0.50	Natural Gas (divide 8)	\$1.00
Transport Costs & Fees	\$0.20	Transport Costs & Fees	\$0.20
Electricity Costs per GGE	\$0.10	Electricity Costs per GGE	\$0.10
Maintenance per GGE	\$0.20	Maintenance per GGE	\$0.20
Federal and State Taxes	\$0.25	Federal and State Taxes	\$0.25
Fuel Card Fees per GGE	\$0.05	Fuel Card Fees per GGE	\$0.05
Retailer Profit Margin	\$0.40	Retailer Profit Margin	\$0.40
CNG at the Pump	\$1.70	CNG at the Pump	\$2.20

**A doubling of the price of natural gas  
increases prices at the pump only \$0.50  
per GGE**

*Figure 5: (Source: CalHEAT Research and Market Transformation Roadmap to 2020 for Medium- and Heavy-Duty Trucks)*

### 1.5.2. Increasing regulatory pressure on lowering NOx Emissions

While recent progress has been significant, diesel-fueled on-road HDVs remain the largest sources of NOx in California's key ozone non-attainment areas. Heavy-duty natural gas vehicles may offer significantly lower NOx emissions than current diesel technology, and slight improvements in GHG emissions. Increasing penetration of natural gas in the heavy-duty truck sector could help to meet mid-term air quality targets both regionally and nationally.

The increasingly stringent pollution control requirements set by the U.S. Environmental Protection Agency for heavy-duty fleets have meant that new diesel powered trucks must be equipped with complex and costly pollution control systems not required for natural gas trucks. This has narrowed the economic advantage diesel long had over natural gas.

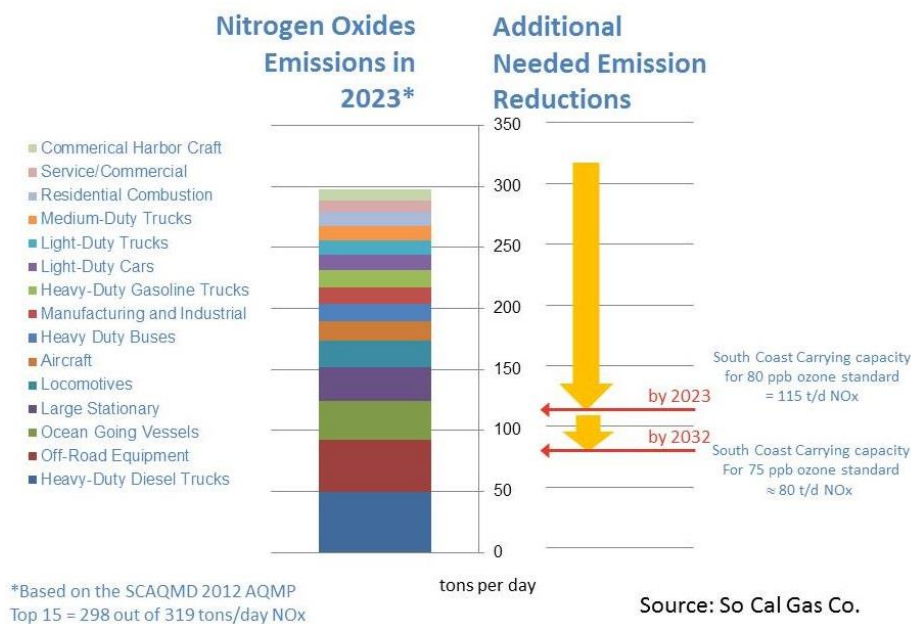
Regionally, federal ozone regulations require South Coast and Central Valley Air Districts to reduce NOx emissions accordingly:

- South Coast Air Basin must reduce Nitrogen Oxides from 319 tons per day (t/d) to:
  - 115 t/d by 2023 - a 64% reduction
  - 80 t/d by 2033 - a 75% reduction
- San Joaquin Valley APCD must reduce Nitrogen Oxides from 257 t/d to:
  - 160 t/d by 2023 - a 38% reduction
- Heavy duty diesel trucks are the number one target for both regions

Increased market penetration of advanced NG technologies is an enabling factor in achieving additional NOx emission reductions. Existing regulations are inadequate. Beyond traditional focus on reducing per-vehicle emission levels, there is the possibility of significant reductions in the South Coast Air Basin. This methodology is also applicable to other air basins (i.e., San Joaquin).

In Figure 6 below, the colored bars on the left signify the projected 2023 SoCal inventory of the top 15 NOx sources after all currently adopted emission control measures have been implemented. These 15 largest sources of NOx make up 93 percent of the total projected inventory of NOx in 2023. Based on the figures in the 2012 Air Quality Management Plan (AQMP) for the South Coast Air Quality Management District (SCAQMD), the NOx inventory in 2023 will be 319 tons per day; this is 204 tons per day more than air quality planners believe is necessary to meet the 1997 ozone NAAQS. The gold arrows on the right show the additional NOx emission reductions that will be needed over the next 10 years to meet the standard. NOx emissions in the SoCAL region must be reduced well beyond the levels that are expected through all existing or currently defined control measures. In the San Joaquin Valley Air Basin, the challenge for the San Joaquin Valley Air Pollution Control District (SJVAPCD) to meet the ozone NAAQS is also quite daunting.<sup>5</sup>

### Major NOx Emission Sources in South Coast Air Basin

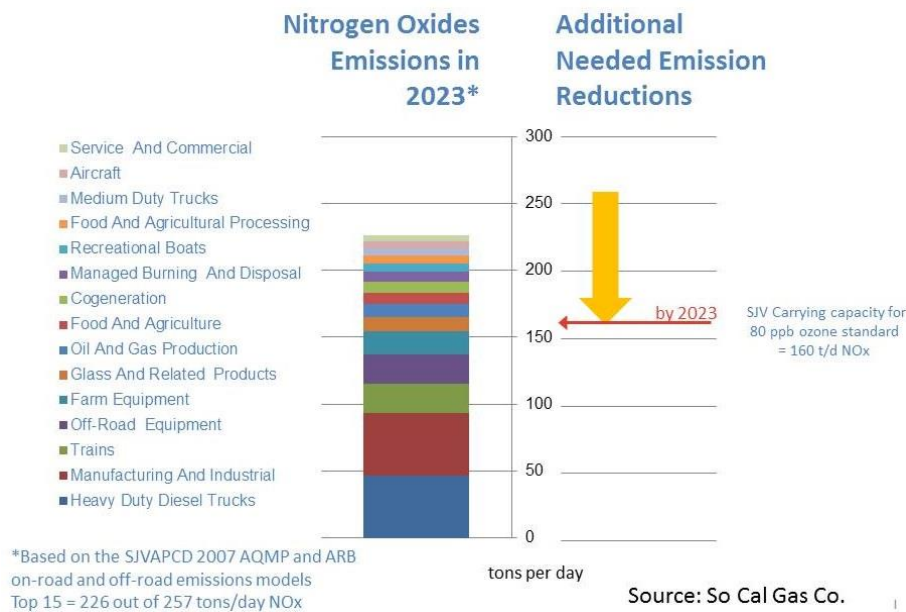


**Figure 6: Current AQMPs do not provide for sufficient NOx reductions to meet NAAQS (Source: SCAQMD)**

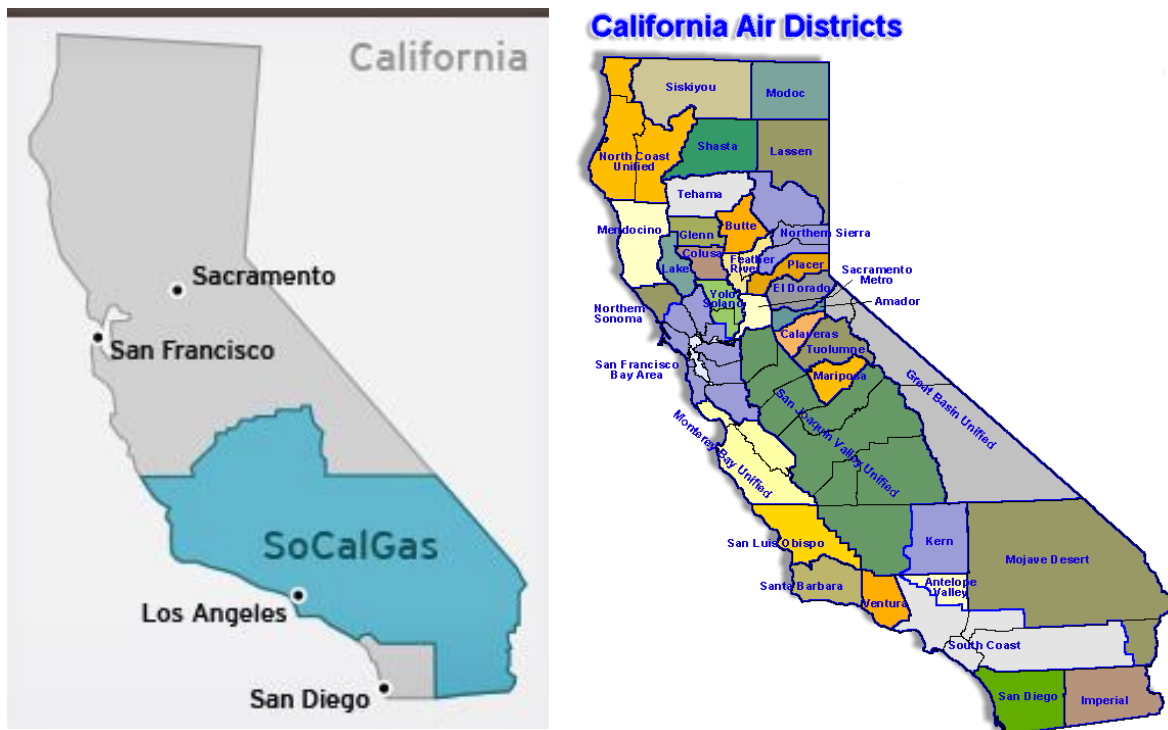
<sup>5</sup> Gladstein, Neandross, and Associates. "Pathways to Near-Zero-Emission Natural Gas Heavy-Duty Vehicles." January 27, 2014



## Major NOx Emission Sources in San Joaquin Valley



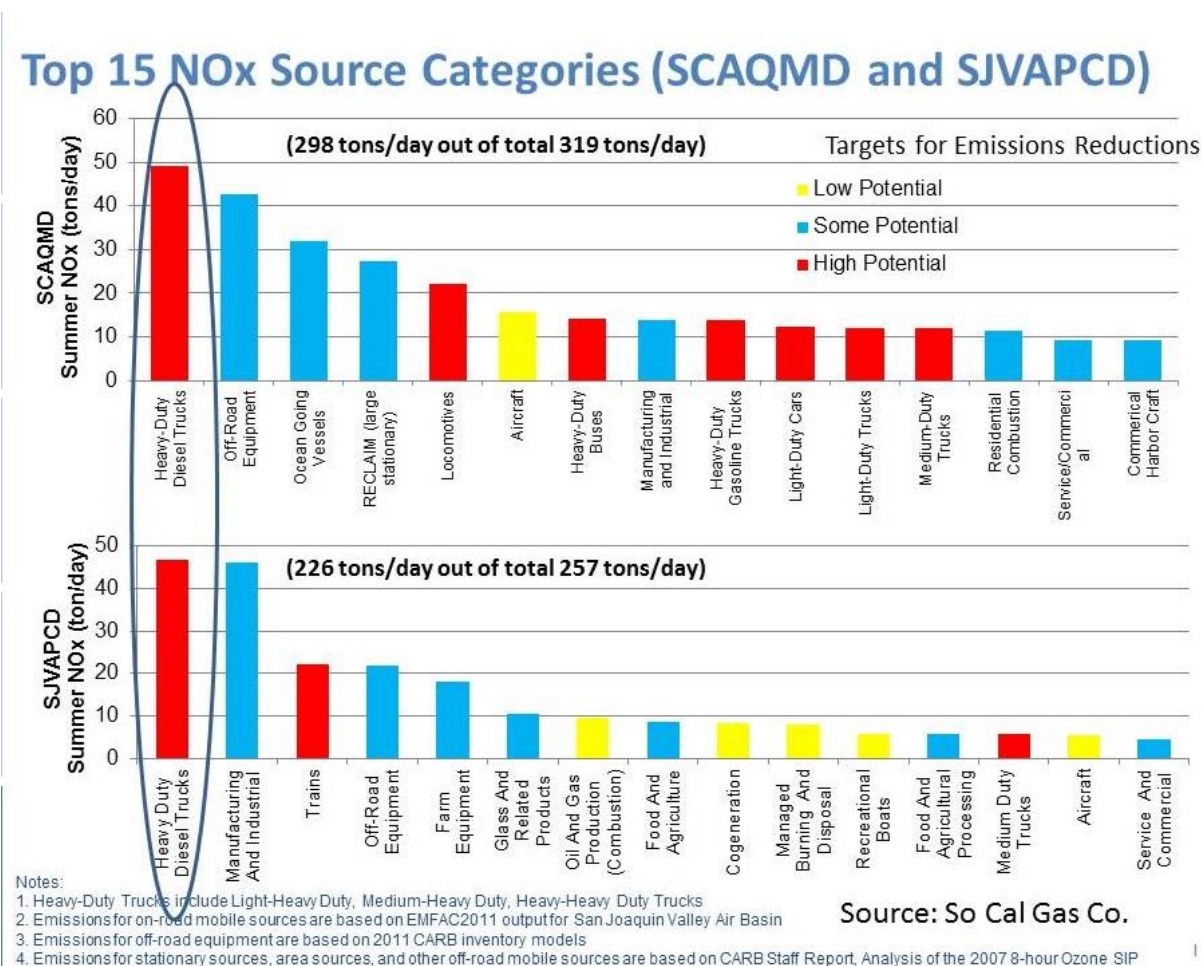
**Figure 7: Major NOx Emission Sources in San Joaquin Valley**  
(Source: SCAQMD)



**Figure 8: The SoCal Gas territory covers all of SCAQMD and significant parts of the SJVAPCD. (Sources: SoCal Gas and California Air Resources Board)**

Heavy duty trucks are the largest contributor to the NO<sub>x</sub> inventory in both the South Coast and San Joaquin regions and a high potential target for emissions reductions from conversion to natural gas.

Figure 9 below shows that most of NO<sub>x</sub> emission reductions beyond those already identified as necessary to meet the 2023 and 2032 ozone NAAQS will need to come from heavy-duty engines, the vast majority of which are fueled by diesel.



**Figure 9: Diesel-fueled technologies are the largest source of NO<sub>x</sub>**  
 (Source: So Cal Gas Co.)

### 1.5.3. Increasing regulatory pressure on greenhouse gases and truck efficiency

This subsection discusses the way in which carbon dioxide (a major contributor to greenhouse gases) will be driven significantly downward by the following federal and state regulations:

- ✓ California's AB 32 and Executive Orders #B-016-2012 & S-03-2005 require a 20% reduction in greenhouse gases (GHG) by 2020 and 80% by 2050 in order to reach levels that are 80% lower than 1990 – this is not mandated yet.

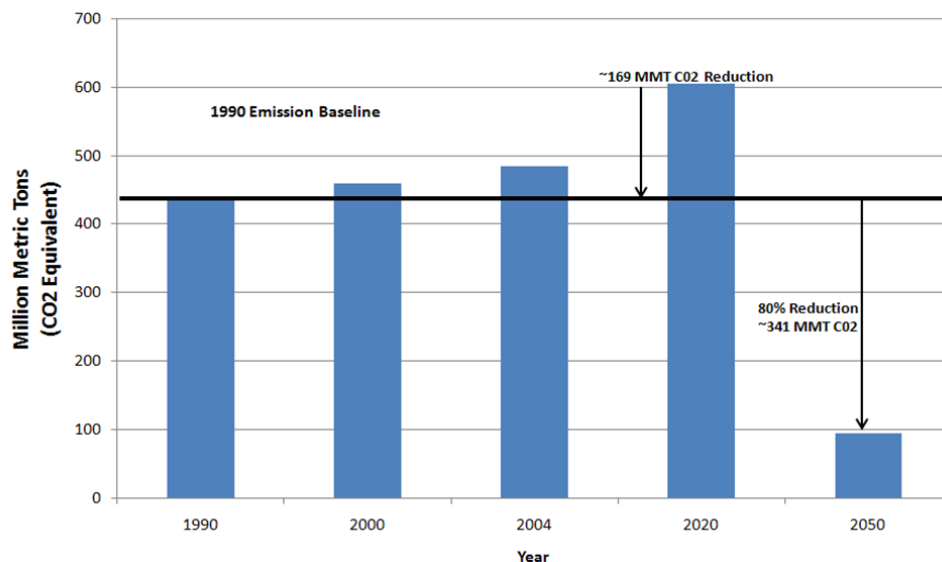


- ✓ EPA/NHTSA CAFÉ Regulations for Trucks Require CO<sub>2</sub> Reductions through Fuel Economy Regulations.
  - Phase 1 10-23% reduction required model year 2014-2018
  - Phase 2 Under development and to be announced by 2015 expected to require more aggressive fuel economy

CalHEAT research has determined a pathway for meeting a 70% CO<sub>2</sub> reduction within the medium- and heavy-duty inventory of trucks in California.

- ✓ Class 8 over-the-road and regional tractors represent 56% of the CO<sub>2</sub> in the truck inventory
- ✓ NG trucks will have to become significantly more efficient
  - Up to 65 % by 2023
  - Renewable fuels derived from natural gas are an equal contributor in reducing CO<sub>2</sub>

AB 32 is also driving change in California. AB 32 requires California to lower greenhouse gas emissions to 1990 levels by 2020, the equivalent of taking approximately 15 million cars off the nation's roads. To meet reduction targets, the California Air Resources Board (CARB), the lead agency responsible for implementing the act, is following a blueprint known as the AB 32 Climate Change Scoping Plan. The plan lays out the strategy and a comprehensive set of actions including establishing targets for transportation-related greenhouse gas emissions for regions throughout California, and pursuing policies and incentives to achieve those targets.



**Note: the 2050 GHG target is still an Executive Order and is not yet law**

**Figure 10: (Source: CalHEAT Research and Market Transformation Roadmap to 2020 for Medium- and Heavy-Duty Trucks)**

There is a growing gap between what is projected and what is needed. We have a short period of time to move the Southern California heavy duty market. As the table below suggests, a broader approach is needed to reach state and regional targets. Targets for NO<sub>x</sub> will not be met in either the South Coast or San Joaquin APCDs

### Broader Approach Needed to Reach State and Regional Targets

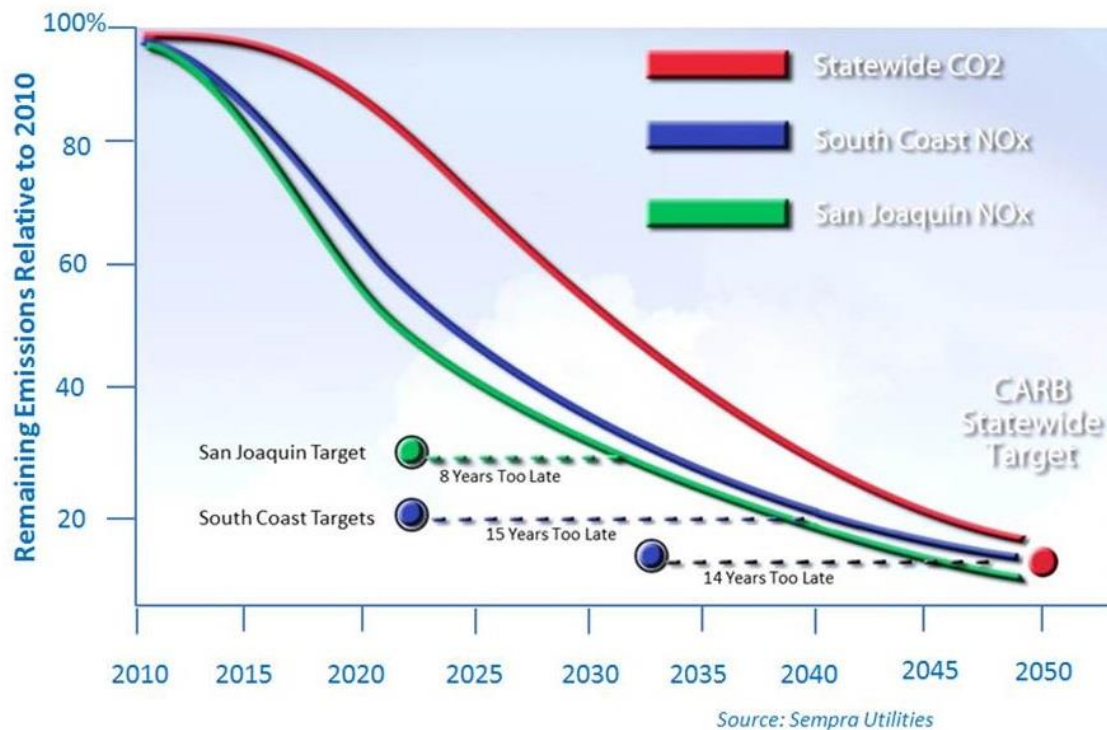


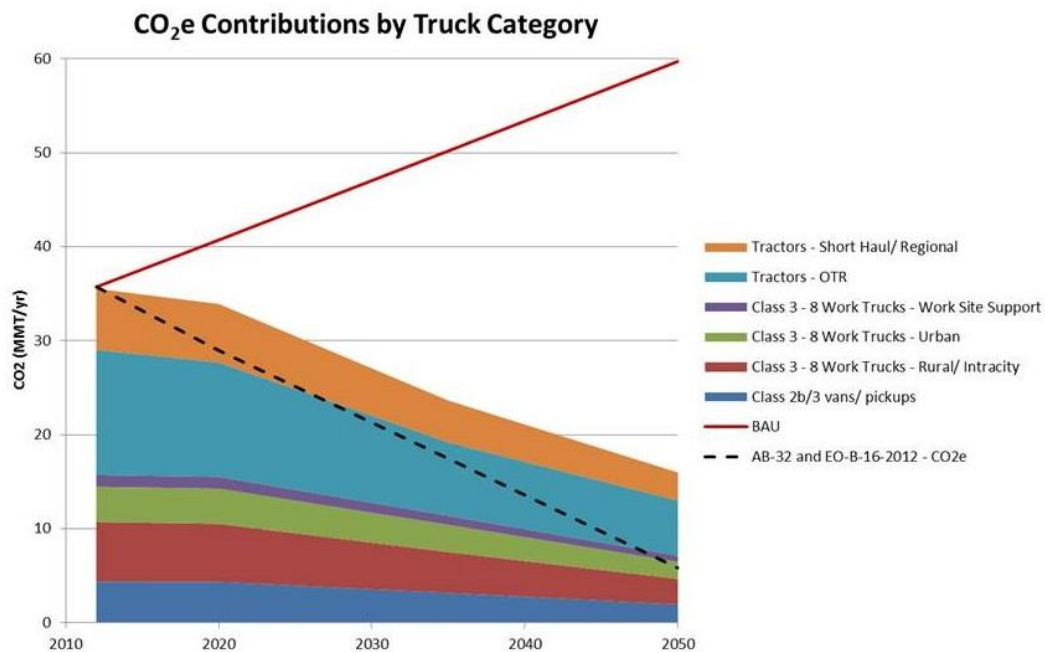
Figure 11: (Source: Sempra Utilities)

The CalHEAT Roadmap illustrates how the state can come very close to meeting its GHG targets through significant funding from the AB 118 cap and trade budget. Thus, AB 118 is itself a driver to further pursue GHG policy goals with respect to MD-HD trucks.

The CalHEAT Roadmap developed a model to project likely CO<sub>2</sub> and NO<sub>x</sub> reductions for near term generation and future long term generation of each truck category. The Roadmap illustrates that reduction in emissions of all medium and heavy duty vehicles through advanced truck technologies by 2050 of more than 40 MMTCO<sub>2</sub>e emissions compared to existing technology, or “Business as Usual” (BAU) is feasible. These projected results are the expected outcome of implementation of the 66 action items in the Roadmap.

The Figure below shows the impact by CalHEAT vehicle category compared to BAU.<sup>6</sup> The Roadmap reductions are based on technology improvements to increase mileage or reduce fuel consumption, including increased adoption of hybrids and E-Trucks. The model is based on a 25% adoption rate of biofuels by 2050. The descending line shows the targeted reduction called for by AB 32 and EO B-16-2013. The gap between the projected reduction and the Roadmap reductions could be met by a higher rate of adoption of biofuels. Increased use of biofuels and decarbonization achieved by using renewable energy sources will contribute to the CO<sub>2</sub> reductions projected by the CalHEAT Roadmap. Significant reductions can be achieved through electricity decarbonization, by using clean or renewable energy sources for electric power, and hydrogen decarbonization, a process that removes carbon while creating hydrogen for use in fuel cells.

## CO<sub>2</sub> Reduction from CalHEAT Roadmap



**Figure 12: The combined impact of the 66 Actions included in the CalHEAT Roadmap as projected to reduce CO<sub>2</sub> equivalent emissions by 2050. Reduction is shown for each of the six CalHEAT truck categories defined in the Roadmap by size and application. The ascending line for “Business as Usual” shows projected emissions without the Roadmap Actions. The dashed line shows the reduction goals set by AB 32 and EO B-16-2012.**

As the table below shows, the EPA and NHTSA are administering CAFE-like standards for M-HD Vehicles Phase 1 Driver for Increased Efficiency.

<sup>6</sup> Silver, Fred, and Brotherton, Tom. (CalHEAT). “Research and Market Transformation Roadmap to 2020 for Medium- and Heavy-Duty Trucks.” California Energy Commission. Draft Rev # 7 Dated 6-14-2013. p. 21.

Final 2017 Standards (% reductions)			
Final Rule	Day Cab		Sleeper Cab
Tractors: 10-23%	Class 7	Class 8	Class 8
Vocational Vehicles: 6-9%	Low Roof (10%)	(10%)	(17%)
Pickup Trucks & Vans: 12-17%	Mid Roof (10%)	(10%)	(17%)
	High Roof (13%)	(13%)	(23%)

*Figure 13: (Source: California Air Resources Board)*

- Phase 2 Standards Under Development
  - Will be more aggressive than phase 1
  - CalHEAT analysis indicates a need for new drivetrains solutions to be 65% more fuel efficient by 2020
  - Will be the basis of full-vehicle certification in Phase 2
- The EPA goals will serve as drivers to technology innovation

## Chapter 2: Pathways

A variety of technological developments are rapidly progressing that show strong promise for heavy-duty NGV engines to emit lower NOx and CO2 levels. Heavy-duty NG engines are on their way to achieving a 90 percent NOx reduction from the existing heavy-duty engine standard, while also becoming increasingly more efficient to reduce GHG emissions.

In order to facilitate the development of heavy-duty natural gas vehicles that are cleaner and more efficient, and guide new investments and strategies by SoCal Gas and other stakeholders, this Roadmap has identified the following four pathways:

1. Natural Gas Engine Technology
2. Fuels, Storage and Infrastructure
3. Policy
4. Range Extended Electric Vehicles and Hybrid Vehicles

All four pathways work together to reduce criteria and greenhouse gas emissions, and improve fuel efficiency of heavy duty vehicles. Hybridization, and fuels and infrastructure all achieve emission reductions. Advanced engines, hybridization, and fuels and infrastructure all achieve improved efficiency, which also reduce mass emissions. Cleaner heavy duty trucks in each sector or sub-sector will be developed by employing a combination of these strategies. An overview of the four pathways is provided below.

# Roadmap Pathways Overview

## NG Fuel Related Strategies for Criteria Emissions, Greenhouse Gas Reductions and Fuel Efficiency

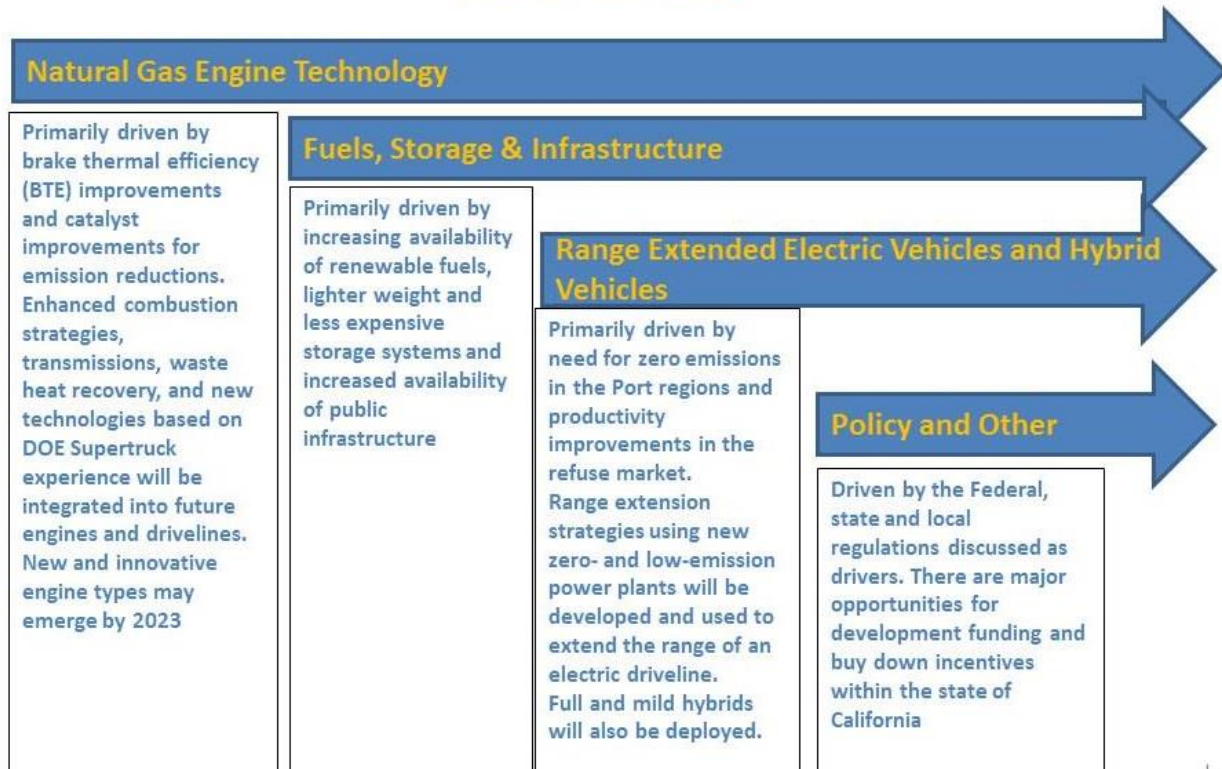


Figure 14: (Source: CalHEAT Research and Market Transformation Roadmap to 2020 for Medium- and Heavy-Duty Trucks)

The following subsections provide brief overviews of each pathway with descriptions of how each is being applied to heavy-duty NG engines in order to achieve NOx emissions, while simultaneously providing low GHG emissions.

## 2.1 Natural Gas Engine Technology

### 2.1.2 Overview

A variety of advanced technology NG engines are being developed to provide enhanced combustion and/or higher systems efficiency. The priority stages for development of natural gas engine technology range from a limited engine size availability, to how natural gas engines will satisfy future emission regulations and improve in performance and efficiency.

- **Stage 1/Current Status:** Limited manufacturers & engine options but portfolio growing; mostly diesel variants; still some reliability, durability & power concerns



- **Stage 2:** More stakeholders & choices; purposeful designs for NG engines; improved ignition controls, thermal controls & air handling
- **Stage 3:** Continued emissions, performance & efficiency gains; increasing use of NG turbines

As the table below illustrates, in the current Stage 1 ( yrs 2013 to 2016), NOx emissions are slightly better than 2010 standards, and engines are approaching 45% brake thermal efficiency. In 2018, Stage 2 ( yrs 2017 to 2020) brings increased engine offerings, including purposefully designed NG engine blocks, and engine brake thermal efficiency approaches 48% through implementation of new Supertruck technologies. In 2023, Stage 3 2020 to 2023 sees continued emission and break thermal efficiency gains. Improved emissions will require more time to reach fruition than expanded engine offerings.

2013	2018	2023
<p><b>Stage 1 Current Status ( Limited Engine Size Availability)</b></p> <ul style="list-style-type: none"> <li>• <i>NOx Emissions slightly better than 2010 Standards</i></li> <li>• <i>EPA/NHTSA Phase 1 Compliant for GHG</i></li> <li>• <i>Engines Approaching 45% Brake Thermal Efficiency</i></li> <li>• <i>Expensive technologies replaced by engines that provide 1-3 year payback for 100,000 miles use</i></li> <li>• <i>Use primarily diesel engine blocks</i></li> </ul> <p><b>ISL-G 8.9L (CWI)</b></p> <ul style="list-style-type: none"> <li>• Stoichiometric spark-ignited with 3-way catalyst</li> <li>• Workhorse for refuse &amp; transit and emerging drayage &amp; regional delivery markets</li> <li>• Payback: 1-3 years – little cost difference vs. diesel for engine components – main costs are gas storage</li> <li>• No DPF and SCR needed</li> <li>• SCAQMD requires use for refuse &amp; transit applications</li> <li>• Emissions level: 2013</li> <li>• CAFÉ Ph.1 compliant</li> </ul> <p><b>ISX-12G (CWI) (New offering)</b></p> <ul style="list-style-type: none"> <li>• 11.9L stoichiometric spark-ignited with 3-way catalyst – emerging for refuse, drayage, regional delivery &amp; OTR</li> <li>• Payback – 1.5 to 3 years</li> <li>• Emissions level: 2013</li> <li>• No DPF and SCR needed</li> <li>• CAFÉ Ph.1 compliant</li> </ul> <p><b>HD15 (Westport) (discontinued production end of 2013 but still in use)</b></p> <ul style="list-style-type: none"> <li>• 15L high-pressure direct injection compression ignition with diesel pilot – limited currently to OTR market</li> <li>• Payback 4 years</li> <li>• Requires diesel pilot + aftertreatment (SCR)</li> <li>• Emissions level: 2010</li> <li>• CAFÉ Ph.1 compliant</li> <li>• Production phasing out - ends early 2014</li> <li>• Best match for LNG applications</li> </ul> <p><b>Doosan 8.9L</b></p> <ul style="list-style-type: none"> <li>• Lean burn SI engine – currently used in some transit applications</li> <li>• Developing 11.9L version</li> </ul>	<p><b>Stage 2 (Increased engine offerings including purposefully designed NG engine blocks)</b></p> <ul style="list-style-type: none"> <li>• 75% less NOx vs. 2010 Standards</li> <li>• NHTSA Ph 2 GHG targets for CO2 (10% improvement?)</li> <li>• Engine brake thermal efficiency approaching 48% through implementation of new Supertruck technologies</li> </ul> <p><b>ISL 8.9L and ISX 12G</b></p> <ul style="list-style-type: none"> <li>• Similar architecture to current but with advanced catalysts &amp; combustion properties – 75% lower NOx than 2010 standards</li> </ul> <p><b>Volvo 13L HPDI</b></p> <ul style="list-style-type: none"> <li>• Emissions level: 2013</li> <li>• Efficiency: same as diesel</li> <li>• CAFÉ Ph.1 compliant</li> <li>• Payback – 2-3 yrs?</li> </ul> <p><b>Cummins 15L SI (2016) – in development now</b></p> <ul style="list-style-type: none"> <li>• Improved performance, reliability &amp; fuel economy</li> <li>• Purposeful block</li> </ul> <p><b>Volvo DME – NG-derived fuel</b></p> <ul style="list-style-type: none"> <li>• Requires minor modifications to D13 engine</li> <li>• 0 PM – no DPF required</li> <li>• 95% lower CO2 emissions than diesel when DME is derived from biosources</li> <li>• Lower pressure than NG, infrastructure similar to propane</li> <li>• Performance similar to diesel</li> </ul> <p><b>Quantum/Ricardo/PSI PIER engine – class 3-7, 8.8L base engine – 20% fuel economy gain, 16% power density gain (proposed but not certain)</b></p> <p><b>Westport HDPI 2.0 (replaces HD15)</b></p> <ul style="list-style-type: none"> <li>• Range of sizes up to locomotives</li> <li>• Optimized combustion</li> <li>• Redesigned electric controls</li> </ul>	<p><b>Stage 3 (Continued Emission , GHG and break thermal efficiency gains)</b></p> <ul style="list-style-type: none"> <li>• 90% less NOx vs 2010 standards</li> <li>• Engines starting to exceed 50% brake thermal efficiencies</li> <li>• GHG Reductions (increasing reductions approx. additional 10% vs. stage 2)</li> </ul> <p>GHG/fuel efficiency gains (hybrids, range extenders, more electrification)</p> <p>Compression ignition (not HPDI)</p> <p>Methane catalysts, especially for HPDI configurations</p> <p>CWI ISL-G 8.9L - .02g</p> <ul style="list-style-type: none"> <li>• Better controls &amp; catalysts</li> </ul> <p>Cummins 15L S.I. (near-zero)</p> <ul style="list-style-type: none"> <li>- Purposeful design</li> <li>- Better ignition controls, fuel injection, thermal management &amp; air handling, waste heat recovery</li> <li>- Commercialization will be dependent on adoption of optional NOx standards</li> </ul> <p><b>Innovative Engine Solutions</b></p> <p><b>Camless engines:</b></p> <ul style="list-style-type: none"> <li>• Commercial production</li> <li>• Using NG to obtain decreased NOx (0.02 g/bhp-h)</li> </ul> <p><b>Opposed Piston and free-piston engines:</b></p> <ul style="list-style-type: none"> <li>• Demonstrations including 21% improved fuel efficiency</li> </ul> <p><b>HCCI:</b></p> <ul style="list-style-type: none"> <li>• Demonstrations</li> </ul> <p><b>ICRC (Brayton) – traction engine not range-extender</b></p>

## 2.1.2 Recommendations for Engines

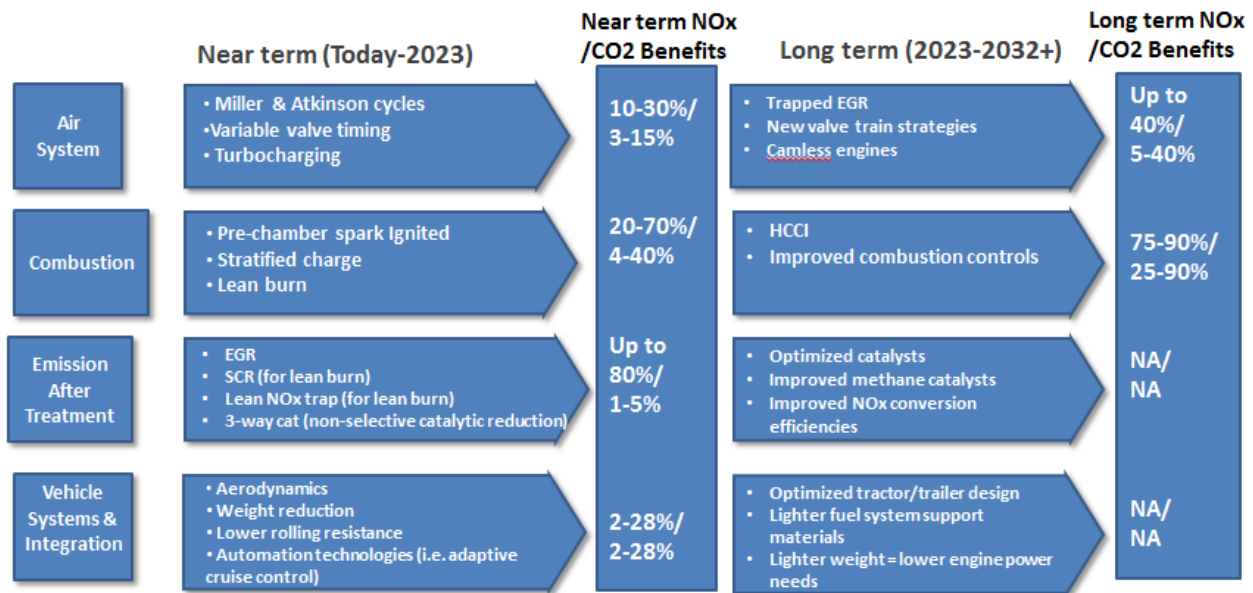
Our recommendations to maintain the viability of all NGVs in the marketplace include the following:

- ✓ Continue participation and tracking of low-NOx engine development programs by SCAQMD and others
- ✓ Work to secure incentives for low-NOx deployments through CEC & air districts Tie these incentives to the voluntary low NOx regulations anticipated from CARB
- ✓ Investigate and encourage the use of NG in new engine development activities such as the Achates opposed piston engines and others
- ✓ Weigh in with NHTSA/EPA on Phase 2 CAFE standards to insure fair recognition of natural gas
- ✓ Consider developing & demonstrating low-NOx DiMethyl Ether engines for regional class 8 applications
- ✓ Provide deployment support activities include providing technical success information to legislators and regulators such as the CEC, the air districts, and NHTSA/EPA in support of NGV industry efforts, to aid the development of new legislation and regulatory policies.

To date, natural gas engines achieve lower emissions primarily due to fundamental fuel properties and in-cylinder combustion modifications. There is a new generation of post-combustion after-treatment technology that can be employed on natural gas engines to further reduce emissions of NOx and CO2, including optimized catalysts and improved conversion efficiencies. An analysis of various advanced technology advancements was performed as part of this report and is included as Appendix. The technologies defined in this analysis have been identified as those holding potential to reduce NOx and CO2 in either a stand-alone or combined manner. These technologies deal with both engine and vehicle improvements and have been identified in numerous studies among those that can reduce emissions regardless of the fuel used. The following chart summarizes select system benefits for emissions & CO2 reductions over the periods to 2023 & 2023+. A detailed analysis by specific technology is illustrated in the Appendix.



## Select NG Engine and Vehicle Technology Advancement Potentials for Lower NOx & CO2 Emissions



*Figure 15: Select NG Engine and Vehicle Technology Advancement Potentials for Lower NOx & CO2 Emissions*

## 2.2 Fuels, Storage & Infrastructure

### 2.2.1 Fuels Trend Overview

Currently, the stable supply of pipeline gas used for CNG & LNG, shale gas, and fracking should ensure consistent supplies, and forecasts indicate that costs will remain low through continued, abundant supplies. In 2018, the goal will be to maximize renewable content. Biogas is also known as renewable natural gas (RNG), because it is generated by feed stocks that can be continually sustained. Future questions may arise about utility acceptance of RNG injection and the long-term security of NG supply through hydraulic fracturing. The EPA will also need to bring certainty to system-wide methane leakage allowances, caused by fracking. Additionally, pipeline injection within California (mixing the RNG into the natural gas system) should be implemented enabling RNG to become more of a factor and support larger adoption of this fuel providing large Greenhouse gas benefit. The California Air Resources Board quantified the CO2 benefits of RNG and found that depending on the feedstock, RNG has 86-88% lower carbon intensity than diesel. Another long term strategy includes increasing the hydrogen content of the natural gas used to fuel vehicles.

- **Stage 1/Current status:** Stable supply of pipeline gas used for CNG & LNG; shale gas & fracking should ensure consistent supplies; cost is 50-60% less than diesel; forecasts are for costs to remain low through continued abundant supplies

- **Stage 2:** More renewable content to lower GHG impact; full implementation of RIN (RFS renewable identification number) & LCFS schemes will affect renewables; increased H2 use including blends & possibly pipeline injection; DME may play significant role; EPA brings certainty to system-wide methane leakage allowances

<p><b>Stage 1 - Current Status</b></p> <ul style="list-style-type: none"> <li>• Minimal renewable NG use and availability</li> <li>• Initial RNG use in California currently through Clean Energy's ReDeem</li> <li>• Pipeline NG – compressed and dispensed as CNG</li> <li>• Liquefied NG – liquefied at remote site, trucked to dispensing location – limited “shelf” life due to boil-off, operational issues (safety equipment required)</li> <li>• CNG from pipeline NG 33% less carbon content than diesel LNG 17-28% less carbon than diesel</li> <li>• Hydrogen – 33% renewable requirement for transportation uses</li> <li>• 5% reduction of GHG for CNG</li> <li>• Focus on WTW methane leakage – EDF study recommends 2.5% systemwide cap</li> </ul>	<p><b>Stage 2 – Goal is maximizing renewable content (GHG)</b></p> <ul style="list-style-type: none"> <li>• RNG – greater production, increased pipeline injection – will the credits be actual or paper? –Utility acceptance of RNG injection?</li> <li>• More RNG produced in-state from landfills &amp; dairies (see policy section)</li> <li>• RIN+LCFS credits for RNG – currently \$0.28/gallon California LCFS + \$0.75/gallon Federal RIN – who will get them remains unclear (ReDEEM pump price = regular CNG price – will that continue?)</li> <li>• RNG – carbon intensity values 86-89% less than diesel – Will there be a new CO2 metric for pipeline gas?</li> <li>• Renewable H2 pipeline injection? - what will be the limit – 5%, 10%?</li> <li>• Bio-DME</li> <li>• Methanation of H2</li> </ul> <p><b>Overall Trends:</b></p> <ul style="list-style-type: none"> <li>• Consistent NG supplies and low costs</li> <li>• Supply security - Growing NG supply through shale discoveries/hydraulic fracturing – how will fracking and systemwide leakage issues affect future supplies &amp; prices? Will there be penalties for released methane?</li> <li>• Consistent gas quality standards (MN-88+?)</li> <li>• DME (low comparative energy content, high cost, lubricity issues w/ injectors) -2015</li> <li>• Renewable H2 – 30% of H2 in transport must be renewable</li> </ul>
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**2013**

**2018**

**2023**

### 2.2.2 Recommendations for Fuels

Our recommendations to maintain the viability and price competitiveness of NG fuels include the following:

- ✓ Track and weigh in on CPUC proceedings re: pipeline injection of RNG
- ✓ Track and weigh in on federal & state LCFS/RIN proceedings
- ✓ Collaborate with and invest in potential RNG producers to increase future supplies with support of PIER and AB 118 funds

### 2.2.3 Onboard Gas Vehicle Storage Overview

To date, current placement configurations (horizontally mounted behind cab) allow for greater on-board storage capacity of CNG, but LNG is still preferable for long-haul due to operational issues and infrastructure, although LNG storage costs are higher. A premium remains for NG vs. diesel storage. Stage 2 brings lower cost, greater capacity, lower weight, and better materials. Stage 2 may also bring improved low-pressure gaseous fuel storage systems that use lightweight composite storage containers filled with pellets of activated carbon.



*Figure 16: CNG tanks mounted behind the cab – Source: Freightliner*



*Figure 17: Typical LNG framerail tank placement – Source: Kenworth Trucks*

- **Stage 1/Current status:** New placement configurations allowing greater onboard storage capacity of CNG; long-haul tractors can now carry up to 140 DGE; LNG is still preferable for long-haul limited only by operational issues & infrastructure
- **Stage 2:** Reduced weight penalties through lighter tanks & support materials; lower storage pressures through use of gas adsorption or pellets; also potentially higher storage pressures

Stage 1 - Current Status and Near-Term Trends – Premium remains for NG vs. diesel storage	Stage 2 - Lower Cost, Greater Capacity, Lower weight , better materials
<p>CNG</p> <ul style="list-style-type: none"> <li>• Framerrail mounted (capacity up to 100 DGE/vehicle – 47 DGE/tank)</li> <li>• Horizontally mounted behind cab (capacity up to 140 DGE/vehicle)</li> <li>• Cost is ~ \$300/DGE</li> <li>• Weight – 10-20 lbs/DGE net</li> <li>• Materials – carbon fiber &gt;&gt; aluminum</li> <li>• Volume – increasing diameter for greater capacity</li> <li>• Weight - ~200 lb. weight penalty vs. diesel</li> <li>• CNG tanks 5:1 size for same range as diesel; LNG 2.3:1</li> </ul> <p>LNG</p> <ul style="list-style-type: none"> <li>• Cryogenic (\$300/DGE)</li> <li>• Weight – 5 lbs/DGE net increase</li> <li>• Capacities (up to 150 DGE/vehicle)</li> <li>• LNG storage costs higher than CNG</li> </ul>	<p>CNG</p> <ul style="list-style-type: none"> <li>• Lighter-weight materials</li> <li>• Optimized designs</li> <li>• Lower cost storage – closer to \$100/DGE</li> <li>• More research into lower-pressure storage - Pellets adsorption (BASF)</li> <li>• Low-pressure storage – less than 1,000 psi (probably 2023+)</li> <li>• High-pressure storage (6,000 to 10,000 psi)</li> <li>• 90” long to 120” long tanks</li> <li>• Better chassis design to incorporate more tanks</li> <li>• Gas adsorption</li> <li>• Conformable tanks</li> <li>• Incorporating tanks into chassis (2023+)</li> <li>• Bladders for CNG</li> <li>• Phase-change materials to offset fill losses</li> <li>• Smaller tanks and less capacity needed in connection with range extenders</li> </ul> <p>LNG</p> <ul style="list-style-type: none"> <li>• Lighter-weight materials</li> <li>• Improved framerrail placement options</li> <li>• Improved connectors and supports</li> </ul>

2013

2018

2023

#### 2.2.4. Recommendations for Gas Storage

Our recommendations to improve the capacity and lower the cost and price competitiveness of gas storage include the following:

- ✓ Contribute to development of standards for gas storage support materials

- ✓ Contribute to industry efforts to develop innovative storage tanks that are integrated into the rails or chassis
- ✓ Support demonstrations of new low-pressure and conformable storage technologies

### 2.2.5. Infrastructure Trend Overview

The reliability and durability of CNG and LNG infrastructure can be improved significantly by providing more station availability and increased dispensing efficiencies. In Stage 2, there may be more opportunities for “NG in a box” solutions that have a smaller footprint and lower cost. The “NG in a box” system is a plug-and-play on-site fueling option that comes with everything retailers need to add NG to their operations quickly. It could enable easier adoption of NG refueling options for both large and small-scale retailers

- **Stage 1/Current status:** Growing state & nationwide network of public access stations
- **Stage 2:** More standardized station designs; increased dispensing efficiencies; better controls, including for time-fill; more opportunities for “NG in a box” solutions with smaller footprint, lower cost

Stage 1 - Current Status ~130 public stations in California	Stage 2 – More station availability (250+ public stations in California), lower costs, better controls
<p>CNG - uses solely pipeline gas</p> <ul style="list-style-type: none"> <li>• Station Costs - \$500K to \$2.5M</li> <li>• Dispensing Capacity - up to 20 DGE/minute</li> <li>• Siting - Private Fleet or Public Corridors</li> <li>• Fast fill for transit, drayage, delivery &amp; long-haul</li> <li>• Slow fill – ideal application is refuse &amp; school buses</li> </ul> <p>LNG - Some local and mostly non-local pipeline gas used for liquefaction</p> <ul style="list-style-type: none"> <li>• Stations Costs - \$2-\$4M+</li> <li>• On-site Storage Capacity – up to 18K gallons storage</li> <li>• Siting- Primarily public/corridors, proximity to liquefaction plants (250 mi. radius)</li> <li>• Transportation - Cost of transporting LNG to stations by truck</li> <li>• Limitations – shelf-life ~7 days due to boil-off</li> <li>• Operational issues – safety equipment required</li> </ul> <p>L/CNG – vaporize &amp; compress LNG – dispense as CNG</p> <p>Compact skid-mounted fueling stations (NG in a box) – GE/Galileo</p> <p>Public access vs. Fleet / cardlock access</p> <p>DME – lower pressures, infrastructure similar to LPG and inexpensive as compared to CNG/LNG</p> <p>H2 – limited availability &amp; high cost</p>	<p>CNG</p> <ul style="list-style-type: none"> <li>• Quicker dispensing for high-volume applications such as transit</li> <li>• Increased capacity &amp; compression efficiency at stations</li> <li>• More efficient dispensers</li> <li>• Better balance between faster dispensing &amp; more storage</li> <li>• Standardized and Modular designs</li> <li>• Better controls for time-fill to take advantage of TOU rates</li> <li>• Lower cost time-fill</li> </ul> <p>LNG</p> <ul style="list-style-type: none"> <li>• Small-scale liquefaction</li> <li>• More “NG in a box” capabilities for CNG &amp; LNG – lower cost, greater use of local pipeline NG for liquefaction onsite</li> <li>• Highway network of LNG stations needed to sustain OTR market, even within Calif.</li> <li>• Lower cost, modular L/CNG stations</li> <li>• 5000 public access stations needed nationwide to get to 25% market penetration</li> <li>• Greater availability of H2 infrastructure, many using NG as feedstock</li> <li>• Greater penetration of DME infrastructure also using NG as feedstock</li> </ul>

2013

2018

2023



## **2.2.6 Recommendations for Infrastructure**

Our recommendations to support the deployment of NG infrastructure include the following:

- ✓ The industry should support the continued and expanded use of CA cap-and-trade funds for infrastructure development. The legislature has authorized the use of cap-and-trade revenues for clean transportation projects starting in 2014 but an effort is required to pinpoint specific infrastructure uses of those funds. Similar investments in subsequent years are also needed.
- ✓ Deploy 65-100 new stations strategically in service area to support long-haul markets – this enables greater use of CNG in this application. Currently long-haul infrastructure opportunities are centered on establishing LNG fueling corridors along interstate highways. As CNG storage capabilities increase the use of CNG in long-haul will also grow. To meet this growth similar CNG fueling corridors will be required.
- ✓ Support and invest in “NG in a box” systems to enable more stations with smaller footprints. These modular options will allow stations to be built in urban locations that were previously seen as too small. This can be a low-cost, flexible solution to NG infrastructure growth.
- ✓ Support and invest in “LNG in a box” systems which would allow for the use of localized NG supplies. LNG is currently produced at remote locations and distributed by truck to dispensing stations in high-use areas. The modular approach will allow localized pipeline gas to be used to produce LNG directly at stations closer to their need.
- ✓ Support industry efforts to increase standardized station designs and modularity

## **2.2.7 Electrification & Hybridization Overview**

Electrification of natural gas fueled drivelines provides an opportunity to both increase fuel economy and at the same time reduce emissions and greenhouse gases. The next two sections focus on two different strategies which both involve the electrification of the natural gas driveline. In the first section we will focus on using NG engines or power plants (such as turbines) as range extenders, which can provide some limited zero emission mile capabilities. The second section we will look at prospects for conventional hybridization

### **2.2.7.1 Range Extension and Electrification**

Currently, there are limited, pre-commercial demonstration options for range extenders for trucks and transit buses. Demonstration projects help manufacturers determine whether new products actually work in common duty cycles as designed, and enable fleets to determine whether these vehicles can meet their performance needs. The current, primary applications

include transit bus applications and drayage demonstrations of fuel cell and stationary designed turbines as generators for electric drivelines.

Stage 2 will see more mainstreaming of zero emission drayage trucks at Los Angeles area ports. The Stage 2 economic goal is a 5-8 year simple payback period with incentives for drayage and transit.

- **Stage 1/Current Status:** Limited demos of fuel cell/range extenders for transit buses; some turbine demos; costs still high but decreasing; limited durability
- **Stage 2:** More fuel cell range extender deployments especially at ports & transit; greater use of NG-fueled turbines; **battery-dominant fuel cells for transit**; lower costs & higher durability

<p><b>Stage 1: Current Status:(pre-commercial demonstrations ongoing)</b></p> <p><b>APPLICATIONS</b> - Transit bus applications and drayage demonstrators of fuel cell and stationary designed turbines as generators for electric drivelines.</p> <p><b>Stage 1 technical characteristics may include:</b></p> <ul style="list-style-type: none"> <li>• Zero emissions (fuel cells) and near-zero emissions (turbines)</li> <li>• Used in series hybrid-electric configurations</li> <li>• Fuel cell hybrids can double fuel economy</li> <li>• NG storage becomes less of an issue in range-extenders due to lower fuel need</li> </ul> <p><b>PERFORMANCE GOALS:</b></p> <ul style="list-style-type: none"> <li>• 50% petroleum reduction</li> <li>• Expanded work site idle reduction</li> <li>• Noise reduction</li> <li>• Productivity gain from idle-free; allows expanded hours of operation</li> </ul> <p><b>POWERPLANTS</b></p> <p><b>Fuel cells</b></p> <ul style="list-style-type: none"> <li>• Derived from H2 (reformed from NG) – 30, 50, 90, 100, 150 kW systems</li> <li>• Manufacturers: Hydrogenics, Ballard, US Hybrid, Nuvera,</li> <li>• Cost approaching \$300/kW now , reliability approaching 20,000 hours of operation</li> <li>• Cummins-Westport 6.7L NG engine as range extender</li> </ul> <p><b>Turbines</b></p> <ul style="list-style-type: none"> <li>• Large sizes now (350 kW now, moving toward 30 kW &amp; 65 kW)</li> <li>• Off-the-shelf components for utility &amp; stationary apps</li> <li>• Used in transit &amp; drayage primarily range-extender</li> <li>• Early demos , uncertain as to final configuration – should meet drayage &amp; transit needs due to pending low-emission regulations – zero-emission miles possible</li> <li>• Emissions 75% lower than 2010 cert level</li> <li>• ~30% efficiency</li> <li>• Payback: ~3 years</li> <li>• No after-treatment necessary</li> <li>• Manufacturers: Capstone, Brayton</li> </ul> <p><b>Conventional Engine Gen Sets</b></p> <p><b>US Hybrid/GTI CNG range extender</b> – ISL-G + 100 kWh battery for 30 mile all-electric operation - demo underway</p> <p><b>DRIVELINES (PLUG-IN AND TRADITIONAL)</b></p> <ul style="list-style-type: none"> <li>• ZE driving capability demonstrated through plug-in configuration</li> <li>• Dual-mode and range-extendors in drayage as second applications (supports pathway for ZE goods movement)</li> <li>• Limited export power</li> <li>• Accessories optimized and customized for this</li> </ul>	<p><b>Stage 2: (Los Angeles area ports mainstreaming of zero emission miles capable drayage trucks and California zero emission transit bus regulation enforced) – commercial production</b></p> <p><b>Stage 2 builds off Stage 1...</b></p> <p><b>Technical characteristics may include:</b></p> <ul style="list-style-type: none"> <li>• Lower Costs</li> <li>• Improved range extenders where applicable</li> <li>• Cost effective electric accessories</li> <li>• Cost effective and larger motors</li> </ul> <p><b>Performance goals may include:</b></p> <ul style="list-style-type: none"> <li>• Greater than 50% petroleum reduction</li> <li>• Zero-emission driving variant available – more ZE miles</li> </ul> <p><b>Stage 2 economic goal:</b> 5-8 year simple payback (with incentives for drayage &amp; transit)</p> <p><b>POWERPLANTS</b></p> <p><b>Fuel cells:</b></p> <ul style="list-style-type: none"> <li>• Move to becoming more battery-dominant – sizes the same</li> <li>• Start deployment in trucks &amp; buses (mostly range extenders)</li> <li>• Reliability – 30,000 hrs</li> <li>• Price reduced to \$100/kW</li> <li>• Manufacturers: same as stage 1</li> </ul> <p><b>Turbines</b></p> <ul style="list-style-type: none"> <li>• 30 kW, 65 kW</li> <li>• Purposely-designed automotive –quality turbines</li> <li>• Used in transit &amp; drayage primarily range-extender</li> <li>• Early demos , uncertain as to final configuration – should meet drayage &amp; transit needs due to pending low-emission regulations – zero-emission miles possible</li> <li>• Emissions 75% lower than 2010 cert level</li> <li>• ~30% efficiency</li> <li>• Payback: ~3 years</li> <li>• No after-treatment necessary</li> <li>• Manufacturers: Capstone, Metis Design, Ricardo, Hybine</li> </ul> <p><b>DRIVELINES</b></p> <ul style="list-style-type: none"> <li>• Improved integration and HEV-plug-in optimization</li> <li>• Optimized and downsized engines</li> <li>• CA OBD compliant</li> </ul> <p>CWI ISB 6.7G - 2016</p> <ul style="list-style-type: none"> <li>• Not applicable for conventional NG engine for HD but as a range extender range extender for class 7&amp;8</li> </ul>
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### 2.2.7.2 Recommendations for Range-Extended Electrics using Alternative Power Plants

Our recommendations for range-extended electrics using alternative power plants include the following:

- ✓ Work with Capstone and other turbine manufacturers to foster transportation applications
  - Collect voice of customer data on more purposeful NG designs for trucks and buses

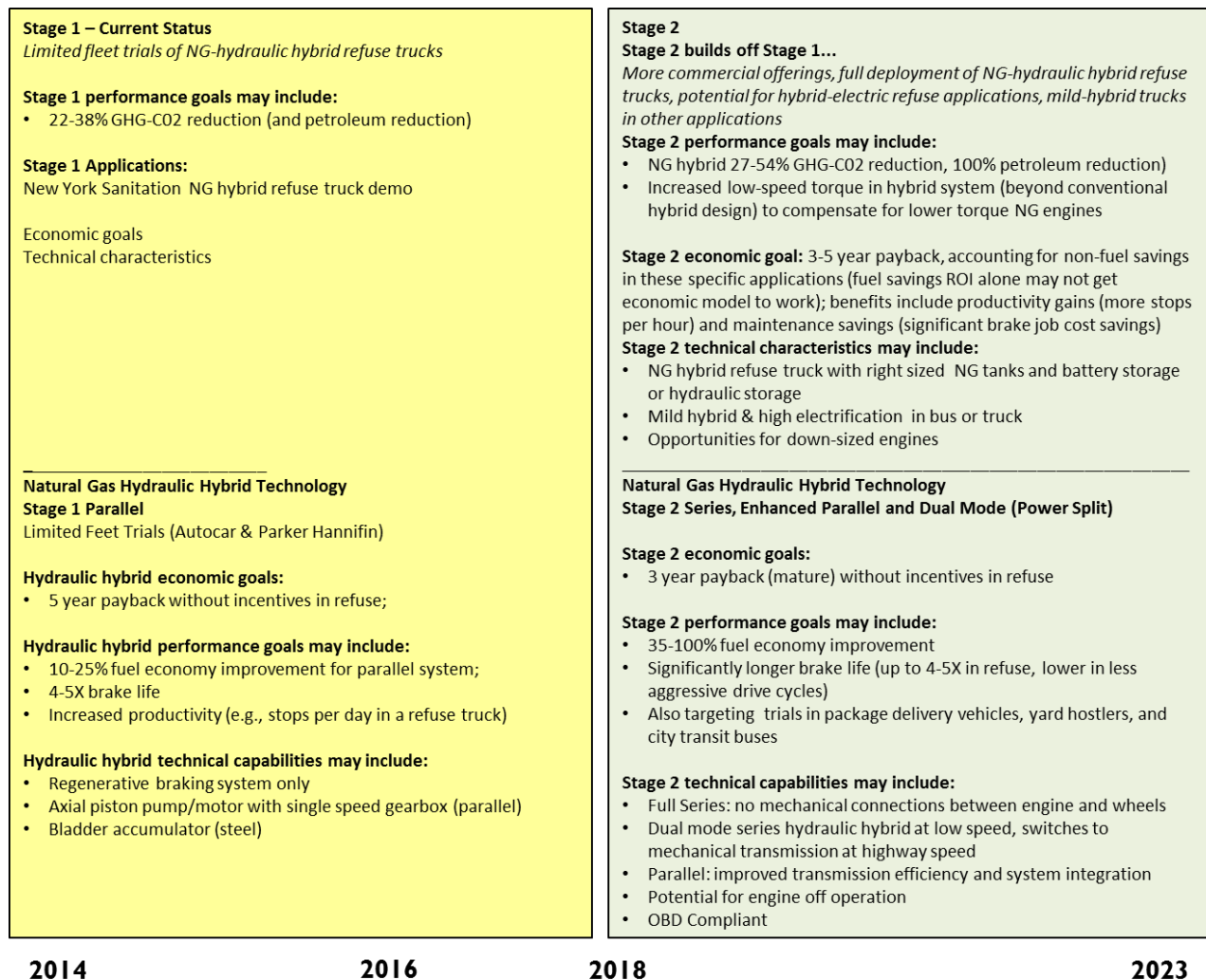


- ✓ Understand and investigate other opportunities for NG power plants such as 6.7-liter engine and other turbine providers
- ✓ Participate in Advisory Committee with FTA/CALSTART's H2 Infrastructure Station Publication to understand the best NG scenarios – an enabler for Port Drayage and Transit

### **2.2.7.3 Natural Gas Hybrids**

As hybrid vehicles increase their market penetration, integration of natural gas into advanced hybrid products in specific NGV applications may occur. Hybridization of a variety of CNG/LNG vehicles still requires a development, demonstration, and deployment program. Since hydraulic systems are technically compatible with refuse haulers, there have been limited fleet trials of NG-hydraulic hybrid refuse trucks, including the New York Sanitation NG hybrid refuse truck demo. In Stage 2, we may see more commercial offerings and full deployment of NG-hybrid hydraulic refuse trucks.

- Stage 1/Current Status: Limited fleet trials with Autocar entering NG hydraulic-hybrid refuse truck market; development & prototyping spurred by interest and PIER funding of NG hybrid drivetrains for trucks; anticipated prototype NG-fueled topologies include hybrid-electric drivetrains for refuse, milder hybridization of transit buses
- Stage 2: Commercial offerings of hydraulic hybrid refuse trucks; mild hybridization using NG deployed in regional delivery and transit buses; prototyping and fleet trials of NG mild hybrid refuse trucks



#### 2.2.7.4 Recommendations for Natural Gas Hybrids (includes Hydraulic Hybrids)

Our recommendations for NG fuelled hybrids include the following.

- ✓ Weigh in on CNG engine onboard diagnostics (OBD) compliance Issues. CARB is in the early stages of requiring certifications for integrated, whole-vehicle OBD systems instead of separate certifications for the engine and drivetrain. This will require that the vehicle manufacturer, engine supplier, and drivetrain supplier will need to coordinate their efforts (meaning integrated diagnostics architecture) to allow for one certification for the vehicle. This will impact hybrid and alternative fuel trucks the most.
- ✓ Consider funding demonstrations of hydraulic-hybrid technology in new applications areas such as transit. Hydraulic hybrid technology has shown to be a good match for urbanized refuse applications. Certain transit applications may also benefit from this technology and should be demonstrated and verified.

## **2.3 Policy**

### **2.3.1 Overview**

This section will review potential policy programs that can hasten the market penetration of NGV's. Overall, the federal government currently has 27 policies in place that promote natural gas as a transportation fuel, covering a range of areas, including infrastructure development, HOV lane use, aftermarket conversions, public transportation and technological development. Also, all U.S. states currently have at least one policy in place to promote CNG and/or LNG. A number of states are particularly strong natural gas supporters, including California (with 27 policies in place), Virginia (16) and Indiana (18). States that produce natural gas also tend to promote its use: Texas (15), Oklahoma (14), Colorado (11) and Utah (10).

Two significant barriers are currently blocking the widespread deployment of NGV's: the higher up-front cost of NGVs and the lack of a comprehensive fueling infrastructure for either CNG or LNG. Both the federal government and many state governments provide subsidies, tax incentives and loan programs to address these barriers. These public policies promote the use of NGVs (and other alternative fuel vehicles) by defraying their higher up-front costs and also support build-out of more natural gas fueling stations. However, more can be done. For example, in California, cap-and-trade funds could be used to support NG vehicle and infrastructure development. Another recommendation is to create a natural gas version of the California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) program.

Current Status and Near-Term Trends	Mid-Term Trends
<p><b>FEDERAL</b></p> <p><i>Mandates/regulations</i></p> <ul style="list-style-type: none"> <li>• Development of NHTSA/EPA Phase 2 fuel economy standards</li> </ul> <p><i>Incentives</i></p> <ul style="list-style-type: none"> <li>• FTA research grants</li> <li>• DOE EERE funding</li> <li>• FTA MAP-21 NOLO deployment funding</li> <li>• Development of next-gen MAP-21 program (2015-2019)</li> </ul> <p><i>Other relevant federal issues</i></p> <ul style="list-style-type: none"> <li>• RIN/LCFS credits for RNG</li> <li>• Systemwide NG leakage studies</li> </ul> <p><b>STATE/LOCAL</b></p> <p><i>Mandates/regulations</i></p> <ul style="list-style-type: none"> <li>• CARB voluntary low-NOx standards</li> <li>• Zero-emission bus regulation under review – how will this affect potential of NG range-extendors?</li> <li>• California cap-and-trade funds for heavy-duty transportation</li> <li>• Potential for Calif. carbon tax – how will it affect cap &amp; trade revenues?</li> <li>• SJVAPCD/SCAQMD NOx standards</li> </ul> <p><i>Incentives</i></p> <ul style="list-style-type: none"> <li>• CEC/PIER program \$3M NG hybrid development program for trucks</li> <li>• CEC NGV incentive program for trucks</li> <li>• CEC Biofuel and RNG demo programs in development</li> <li>• Continuation of AB 118 funding for demos</li> </ul> <p><i>Other relevant state/local issues</i></p> <ul style="list-style-type: none"> <li>• CPUC determination of RNG pipeline injection</li> <li>• AB 118 funding for infrastructure</li> <li>• CARB undergoing planning on their sustainable freight strategy</li> <li>• POLA/POLB roadmapping and planning for zero-emission freight corridor</li> </ul>	<p><b>FEDERAL</b></p> <ul style="list-style-type: none"> <li>• Adoption of NHTSA/EPA phase 2 GHG/mileage standards – will require better vehicle/engine design optimization</li> <li>• MAP-21 may include GHG performance-based metrics</li> <li>• Will the federal government or other state governments bring changes to allowable vehicle lengths and weights to better balance reduced payload due to heavier tanks?</li> <li>• The establishment of a mature, robust re-sale market for NG trucks could bring more stability to the overall NGV market and increase fleet adoption</li> </ul> <p><b>STATE/LOCAL</b></p> <ul style="list-style-type: none"> <li>• CARB voluntary GHG regulations adopted</li> <li>• Zero-emission bus regulations implemented</li> <li>• Cap and trade revenues used for transportation</li> <li>• Renewable content standards - when will they apply to NG for transportation? Will it be imposed on pipeline in general or just to transportation? – need to monitor both</li> <li>• CARB ultra-low NOx voluntary standards adopted</li> <li>• CPUC regulations on pipeline injection of RNG – will this bring better access by producers ?</li> <li>• Will CPUC bring consistency to fuel quality standards (possibly higher methane numbers)?</li> <li>• How will the settlement of California OBD issues affect AFVs?</li> <li>• Passage of AB 8 will bring more funds for more infrastructure, vehicles &amp; the development of RNG</li> <li>• Port zero-emission freight corridor implementation</li> </ul>
2013	2018
	2023

### 2.3.2 Recommendations for Policy

To accelerate the development of NGV's HDVs, we recommend that the following federal and state policies be instituted.

- ✓ Support use of CA cap-and-trade funds for NG vehicle & infrastructure development. As mentioned in the infrastructure section, continued and targeted use of these funds to include NGVs for Class 8 Tractors need to be endorsed.
- ✓ Insure that NHTSA/EPA Phase 2 fuel economy standards give fair recognition to natural gas. As standards are developed for different vehicle types and applications, regulators should be cognizant of the effects of NG on fuel economy.
- ✓ Track and weigh in on federal & state RIN/LCFS proceedings to promote greater use of RNG and to mitigate risk for producers. The regulatory future of renewables is still uncertain at both the state and federal levels and is subject to changing political

circumstances. In order to optimize the renewable content of natural gas, the industry needs to be a presence during the evolution of the proceedings.

- ✓ Track and weigh in on CPUC proceedings regarding pipeline injection of RNG. Regulations allowing the pipeline injection of renewable natural gas are still evolving and the industry must continue to participate in these proceedings in order to maintain gas quality standards.
- ✓ Weigh in on system wide NG leakage studies. The Environmental defense Fund and others are studying the overall amount of methane leakage that occurs in the entire NG supply chain. This will have an effect on future climate change regulations.
- ✓ Monitor & contribute to issues affecting NG engine OBD compliance issues. See the section on Hybrids.
- ✓ Work to encourage CEC to make NG truck incentives more transparent by adopting HVIP-like voucher structure. Current incentives for NGVs are often difficult for fleet purchasers to understand. Funds are allotted to vehicle manufacturers, converters and dealers, often leaving the purchaser unaware of where to apply. A voucher structure similar to CARB's Hybrid Truck and Bus Voucher Incentive Program (HVIP) simplifies the process for the user and does not use tax credits or grants.

## 2.4 Pathways by Vehicle Application

### 2.4.1 Overview

Below are summaries of pathways to reduce NOx and GHG emissions for specific heavy-duty trucking applications:

- ✓ **Transit:** early adopter of NG; moving toward implementation of zero- and near zero-emission solutions such as NG range-extendors & mild-hybrids
- ✓ **Refuse:** another early adopter; best candidate application for RNG and hydraulic-hybrid/NG configurations
- ✓ **Port drayage:** POLB/POLA funded some early deployments of NG; zero-emission zones will encourage NG range extendors
- ✓ **Local/regional delivery:** currently untapped market; good candidate for Natural Gas fueled mild hybrids
- ✓ **Over-the-Road:** fast growing LNG market due to infrastructure but hampered by limited engine options; new efficiencies possible with SuperTruck technologies and possibly DME





#### **2.4.2.2 Refuse Collection**

- Weigh in with CEC on PIER and AB-118 funding for NG-hybrid refuse trucks - excellent early market. May be potential to add SCAQMD funding
- Participate in M-HD CEC pre-commercial demonstration project with NG Hybrid technology providers
- Work with technical partners like Parker Hannifin and BAE to garner Cummins support for providing appropriate engine to allow commercialization of NG-hybrid trucks
- Analyze best way to support and invest in growth of RNG as it relates to refuse by cooperating with producers such as Waste Management



#### **2.4.2.3 Port Drayage**

- Help to secure best possible outcome for NG range extenders in drayage applications to meet needs of Zero Emissions Corridor and Zones to be implemented around 2020 (I-710 and POLB/POLA)
  - Participate in CEC M-HD demo activity as it relates to NG range extenders demonstrations
  - Work with CEC-PIER and AB-118 to determine funding interest



#### **2.4.2.4 Regional and Local Delivery Class 8 Trucks**

- Track and understand the adoption of the new 11.9 liter engines, a major enabling pathway for greater use of NG in this class
- Understand and investigate innovative shorter length truck configurations that can enable the greater use of CNG



#### **2.4.2.5 Over the Road Trucks**

- Encourage and sponsor NG Users Group in order to share early findings and learnings
- Work with major truck makers and major fleets to mitigate risk of adoption of new larger NG engines as part of user group activities
- Sponsor or encourage deployment of more new NG stations on major highways





## Appendix

The development of this Technology Roadmap included a detailed assessment of engine, drivetrain, and vehicle technologies/measures that have been identified as showing high potential for reducing NOx and CO2 emissions. The Technology Capability Assessment was performed through a series of public domain literature reviews that were then used to draw relevant inferences about NOx and CO2 reduction capabilities of each technology on a stand-alone basis. The assessment includes definitions of each technology/measure along with estimations of emissions reductions in the timeframes covered by this report. Since the Technology Assessment was done on a stand-alone basis, the overall NOx and CO2 reduction capabilities of a combination of technologies are not additive.

The Technology Capability Assessment assumes natural gas as the primary fuel and assesses NOx reductions versus the 2010 emissions certification level of 0.15 g/hp-hr.

Technology Description

### Down selected engine and vehicle technology descriptions (1/3) – Air System, Combustion and Fuel System



#### Technology Description – (1/3)

System	Technology	Description
Air System	Miller Cycle	• Miller cycle for natural gas engines involves increased boosting coupled with early or late closure of intake valves during intake and compression strokes, which results in longer effective expansion ratios than compression ratios and hence reduces compression work (Compression work is partly transferred to the turbocharger) on fuel air mixture and leads to greater degree of fuel air mixture cooling, yielding lower temperatures at end of compression, enabling both lower NOx emissions (Due to lower charge temperatures) and fuel consumption (Due to potential for spark timing advance w/o knock)
	Atkinson Cycle	• Atkinson cycle for gas engines also involves longer effective expansion ratios than compression ratios by early/late intake valve closure or through slider mechanism in crank train
	Camless Engine	• Camless technology employs electro mechanical or hydraulic actuator that does away with camshafts and associated components and offers greater flexibility of intake, exhaust valve timings, durations, opening/closing profiles etc., thus offering addl. control variables to enable low NOx, CO2 combustion
Combustion	Lean Burn	• Combustion of fuel in a mixture with excess amount of air (Anywhere from to ~40% - 100% more) than what is necessary to completely combust fuel into CO2 and water vapor, resulting in lower combustion temperatures and reduced NOx formation
	HCCI (Homogenous Charge Compression Ignition)	• HCCI with natural gas refers to compression ignition (At high compression ratios) of a homogenous (highly premixed charge attained via port gas injection or very early in cylinder gas injection) natural gas and air mixture, which offers the potential to achieve ultra low in cylinder NOx and PM emissions and potentially reduced fuel consumption (CO2 emissions) if the rapid heat release due to combustion is controlled and occurs near the thermodynamically efficient location of top dead center
	Pre-Chamber Spark Ignited	• Pre-chamber natural gas engines have a smaller volume, pre combustion chamber with a spark plug, within the main cylinder and this confined volume leads to charge stratification, with a rich mixture within the pre-chamber igniting first, which then enables ignition of overall very leaner mixtures within the rest of the cylinder, which results in lower combustion temperatures and reduced NOx emissions
	Stratified Charge	• Stratification is an enabler of lean burn combustion and refers to creating thermal or chemical non homogeneity in the fuel air mixture within cylinder, both temporally and spatially and this can be done in many ways, e.g. by employing a pre-chamber or by direct injection of a 2 <sup>nd</sup> pilot ignition fuel like in a HPDI gas engine or via induced turbulence etc., all of which aids in ignition of a variety of natural gas mixtures, incl. lean mixtures, leading to potential NOx and fuel consumption benefits

Source: Ricardo Analysis, Public Domain

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## Down selected engine and vehicle technology descriptions (2/3) – Waste Heat Recovery and Emissions Treatment



### Technology Description – (2/3)

System	Technology	Description
Fuel System	Increased Fuel Injection Pressure	• Higher fuel injection pressures are associated with in cylinder injection systems used for main injection of gas and pilot injection of diesel in HPDI gas engines that enable better atomization and associated better mixing of fuel air mixture and also enables further optimization of main and pilot fuel injection events and overall engine calibration for favorable NOx, fuel consumption trade off
	Rankine Cycle	• Thermodynamic cycle that recovers heat from engine exhaust and other heat exchangers (e.g. EGR coolers) by using a refrigerant fluid like R245fa that absorbs waste heat and is then expanded in a downstream turbine, thus producing additional useful power and lowering overall CO <sub>2</sub> emissions
Waste Heat Recovery	Thermo-Chemical Recuperation	• TCR refers to a means to recover heat from engine exhaust and other heat exchangers (e.g. EGR coolers) by using the heat to reform a hydrocarbon fuel typically into syngas (mixture of CO and H <sub>2</sub> ) with higher calorific energy content and combusting this syngas in the cylinder, which then permits ignition of leaner mixtures due to the H <sub>2</sub> content in the syngas, thus enabling lower NOx emissions
	Steam/Water Injection	• Involves injecting steam or water directly in cylinder or upstream in the port or manifold, which results in lowering the charge temperature, thus resulting in lower end of compression temperatures and hence lower NOx emissions and also potentially permits spark timing advance, leading to lower CO <sub>2</sub> emissions
Emissions Treatment	Exhaust Gas Recirculation	• Involves recirculating portion of combusted gases from previous cycle to mix with fresh fuel air charge, which increases specific heat of new in cylinder charge, leading to lower combustion temp. and results in lower NOx emissions and potentially permits spark timing advance, leading to lower CO <sub>2</sub> emissions
	Selective Catalytic Reduction	• SCR is an emissions aftertreatment solution typically employed on lean burn natural gas engines today to reduce NOx emissions and involves injecting a reductant like Urea (typically diluted in two thirds water) into the exhaust stream after the turbocharger, which mixes with the exhaust and reduces engine out NOx into N <sub>2</sub> and water over a catalyst (e.g. catalysts like Vanadia, Cu-Zeolite)
	Non Selective Catalytic Reduction	• NSCR (Pt, Pd based 3 way cat.) is an emissions aftertreatment solution typically employed after the turbocharger on stoichiometric (rich burn) natural gas engines today to reduce NOx, CO, HC emissions
	Lean NOx Trap	• LNT or NOx adsorbers is an emissions aftertreatment solution typically employed after the turbocharger on lean burn natural gas engines to reduce NOx emissions by adsorbing NOx onto an adsorbent during lean operations and reducing it to N <sub>2</sub> over a reduction catalyst during rich operations (Can be attained by injecting fuel into exhaust or via in cylinder injection strategies)

## Down selected engine and vehicle technology descriptions (3/3) – Ignition System, Design, Vehicle System and Powertrain



### Technology Description – (3/3)

System	Technology	Description
Ignition System	Improved Ignition	• Technologies that enable precise control of spark ignition timing, duration, energy discharge rates, number of spark events etc., all of which then enables ignition of a wide variety of natural gas mixtures with different ignition chemistries and kinetics (Lean, high EGR, varying gas quality mixtures)
Design	Increased Firing Pr. And Peak Cyl. Pr.	• Increasing engine firing pressure and peak cylinder pressure capability is a potential enabler for HCCI, overall engine downsizing, higher part load efficiencies and operation at higher BMEP's, which enables both lower NOx and fuel consumption (CO <sub>2</sub> emissions) and this requires appropriate material selection (e.g. CGI) for the engine structure, in particular the head and block
Friction & Parasitics	Reduced accessory load	• Involves reduction of engine accessory parasitic loads from the fuel system, cooling system etc. through the use of intelligent, engine load/operating cycle dependent parasitic power demand from the accessories, which then enables overall reduced fuel consumption (CO <sub>2</sub> emissions)
	Reduced friction	• Involves use of combination of technologies like engine down-speeding, use of friction reducing lubricants with properties that ensure appropriate lube film thickness under high temperatures, pressures and exhaust gas concentrations in cylinder, coatings and intelligent lubrication systems, which then enables overall reduced fuel consumption (CO <sub>2</sub> emissions)
Vehicle System	Aerodynamics	• Involves reduction of the overall coefficient of drag of the truck and trailer combination (Incl. undercarriage) through the use of advanced CFD modeling and associated wind tunnel testing, which then enables lower overall wind resistance and reduced fuel consumption (CO <sub>2</sub> emissions)
	Lower Rolling Resistance	• Involves development of advanced tire technology (Tread patterns, width and depth, sidewall construction, compounds used) and associated pressure monitoring systems that reduces rolling resistance coefficients for smaller energy consumption per tire for distance travelled
	Lower Weight	• Involves overall mass reduction at vehicle level by strategically using a variety of light weight materials ranging from plastics, aluminum, high strength steel, magnesium, composites etc. across body, chassis and interior of vehicle, all of which adds to lower overall vehicular mass and lower fuel consumption
Powertrain	Hybridization	• Typically accomplished via hydraulic, pneumatic, flywheel or electric means and typically involves recuperation and storage of energy for short periods of time during select parts of a drive cycle and discharge of this stored energy to either replace or augment the engine power during parts of a drive cycle, thus reducing overall fuel consumption (CO <sub>2</sub> emissions)

## Engine air System and combustion technology assessment for NO<sub>x</sub> and CO<sub>2</sub> reductions on natural gas engines



### Technology Capabilities Assessment – (1/4)

Before 2023

2023 - 2032

Sub System	Technology	Est. Tailpipe NO <sub>x</sub> (g/hp-hr) Reduction From Base EPA 2010		Est. Engine Level CO <sub>2</sub> Reduction	
Air System	Miller & Atkinson Cycles	10% - 30%	<ul style="list-style-type: none"> <li>Est. based on larger off highway gas engines; when coupled with 2 stage turbocharging systems, upper limits could be attained</li> </ul>	3% - 15%	<ul style="list-style-type: none"> <li>Combination of variable valve timing + lift and optimized turbocharging</li> </ul>
	Camless Engine	Up to 30% to 40 %	<ul style="list-style-type: none"> <li>Est. based on claims from efforts in R&amp;D stage and can vary based on trapped EGR and overall valve train, air system strategies</li> </ul>	5% - 20%	<ul style="list-style-type: none"> <li>Est. based on claims from efforts in the R&amp;D stage currently</li> </ul>
Combustion	HCCI	75% - 90%	<ul style="list-style-type: none"> <li>HCCI expected to be more of a NO<sub>x</sub> reduction tool</li> </ul>	5% - 25%	<ul style="list-style-type: none"> <li>Est. based on using HCCI as part of a multi mode combustion strategy, i.e. implies HCCI not used at full loads due to controls limitations</li> </ul>
	Pre-Chamber Spark Ignited (Lean burn)	20% - 25%	<ul style="list-style-type: none"> <li>Based on est. from large off highway gas engines; overall reduction could be higher when combined w/ EGR, boosting, suitable ignition systems</li> </ul>	4% - 18%	<ul style="list-style-type: none"> <li>Based on est. from large off highway gas engines and current on highway pre chamber systems being developed</li> </ul>
	Stratified Charge	20% - 70%	<ul style="list-style-type: none"> <li>Assumes using lean burn or stratified charge near the natural gas flammability limit with suitable ignition system to achieve upper ends of NO<sub>x</sub> reduction potential</li> </ul>	5% - 40%	<ul style="list-style-type: none"> <li>Benefit will depend on means adopted to achieve stratification or to lean mixture close to the natural gas flammability limit – Pre chamber, improved ignition system etc.</li> </ul>
	Lean Burn				

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# Engine design, heat recovery and ignition system technology assessment for NO<sub>x</sub> and CO<sub>2</sub> reductions on natural gas engines



## Technology Capabilities Assessment – (2/4)

Before 2023

2023 - 2032

Sub System	Technology	Est. Tailpipe NO <sub>x</sub> (g/hp-hr) Reduction From Base EPA 2010		Est. Engine Level CO <sub>2</sub> Reduction	
Fuel System	Increased Fuel Injection Pressure (Diesel only)		• Primarily diesel		•
Design	Increased Firing Pr. And Peak Cylinder Pr.	Minimal on a g/hp-hr basis	• Typically NO <sub>x</sub> reduction by increasing PCP is due to overall engine downsizing and associated fuel consumption benefits, which translates into a g/mile NO <sub>x</sub> benefit	1% - 3%	• Increased PCP's through higher compression ratio, BMEP's
Waste Heat Recovery	Thermo-Chemical Recuperation	40% - 80%	• H <sub>2</sub> rich intake fuel extends lean flammability limit, thus enabling running gas engine at lower AFR's	Up to 8%	• Studies have shown 4% - 8% benefit in CO <sub>2</sub> emissions with exhaust gas TCR that creates H <sub>2</sub> rich intake fuel
Ignition System	Improved Ignition	Up to 70%	• Laser ignition in R&D phase has shown up to 70% NO <sub>x</sub> reduction capability	8% - 40%	• Laser ignition and plasma ignition have shown up to 30% to 40% efficiency improvement

## Engine emissions reduction technology assessment for NO<sub>x</sub> and CO<sub>2</sub> reductions on natural gas engines



### Technology Capabilities Assessment – (3/4)

Before 2023

2023 - 2032

Sub System	Technology	Est. Tailpipe NO <sub>x</sub> (g/hp-hr) Reduction From Base EPA 2010	Est. Engine Level CO <sub>2</sub> Reduction
Emissions Treatment	Steam/Water Injection	10% – 40% • NO <sub>x</sub> reduction varies depending on mechanism employed – Fumigation vs. in cylinder injection	(2%) - 1% • Small penalties have been recorded in some cases with H <sub>2</sub> O injection
	Exhaust Gas Recirculation <sup>1</sup>	30% - 80% • Increasing EGR by 5 to 20% points on a 2010 gas engine could yield ~30 to 80% lower tailpipe out NO <sub>x</sub> emissions vs. 2010	1% - 5% • Typical CO <sub>2</sub> benefits gained by being able to advance injection timing at same NO <sub>x</sub> level or by improving knock limit
	Selective Catalytic Reduction (Lean Burn Only)	50% - 80% • Improving SCR NO <sub>x</sub> conversion eff. on a 2010 lean burn gas engine from current ~90% avg. to 95% to 98% will yield ~50 to 80% lower tailpipe out NO <sub>x</sub> vs. 2010	1% - 3% • Overall CO <sub>2</sub> benefit with improved SCR will be limited due to lower tailpipe out NO <sub>x</sub> targets desired and already high SCR conversion efficiencies
	Non Selective Catalytic Reduction (3 way cat.)	60% – 80% • Improving TWC NO <sub>x</sub> conversion eff. on a 2010 stoichiometric gas engine from current ~95% avg. to 98% to 99% will yield ~60 to 80% lower tailpipe out NO <sub>x</sub> vs. 2010	1% - 2% • Overall CO <sub>2</sub> benefit with improved TWC will be limited due to lower tailpipe out NO <sub>x</sub> targets desired and already high TWC conversion efficiencies
	Lean NO <sub>x</sub> Trap (Lean Burn Only)	25% - 50% • Improving LNT NO <sub>x</sub> conversion eff. on a 2010 lean burn gas engine from current ~80% avg. to 85% to 90% will yield ~25 to 50% lower tailpipe out NO <sub>x</sub> vs. 2010	3% - 4% • Overall CO <sub>2</sub> benefit with improved LNT will be ~3% - 4% due to lower tailpipe out NO <sub>x</sub> targets desired and overall lower current NO <sub>x</sub> conversion efficiencies

1 – Depends on ignition system to increase tolerance to higher EGR %

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## Engine vehicle level technology assessment for NOx and CO<sub>2</sub> reductions on natural gas engines – On a g/mile basis



### Technology Capabilities Assessment – (4/4)

Before 2023

2023 - 2032

Sub System	Technology	Est. g/mile NOx Reduction		Est. g/mile CO <sub>2</sub> Reduction	
Vehicle System	Aerodynamics	2% - 28%	<ul style="list-style-type: none"> <li>Est. based on lower engine power needs; tractor and trailer optimized for low C<sub>d</sub> (outfitted with multiple drag reduction devices) to attain upper end of NOx reduction potential</li> </ul>	2% - 28%	<ul style="list-style-type: none"> <li>Tractor and trailer optimized for low C<sub>d</sub> (outfitted with multiple drag reduction devices) to attain upper end of CO<sub>2</sub> reduction potential</li> </ul>
	Lower Rolling Resistance	1% - 6%	<ul style="list-style-type: none"> <li>Est. based on lower engine power needs; ~1% CO<sub>2</sub> reduction per 5% decrease in rolling resistance and a 30% rolling resistance reduction target</li> </ul>	1% - 6%	<ul style="list-style-type: none"> <li>Est. ~1% CO<sub>2</sub> reduction per 5% decrease in rolling resistance and a 30% rolling resistance reduction target</li> </ul>
	Lower Weight	1.5% - 6%	<ul style="list-style-type: none"> <li>Est. based on lower engine power needs; est. ~0.5% CO<sub>2</sub> reduction per 1000 lb. weight reduction for a 10% - 15% overall weight reduction target</li> </ul>	1.5% - 6%	<ul style="list-style-type: none"> <li>Est. ~0.5% CO<sub>2</sub> reduction per 1000 lb. weight reduction for a 10% - 15% overall weight reduction target</li> </ul>
Powertrain	Hybridization	5% - 30%	<ul style="list-style-type: none"> <li>Est. based on lower engine power needs</li> </ul>	5% - 30%	<ul style="list-style-type: none"> <li>Overall CO<sub>2</sub> benefit sensitive to drive cycle and chosen technology</li> </ul>
Waste Heat Recovery	Rankine Cycle	2% - 8%	<ul style="list-style-type: none"> <li>Est. based on lower engine power needs</li> </ul>	2% - 8%	<ul style="list-style-type: none"> <li>Overall CO<sub>2</sub> benefit sensitive to drive cycle</li> </ul>
Friction and Parasitics	Reduced accessory load	1% - 3%	<ul style="list-style-type: none"> <li>Through load dependent deployment of pumps and/or by electrification</li> </ul>	1% - 3%	<ul style="list-style-type: none"> <li>Through load dependent deployment of pumps and/or by electrification</li> </ul>
	Reduced friction	0.5% - 3%	<ul style="list-style-type: none"> <li>Combined impact of lubricants, ring pack design, advanced bearings etc.</li> </ul>	0.5% - 3%	<ul style="list-style-type: none"> <li>Combined impact of lubricants, ring pack design, advanced bearings etc.</li> </ul>

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