CalHEAT TRUCK RESEARCH CENTER

California Energy Commission
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CALSTART

# Heavy-Duty Truck and Bus Natural Gas Vehicle Technology Roadmap

## FINAL VERSION – June 2014

# Contents

# Key Findings

- Market for heavy-duty natural gas trucks in So Cal Gas territory expected to grow 5X by 2020 and 15X by 2030, reaching 115,000 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

# Key Recommendations - Technology

- Work with MTA and others 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 "NG in a box" modular stations to allow greater usage of localized natural gas for LNG & CNG (*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 CEC-PIER to determine funding interest
- 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*)

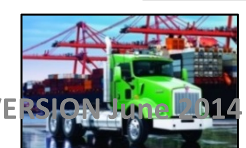
# Key Recommendations - Policy

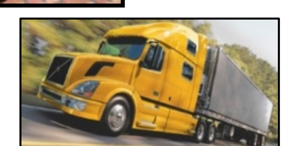
- Support use of CA cap-and-trade funds for vehicle purchases & infrastructure development (*see Policy section*)
- Work to encourage CEC to make NG truck incentives more transparent by adopting HVIP-like voucher structure (*see Policy section*)
- Weigh in with NHTSA/EPA on Phase 2 fuel economy standards 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*)

# Roadmap Purpose

- Goal: To Develop a Natural Gas Vehicle Technology Roadmap Commercialization Class 7/8 Heavy Duty Vehicles in the SoCalGas territory
  - 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.
  - NG a Significant Enabler for California and the SoCalGas region to enable a reduction in the use of petroleum as well as reduce criteria emissions in heavy duty vehicles
    - The CalHEAT's "Market Transformation Roadmap for M-HD Trucks" addressed NG as a key component and Enabler in its goal to developed a pathway for the state to reduce petroleum use, reduce GHG as well as NOx emissions/Near Zero Technology
- Roadmap Approach
  - Develop a series of stepping stones towards commercial product offerings in the year 2023 for regions serviced by the Southern California Gas Company.
  - Provide SoCalGas and NG Industry with pathways for investment and adoptions to further support the successful deployment of NG technologies
    - Engine
    - Drive Train
    - NG and Other NG Derived Fuels
    - Infrastructure
    - NG Storage



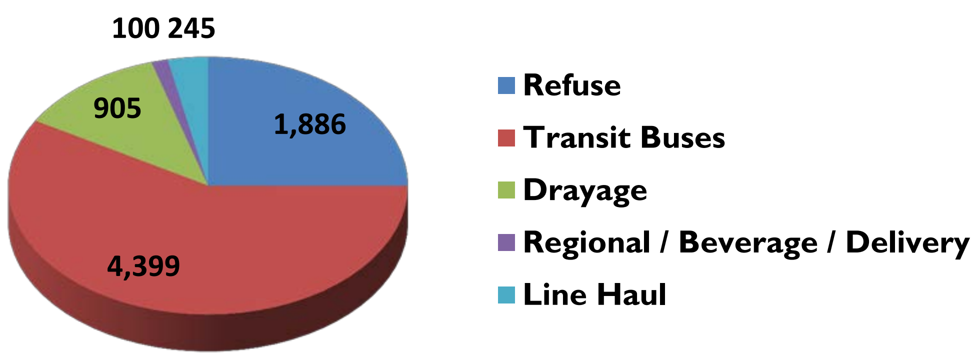




# Baseline Inventory of Natural Gas Trucks and Buses In SoCalGas Territory




| | 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 | 5 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%** |



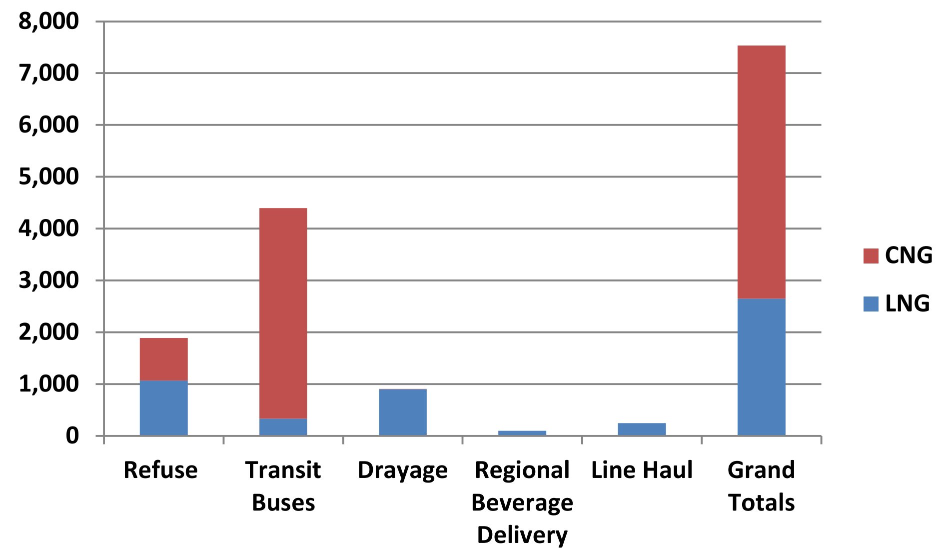

**Note: market forecast figures are currently undergoing final revisions in conjunction with ENVIRON**



Citation: CalHEAT

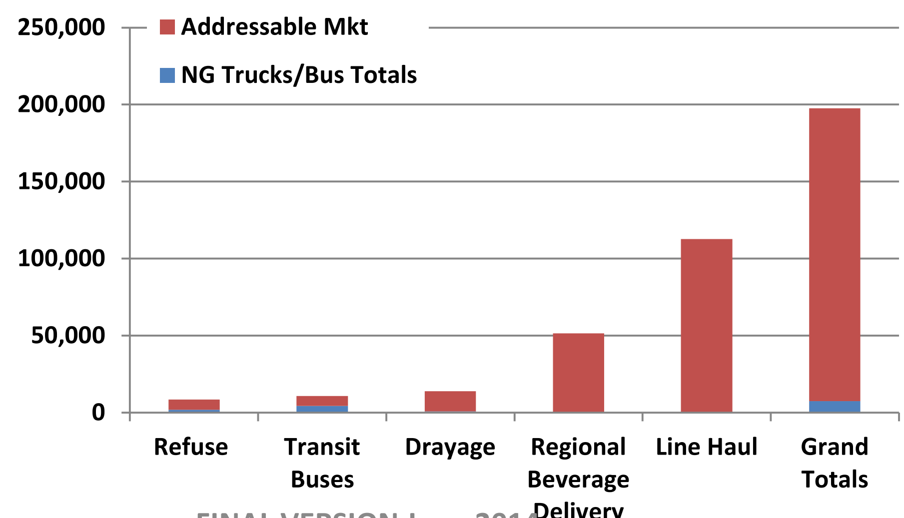
# Baseline Inventory of Natural Gas Trucks and Buses In SoCalGas Territory (Continued)

CNG v. LNG
Based on 2013 NG Vehicle Population Estimate




65% CNG
35% LNG

NG Trucks Compared to 2013 Addressable Market

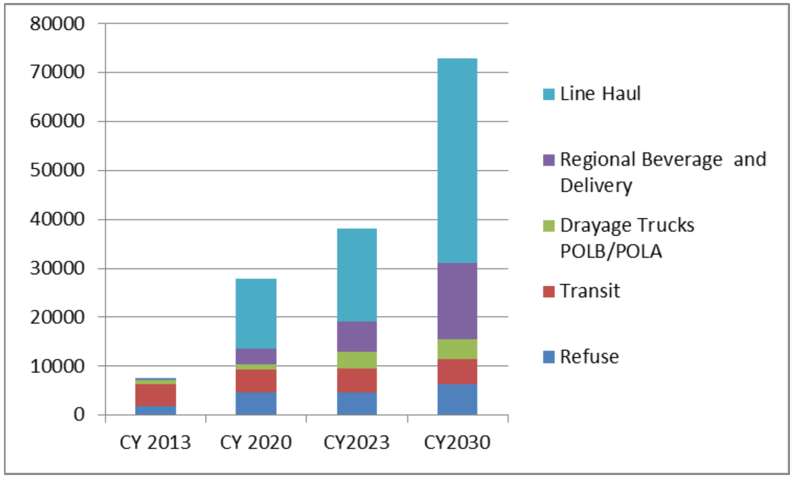



4% NG
96% Conventional

Citation: CalHEAT

# 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 |
| Total NG | 7535 | 27868 | 38210 | 72853 |




| 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% |
| Total | 4.0% | 10.9% | 14.5% | 24.6% |

NG as a Percentage of the Total or Addressable market

Citations: CalHEAT and ACT



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

# Drivers of Change

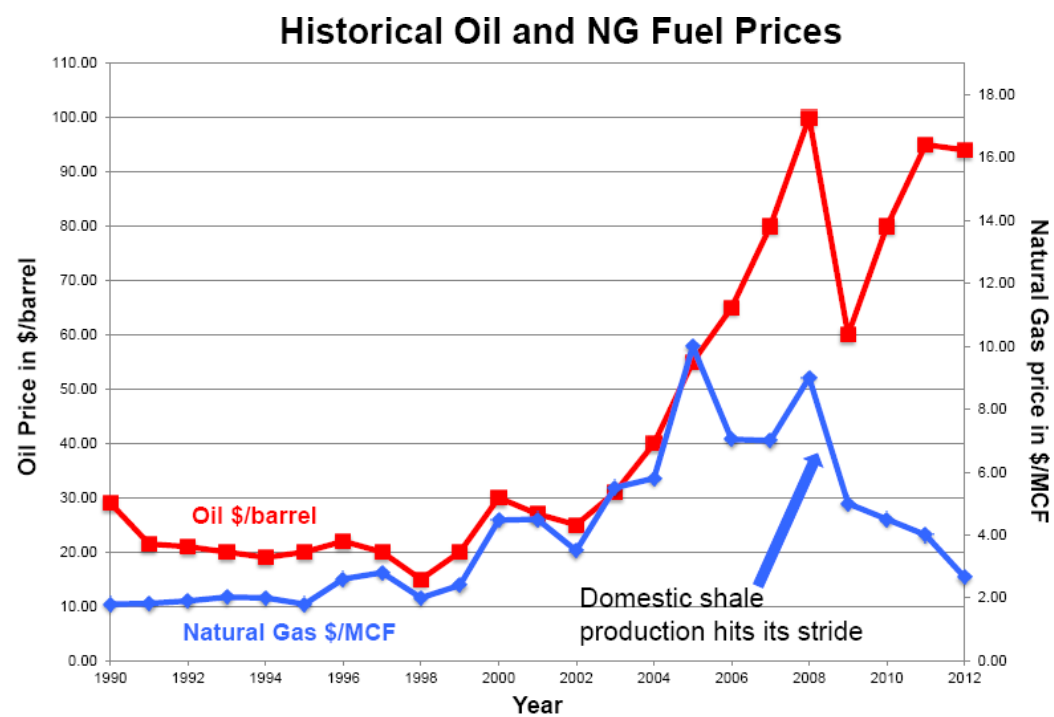
The following section addresses the three primary drivers of change from now through 2023

These are:

- Continuation of low natural gas prices
- Increasing regulatory pressure on lowering NOx Emissions
- Increasing regulatory pressure on greenhouse gases and truck efficiency

# Natural Gas
# Compelling Long Term Fuel For Vehicles

- New fracturing technology allows economical access to natural gas
- Current and future production projected to outstrip demand
- US has some of the largest NG reserves in the world
- Frost and Sullivan and ACT projecting significant adoption in the heavy duty vehicle market
- Fleets seek price certainty & stability




 Source: E-Controls

# Natural Gas Pump Price Low Price Volatility

Natural Gas @ $4.00 per MCF

| INPUT | COST |
|---|---|
| Natural Gas (divide by 8) | $0.50 |
| Transport Costs & Fees | $0.20 |
| Electricity Costs per GGE | $0.10 |
| Maintenance per GGE | $0.20 |
| Federal and State Taxes | $0.25 |
| Fuel Card Fees per GGE | $0.05 |
| Retailer Profit Margin | $0.40 |
| **CNG at the Pump** | **$1.70** |

Natural Gas @ $8.00 per MCF

| INPUT | COST |
|---|---|
| Natural Gas (divide 8) | $1.00 |
| Transport Costs & Fees | $0.20 |
| Electricity Costs per GGE | $0.10 |
| Maintenance per GGE | $0.20 |
| Federal and State Taxes | $0.25 |
| Fuel Card Fees per GGE | $0.05 |
| Retailer Profit Margin | $0.40 |
| **CNG at the Pump** | **$2.20** |

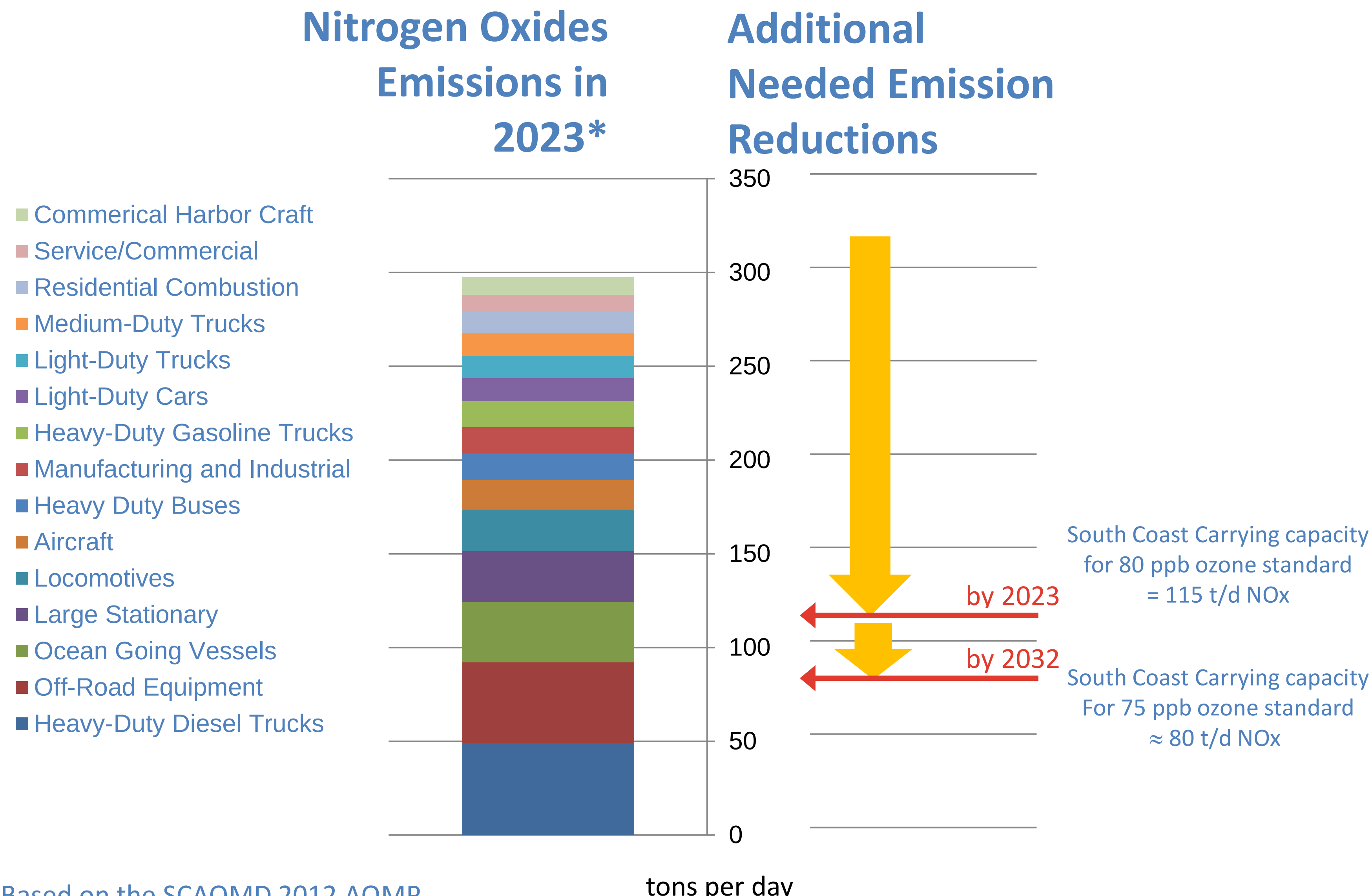
**A doubling of the price of natural gas increases prices at the pump only $0.50 per GGE**

Source: So Cal Gas Co.

# Federal Ozone Regulations Requiring South Coast and Central Valley to Reduce NOx Emissions

- 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

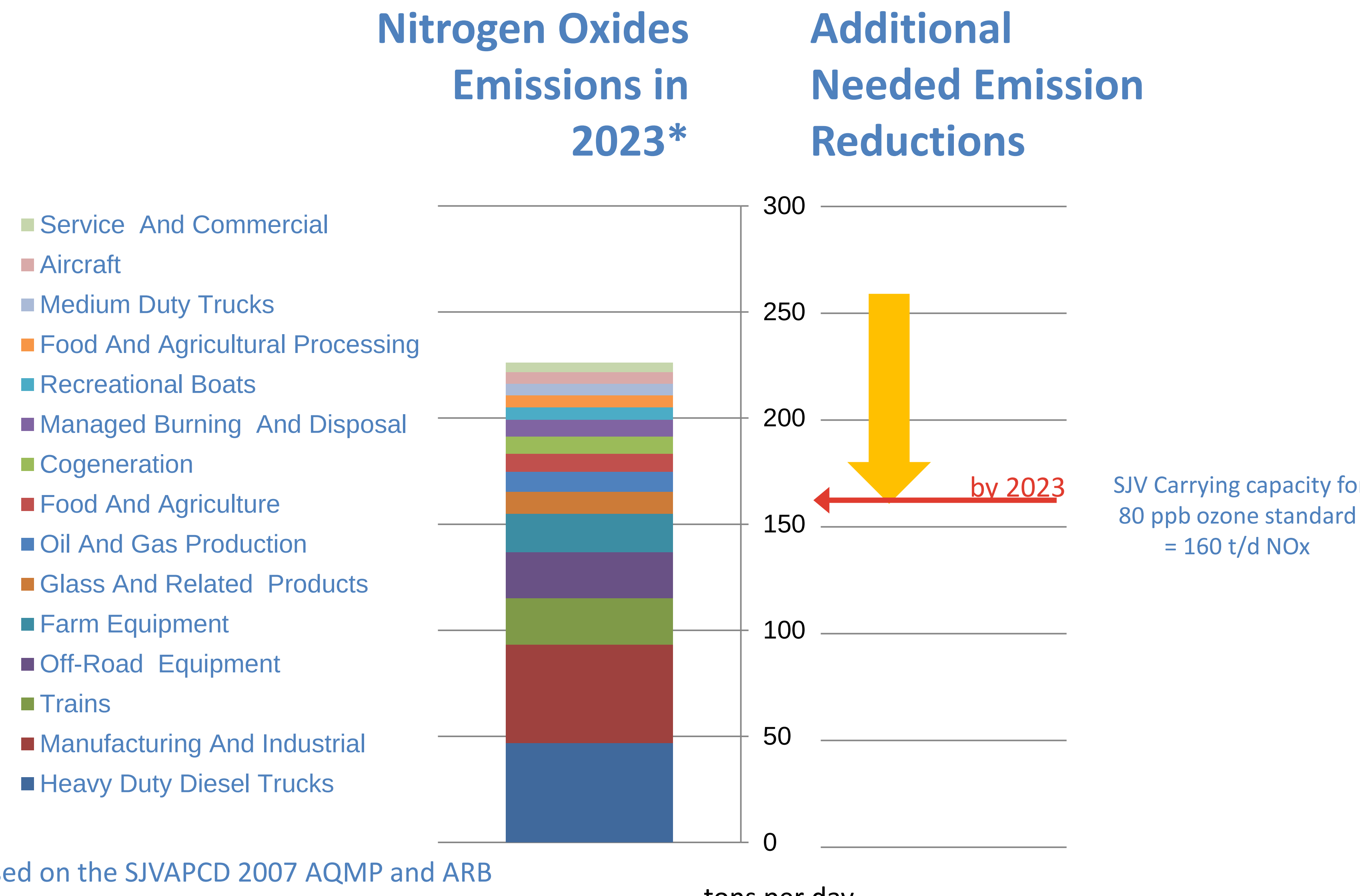
# Major NOx Emission Sources in South Coast Air Basin




*Based on the SCAQMD 2012 AQMP
Top 15 = 298 out of 319 tons/day NOx

Source: So Cal Gas Co.

# Major NOx Emission Sources in San Joaquin Valley




*Based on the SJVAPCD 2007 AQMP and ARB on-road and off-road emissions models
Top 15 = 226 out of 257 tons/day NOx

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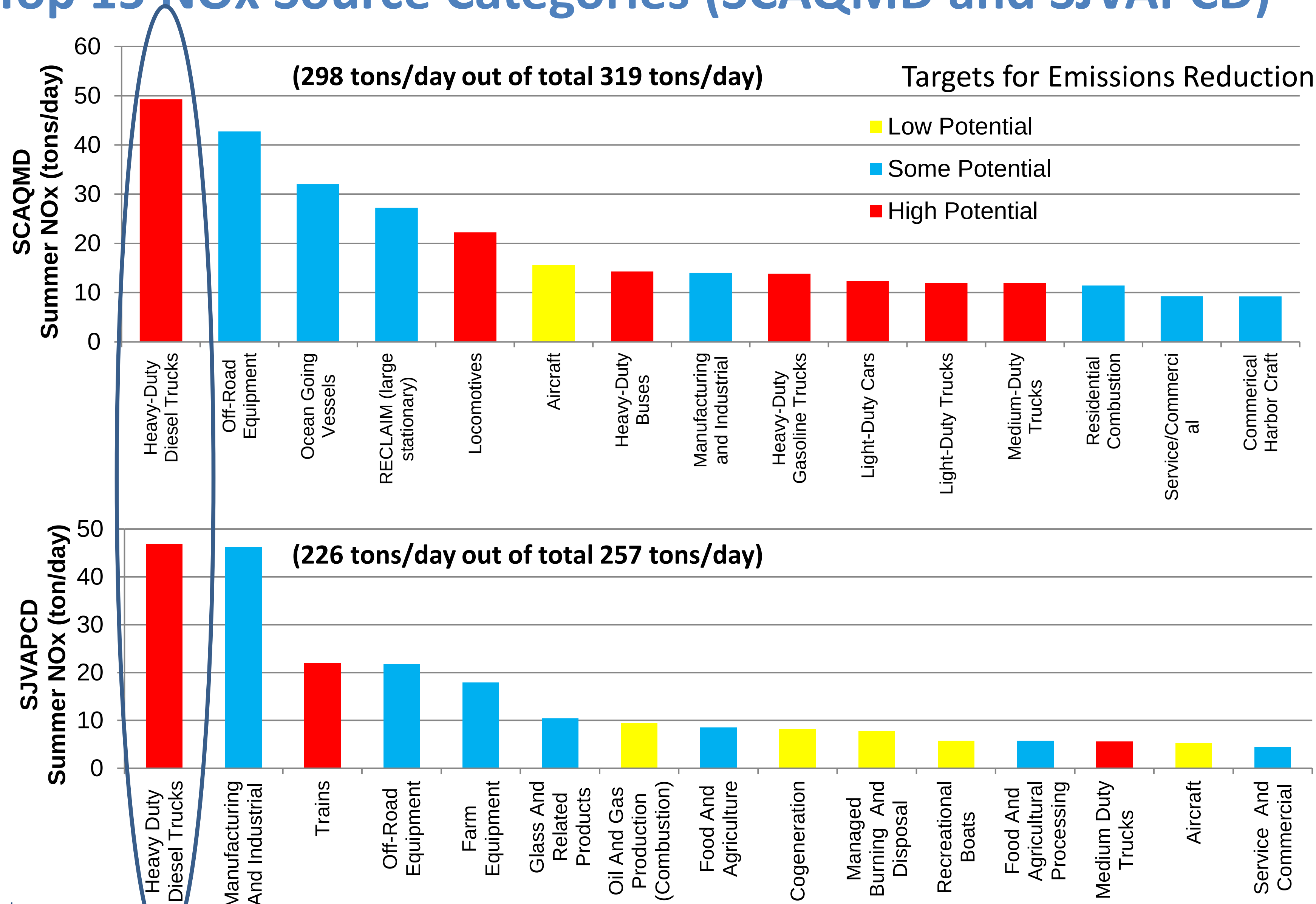
Source: So Cal Gas Co.

# Top 15 NOx Source Categories (SCAQMD and SJVAPCD)




Notes:
1. Heavy-Duty Trucks include Light-Heavy Duty, Medium-Heavy Duty, Heavy-Heavy Duty Trucks
2. Emissions for on-road mobile sources are based on EMFAC2011 output for San Joaquin Valley Air Basin
3. Emissions for off-road equipment are based on 2011 CARB inventory models
4. Emissions for stationary sources, area sources, and other off-road mobile sources are based on CARB Staff Report, Analysis of the 2007 8-hour Ozone SIP

Source: So Cal Gas Co.

# Carbon Dioxide as a Major Contributor to Greenhouse Gases will be Driven Significantly Downward

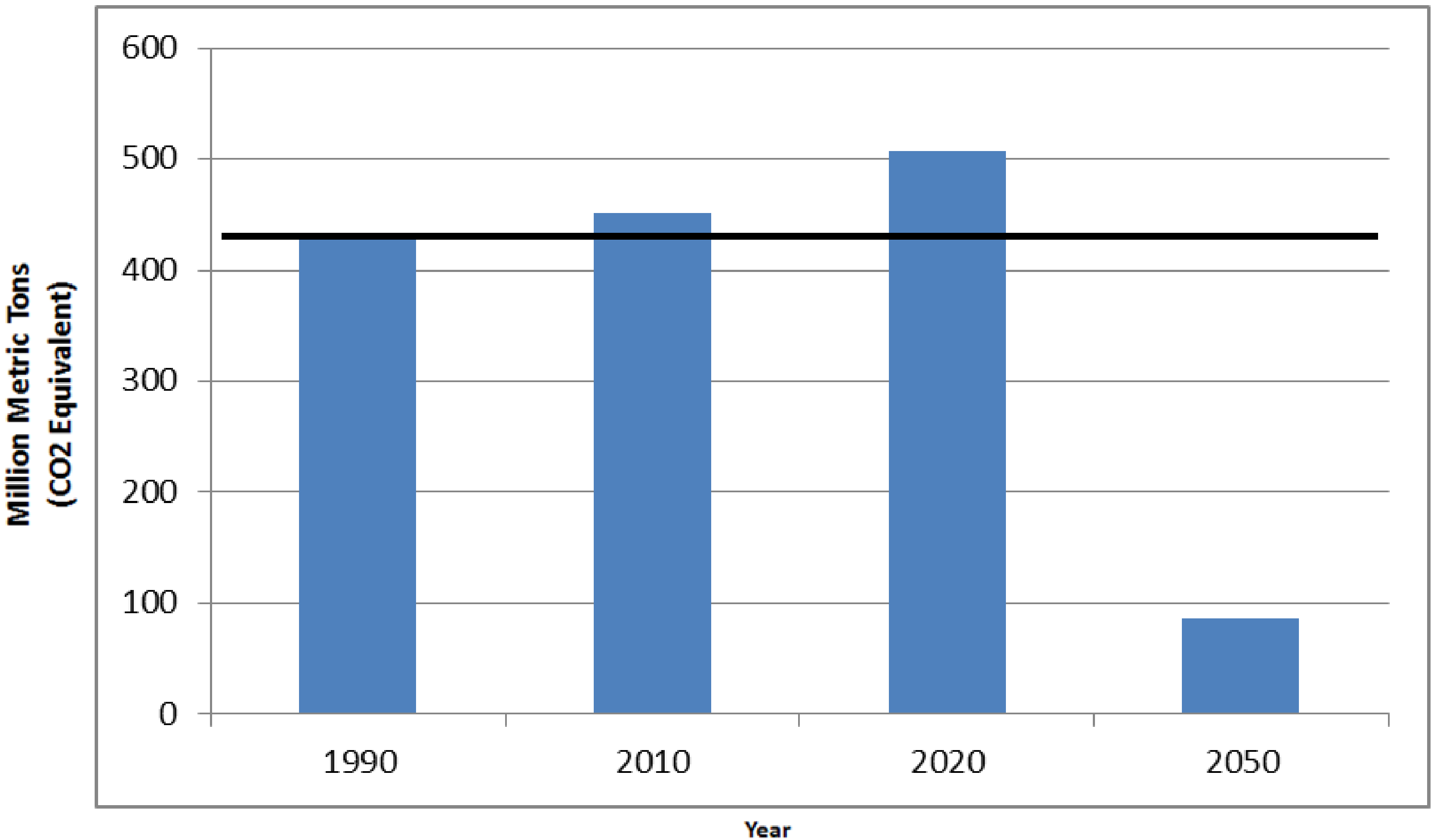
- California's AB 32 and Executive Orders #B-016-2012 & S-03-2005 require a 20% reduction in greenhouse gases (GHG) by 2020 and 80% by 2050 in order to reach levels that are 80% lower than 1990 – **this is not mandated yet**

- EPA/NHTSA CAFÉ Regulations for Trucks Require C02 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 requires more aggressive fuel economy

# CalHEAT Pathways for CO2 Reductions

- CalHEAT research has determined a pathway for meeting a 70%  reduction within the medium- and heavy-duty inventory of trucks in California
  - Class 8 over-the-road and regional tractors represent 56% of the $CO_2$ 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 C02

# AB 32 Driving Change

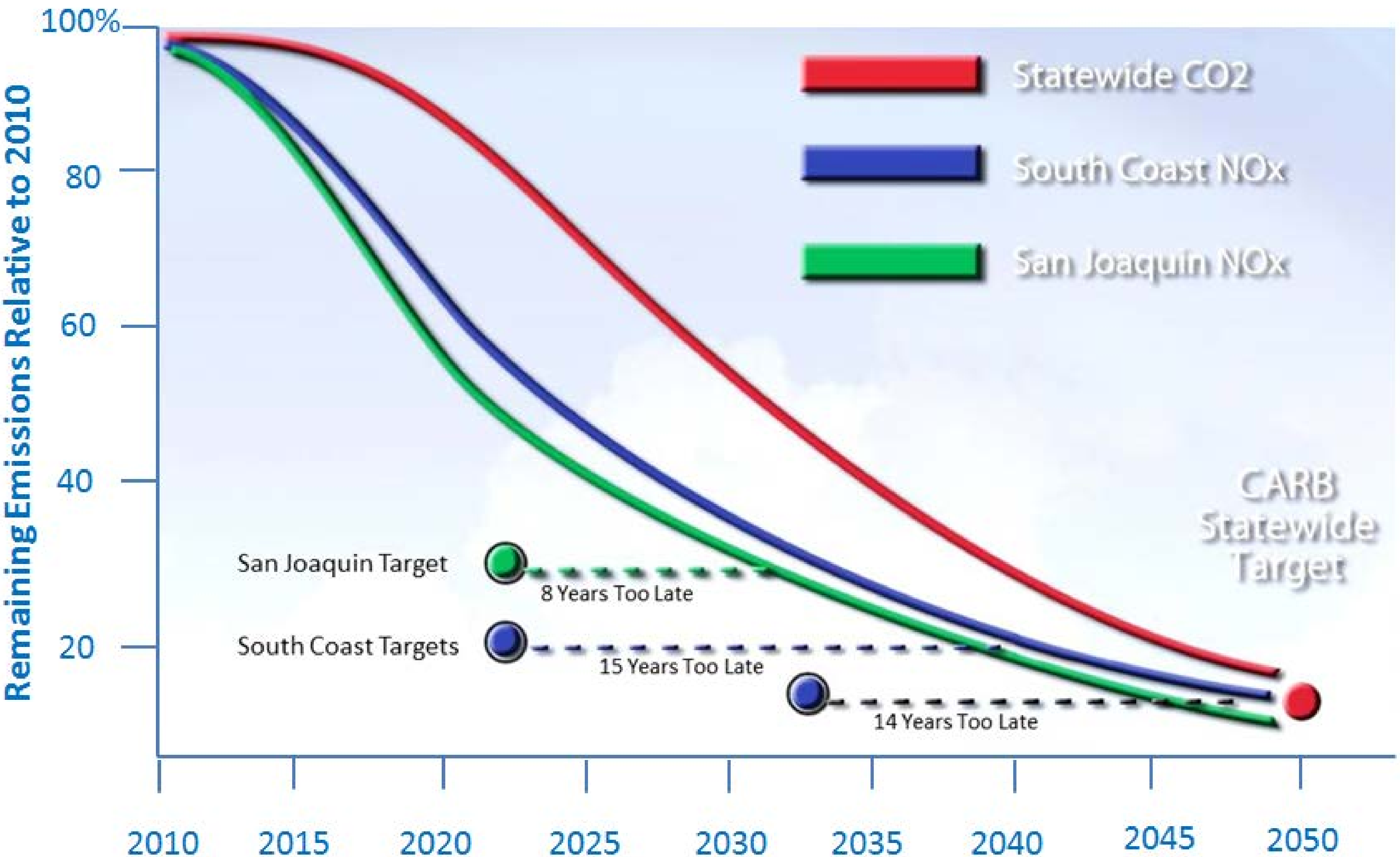



Note: the 2050 GHG target is still an Executive Order and is not yet law



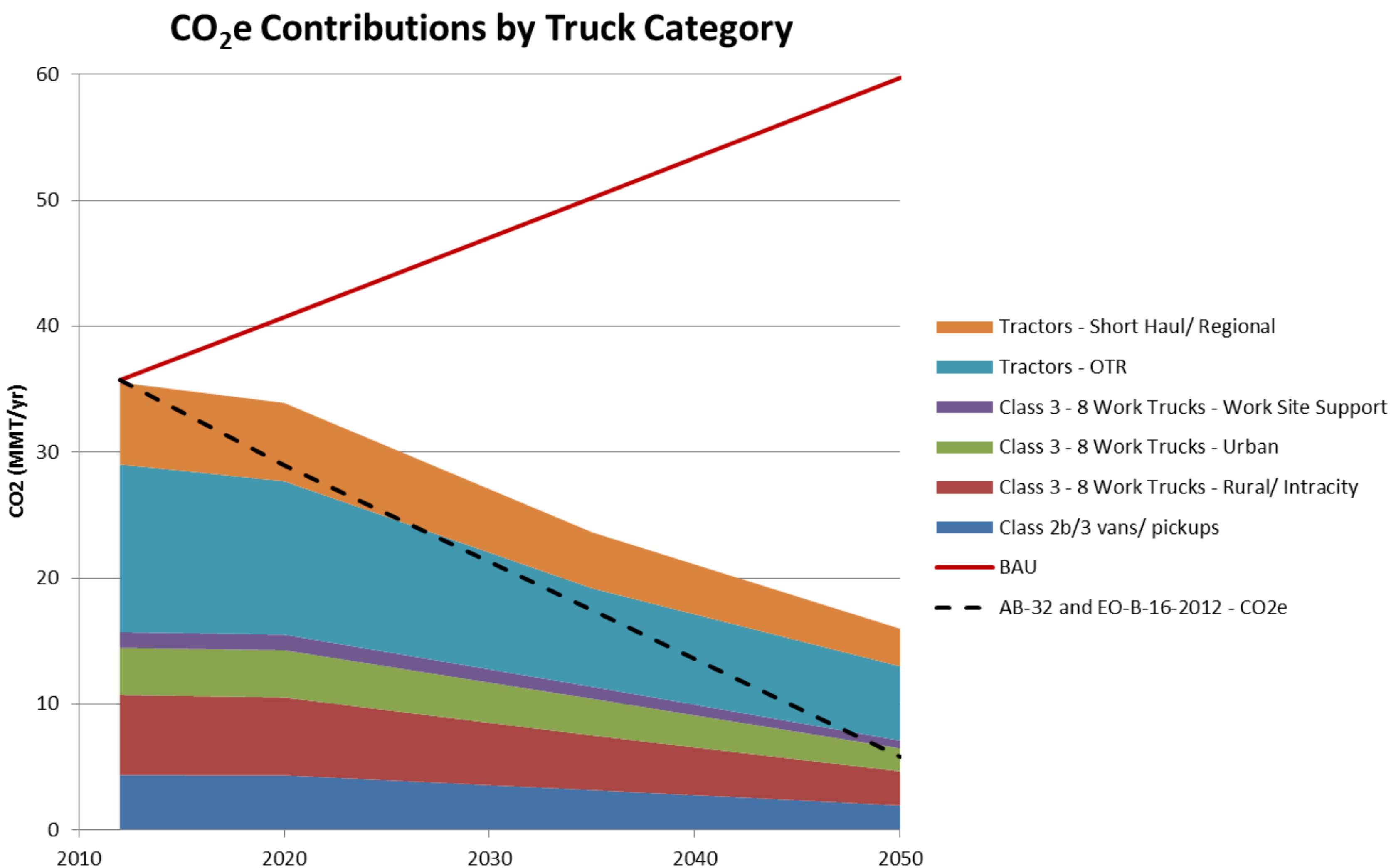
Source: CALSTART

# Broader Approach Needed to Reach State and Regional Targets




*Source: Sempra Utilities*

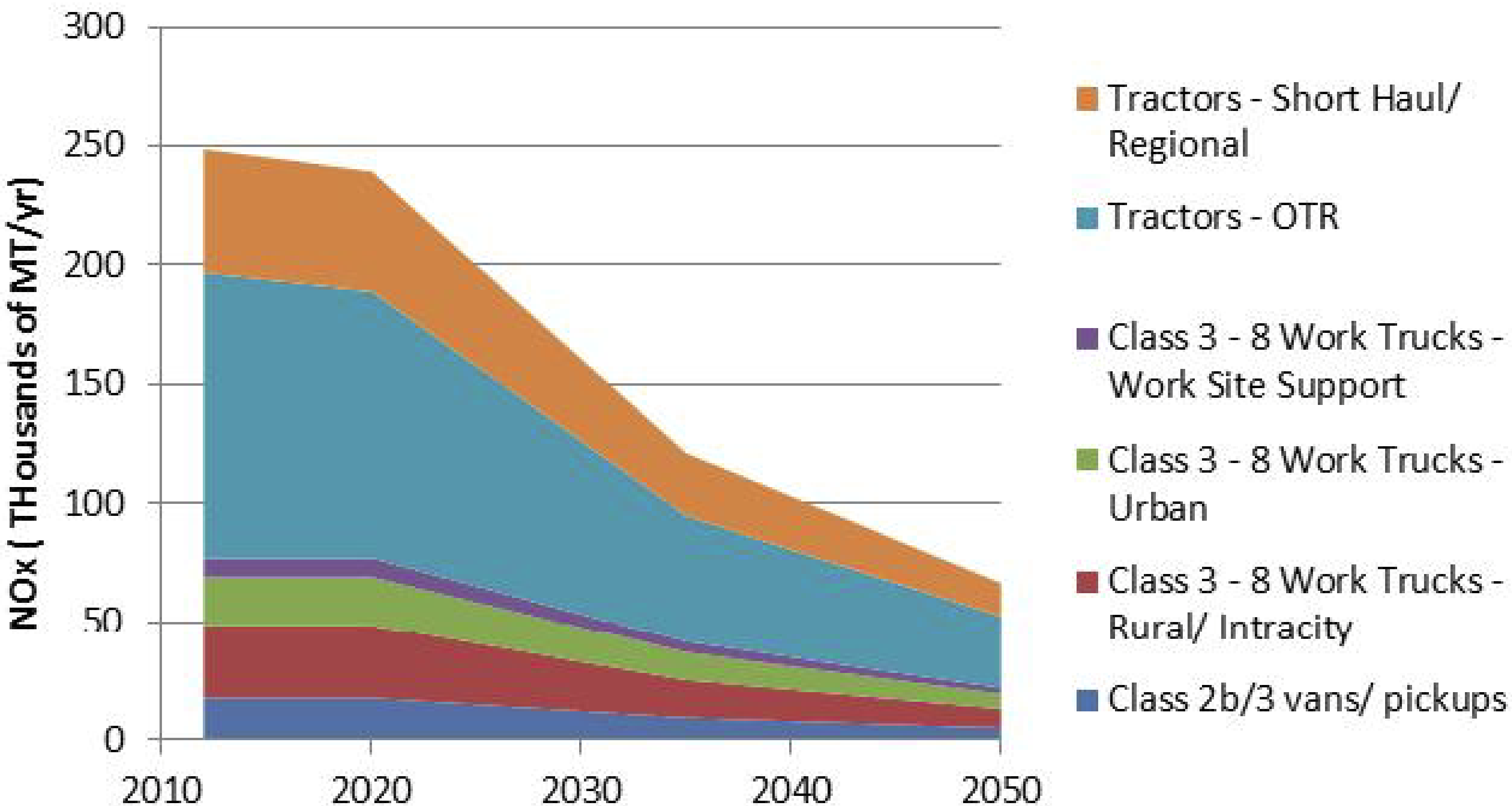
# CO2 Reduction from CalHEAT Roadmap






Source: CalHEAT

# NOx Reduction from CalHEAT Roadmap






Source: CalHEAT

# EPA and NHTSA Administering CAFE-like Standards for M-HD Vehicles Phase 1 Driver for Increased Efficiency

| Final Rule |
|---|
| Tractors: 10-23% |
| Vocational Vehicles: 6-9% |
| Pickup Trucks & Vans: 12-17% |

Final 2017 Standards (% reductions)

| | Day Cab | | Sleeper Cab |
|---|---|---|---|
| | Class 7 | Class 8 | Class 8 |
| Low Roof | (10%) | (10%) | (17%) |
| Mid Roof | (10%) | (10%) | (17%) |
| High Roof | (13%) | (13%) | (23%) |

- 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

# Roadmap & Technology Pathways

# Roadmap Pathways Overview

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

### Natural Gas Engine Technology

Primarily driven by brake thermal efficiency (BTE) improvements and catalyst improvements for emission reductions. Enhanced combustion strategies, transmissions, waste heat recovery, and new technologies based on DOE Supertruck experience will be integrated into future engines and drivelines. New and innovative engine types may emerge by 2023

### Fuels, Storage & Infrastructure

Primarily driven by increasing availability of renewable fuels, lighter weight and less expensive storage systems and increased availability of public infrastructure

### Range Extended Electric Vehicles and Hybrid Vehicles

Primarily driven by need for zero emissions in the Port regions and productivity improvements in the refuse market. Range extension strategies using new zero- and low-emission power plants will be developed and used to extend the range of an electric driveline. Full and mild hybrids will also be deployed.

### Policy and Other

Driven by the Federal, state and local regulations discussed as drivers. There are major opportunities for development funding and buy down incentives within the state of California

# Natural Gas Engine Trend Overview

- **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

# Natural Gas Engine Technology

TECHNOLOGY

**Stage 1 Current Status** ( Limited Engine Size Availability)

- *NOx Emissions slightly better that 2010 Standards*
- *EPA/NHTSA Phase 1 Compliant for GHG*
- *Engines Approaching 45% Brake Thermal Efficiency*
- *Expensive technologies replaced by engines that provide 1-3 year payback for 100,000 miles use*
- *Use primarily diesel engine blocks*

*ISL-G 8.9L (CWI)*

- Stoichiometric spark-ignited with 3-way catalyst
- Workhorse for refuse & transit and emerging drayage & regional delivery markets
- Payback: 1-3 years – little cost difference vs. diesel for engine components – main costs are gas storage
- No DPF and SCR needed
- SCAQMD requires use for refuse & transit applications
- Emissions level: 2013
- CAFÉ Ph.1 compliant

*ISX-12G (CWI)* ***(New offering)***

- 11.9L stoichiometric spark-ignited with 3-way catalyst – emerging for refuse, drayage, regional delivery & OTR
- Payback – 1.5 to 3 years
- Emissions level: 2013
- No DPF and SCR needed
- CAFÉ Ph.1 compliant

*HD15 (Westport)* ***(discontinued production end of 2013 but still in use)***

- 15L high-pressure direct injection compression ignition with diesel pilot – limited currently to OTR market
- Payback 4 years
- Requires diesel pilot + aftertreatment (SCR)
- Emissions level: 2010
- CAFÉ Ph.1 compliant
- Production phasing out - ends early 2014
- Best match for LNG applications

*Doosan 8.9L*

- Lean burn SI engine – currently used in some transit applications
- Developing 11.9L version

**Stage** 2 (Increased engine offerings including purposefully designed NG engine blocks)

- *75% less NOx vs. 2010 Standards*
- *NHTSA Ph 2 GHG targets for CO2 (10% improvement?)*
- *Engine brake thermal efficiency approaching 48% through implementation of new Supertruck technologies*

ISL 8.9L and ISX 12G

- Similar architecture to current but with advanced catalysts & combustion properties – 75% lower NOx than 2010 standards

Volvo 13L HPDI

- Emissions level: 2013
- Efficiency: same as diesel
- CAFÉ Ph.1 compliant
- Payback – 2-3 yrs?

Cummins 15L SI (2016) – in development now

- Improved performance, reliability & fuel economy
- Purposeful block

Volvo DME – NG-derived fuel

- Requires minor modifications to D13 engine
- 0 PM – no DPF required
- 95% lower CO2 emissions than diesel when DME is derived from biosources
- Lower pressure than NG, infrastructure similar to propane
- Performance similar to diesel

Quantum/Ricardo/PSI PIER engine – class 3-7, 8.8L base engine - 20% fuel economy gain, 16% power density gain (proposed but not certain)

Westport HDPI 2.0 (replaces HD15)

- Range of sizes up to locomotives
- Optimized combustion
- Redesigned electric controls

**Stage** 3 (Continued Emission , GHG and break thermal efficiency gains)

- *90% less NOx vs 2010 standards*
- *Engines starting to exceed 50% brake thermal efficiencies*
- *GHG Reductions (increasing reductions approx. additional 10% vs. stage 2)*

GHG/fuel efficiency gains (hybrids, range extenders, more electrification)

Compression ignition (not HPDI)

Methane catalysts, especially for HPDI configurations

CWI ISL-G 8.9L - .02g

- Better controls & catalysts

Cummins 15L S.I. (near-zero)

- Purposeful design
- Better ignition controls, fuel injection, thermal management & air handling, waste heat recovery
- Commercialization will be dependent on adoption of optional NOx standards

**Innovative Engine Solutions**
**Camless engines:**

- Commercial production
- Using NG to obtain decreased NOx (0.02 g/bhp-h)

**Opposed Piston and free-piston engines:**

- Demonstrations including 21% improved fuel efficiency

**HCCI:**

- Demonstrations

**ICRC (Brayton)** – traction engine not range-extender

**2013** **2018** **2023**

# Recommendations for Engines

- 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
- Investigate and encourage the use of NG in new engine development activities such as the Achates opposed piston engines
- Weigh in with NHTSA/EPA on Phase 2 CAFE standards to insure fair recognition of natural gas
- Consider developing & demonstrating low-NOx DME engines for regional class 8 applications

# Engine and Vehicle Technology Capabilities Assessment

- The following chart summarizes select system benefits for emissions & $CO_2$ reductions over the periods to 2023 & 2023+
- See detailed appendix for technology descriptions and associated benefits of the following components/systems
  - Air system
  - Combustion
  - Fuel system
  - Waste heat recovery
  - Emissions treatment
  - Ignition system
  - Design
  - Friction & parasitic
  - Vehicle system
  - Powertrain

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

| | Near term (Today-2023) | Near term NOx /CO2 Benefits | Long term (2023-2032+) | Long term NOx /CO2 Benefits |
|---|---|---|---|---|
| Air System | • Miller & Atkinson cycles<br>• Variable valve timing<br>• Turbocharging | 10-30%/ 3-15% | • Trapped EGR<br>• New valve train strategies<br>• Camless engines | Up to 40%/ 5-40% |
| Combustion | • Pre-chamber spark Ignited<br>• Stratified charge<br>• Lean burn | 20-70%/ 4-40% | • HCCI<br>• Improved combustion controls | 75-90%/ 25-90% |
| Emission After Treatment | • EGR<br>• SCR (for lean burn)<br>• Lean NOx trap (for lean burn)<br>• 3-way cat (non-selective catalytic reduction) | Up to 80%/ 1-5% | • Optimized catalysts<br>• Improved methane catalysts<br>• Improved NOx conversion efficiencies | NA/ NA |
| Vehicle Systems & Integration | • Aerodynamics<br>• Weight reduction<br>• Lower rolling resistance<br>• Automation technologies (i.e. adaptive cruise control) | 2-28%/ 2-28% | • Optimized tractor/trailer design<br>• Lighter fuel system support materials<br>• Lighter weight = lower engine power needs | NA/ NA |

## See appendix for technology descriptions

# Fuels Trend Overview

- **Stage 1/Current status:** Stable supply of pipeline gas used for CNG & LNG; shale gas & fracking should insure 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

# Fuels

FUELS

**Stage 1 - Current Status**

- Minimal renewable NG use and availability
- Initial RNG use in California currently through Clean Energy's ReDeem

- Pipeline NG – compressed and dispensed as CNG
- Liquefied NG – liquefied at remote site, trucked to dispensing location – limited "shelf" life due to boil-off, operational issues (safety equipment required)

- CNG from pipeline NG 33% less carbon content than diesel LNG 17-28% less carbon than diesel

- Hydrogen – 33% renewable requirement for transportation uses

- 5% reduction of GHG for CNG

- Focus on WTW methane leakage – EDF study recommends 2.5% systemwide cap

**Stage 2 – Goal is maximizing renewable content (GHG)**

- RNG – greater production, increased pipeline injection – will the credits be actual or paper? –Utility acceptance of RNG injection?
- More RNG produced in-state from landfills & dairies (see policy section)
- 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?)
- RNG – carbon intensity values 86-89% less than diesel – Will there be a new CO2 metric for pipeline gas?
- Renewable H2 pipeline injection? - what will be the limit – 5%, 10%?
- Bio-DME
- Methanation of H2

**Overall Trends:**

- Consistent NG supplies and low costs
- Supply security - Growing NG supply through shale discoveries/hydraulic fracturing – how will fracking and systemwide leakage issues affect future supplies & prices? Will there be penalties for released methane?
- Consistent gas quality standards (MN-88+?)
- DME (low comparative energy content, high cost, lubricity issues w/ injectors) -2015
- Renewable H2 – 30% of H2 in transport must be renewable



2013 2018 2023

# Recommendations for Fuels

- 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

# Onboard Gas Storage Trend Overview

- **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

# Gas Storage

STORAGE

**Stage 1 - Current Status and Near-Term Trends – Premium remains for NG vs. diesel storage**

CNG
- Framerail mounted (capacity up to 100 DGE/vehicle – 47 DGE/tank)
- Horizontally mounted behind cab (capacity up to 140 DGE/vehicle)
- Cost is ~ $300/DGE
- Weight – 10-20 lbs/DGE net
- Materials – carbon fiber >> aluminum
- Volume – increasing diameter for greater capacity
- Weight - ~200 lb. weight penalty vs. diesel
- CNG tanks 5:1 size for same range as diesel; LNG 2.3:1

LNG
- Cryogenic ($300/DGE)
- Weight – 5 lbs/DGE net increase
- Capacities (up to 150 DGE/vehicle)
- LNG storage costs higher than CNG

**Stage 2 - Lower Cost, Greater Capacity, Lower weight , better materials**
- Lower cost storage – closer to $100/DGE
- Lighter-weight materials
- Optimized designs
- More research into lower-pressure storage - Pellets adsorption (BASF)
- Low-pressure storage – less than 1,000 psi (probably 2023+)
- High-pressure storage (6,000 to 10,000 psi)
- 90” long to 120” long tanks for CNG
- Better chassis design to incorporate more tanks
- Gas adsorption
- Conformable tanks
- Incorporating tanks into chassis (2023+)
- Bladders for CNG
- Phase-change materials to offset fill losses
- Smaller tanks and less capacity needed in connection with range extenders

2013 2018 2023

# Recommendations for Gas Storage

- 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

# Infrastructure Trend Overview

- **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

NG Engine Technology

Range Extended EV & Hybrid Vehicles

Fuels, Storage & Infrastructure

Policy

Pathways by Vehicle Application

# Infrastructure

TECHOLOGY

**Stage 1 - Current Status ~130 public stations in California**

CNG - uses solely pipeline gas

- Station Costs - $500K to $2.5M
- Dispensing Capacity - up to 20 DGE/minute
- Siting - Private Fleet or Public Corridors
- Fast fill for transit, drayage, delivery & long-haul
- Slow fill – ideal application is refuse & school buses

LNG - Some local and mostly non-local pipeline gas used for liquefaction

- Stations Costs - $2-$4M+
- On-site Storage Capacity – up to 18K gallons storage
- Siting- Primarily public/corridors, proximity to liquefaction plants (250 mi. radius)
- Transportation - Cost of transporting LNG to stations by truck
- Limitations – shelf-life ~7 days due to boil-off
- Operational issues – safety equipment required

L/CNG – vaporize & compress LNG – dispense as CNG

Compact skid-mounted fueling stations (CNG in a box) – GE/Galileo

Public access vs. Fleet / cardlock access

DME – lower pressures, infrastructure similar to LPG and inexpensive as compared to CNG/LNG

H2 – limited availability & high cost

**Stage 2 – More station availability (250+ public stations in California), lower costs, better controls**

- Quicker dispensing for high-volume applications such as transit
- Increased capacity & compression efficiency at stations
- More efficient dispensers
- Better balance between faster dispensing & more storage
- Standardized and Modular designs
- Better controls for time-fill to take advantage of TOU rates
- Small-scale liquefaction

- 5000 public access stations needed nationwide to get to 25% market penetration
- Highway network of LNG stations needed to sustain OTR market, even within Calif.
- Lower cost, modular L/CNG stations
- Lower cost time-fill

- More “NG in a box” capabilities for CNG & LNG – lower cost, greater use of local pipeline NG for liquefaction onsite



**2013** **2018** **2023**

# Recommendations for Infrastructure

- Support use of CA cap-and-trade funds for infrastructure development
- Deploy 65-100 new stations strategically in service area to support long-haul markets – enables greater use of CNG in this application
- Support and invest in “CNG in a box” systems to enable mores stations with smaller footprints
- Support and invest in “LNG in a box” systems which would allow for the use of localized NG supplies
- Support industry efforts to increase standardized station designs and modularity

# Electrification & Hybridization Trend Overview

- **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

NG Engine Technology

Range Extended EV & Hybrid Vehicles

Fuels, Storage & Infrastructure

Policy

Pathways by Vehicle Application

TECHNOLOGY

# Range Extended Electrics using Alternative Power Plants for Electrified Drivetrain Solutions

**Stage 1: Current Status:(pre-commercial demonstrations ongoing)**
**APPLICATIONS -** Transit bus applications and drayage demonstrators of fuel cell and stationary designed turbines as generators for electric drivelines.

**Stage 1 technical characteristics may include:**
- Zero emissions (fuel cells) and near-zero emissions (turbines)
- Used in series hybrid-electric configurations
- Fuel cell hybrids can double fuel economy
- NG storage becomes less of an issue in range-extenders due to lower fuel need

**PERFORMANCE GOALS:**
- 50% petroleum reduction
- Expanded work site idle reduction
- Noise reduction
- Productivity gain from idle-free; allows expanded hours of operation

**POWERPLANTS**
***Fuel cells***
- Derived from H2 (reformed from NG) – 30, 50, 90, 100, 150 kW systems
- Manufacturers: Hydrogenics, Ballard, US Hybrid, Nuvera,
- Cost approaching $300/kW now , reliability approaching 20,000 hours of operation
- Cummins-Westport 6.7L NG engine as range extender

***Turbines***
- Large sizes now (350 kW now, moving toward 30 kW & 65 kW)
- Off-the-shelf components for utility & stationary apps
- Used in transit & drayage primarily range-extender
- Early demos , uncertain as to final configuration – should meet drayage & transit needs due to pending low-emission regulations – zero-emission miles possible
- Emissions 75% lower than 2010 cert level
- ~30% efficiency
- Payback: ~3 years
- No after-treatment necessary
- Manufacturers: Capstone, Brayton

**Conventional Engine Gen Sets**
**US Hybrid/GTI CNG range extender –** ISL-G + 100 kWh battery for 30 mile all-electric operation - demo underway

**DRIVELINES (PLUG-IN AND TRADITIONAL)**
- ZE driving capability demonstrated through plug-in configuration
- Dual-mode and range-extenders in drayage as second applications (supports pathway for ZE goods movement)
- Limited export power
- e accessories optimized and customized for this application

**Stage 2:** (Los Angeles area ports mainstreaming of zero emission miles capable drayage trucks and California zero emission transit bus regulation enforced**) – commercial production**
**Stage 2 builds off Stage 1...**

**Technical characteristics may include:**
- Lower Costs
- Improved range extenders where applicable
- Cost effective electric accessories
- Cost effective and larger motors

**Performance goals may include:**
- Greater than 50% petroleum reduction
- Zero-emission driving variant available – more ZE miles

**Stage 2 economic goal:** 5-8 year simple payback (with incentives for drayage & transit)

**POWERPLANTS**
**Fuel cells:**
- Move to becoming more battery-dominant – sizes the same
- Start deployment in trucks & buses (mostly range extenders)
- Reliability – 30,000 hrs
- Price reduced to $100/kW
- Manufacturers: same as stage 1

**Turbines**
- 30 kW, 65 kW
- Purposely-designed automotive –quality turbines
- Used in transit & drayage primarily range-extender
- Early demos , uncertain as to final configuration – should meet drayage & transit needs due to pending low-emission regulations – zero-emission miles possible
- Emissions 75% lower than 2010 cert level
- ~30% efficiency
- Payback: ~3 years
- No after-treatment necessary
- Manufacturers: Capstone, Metis Design, Ricardo, Hybine

**DRIVELINES**
- Improved integration and HEV-plug-in optimization
- Optimized and downsized engines
- CA OBD compliant

CWI ISB 6.7G - 2016
- Not applicable for conventional NG engine for HD but as a range extender range extender for class 7&8

# Recommendations for Range-Extended Electrics using Alternative Power Plants

- 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

# Natural Gas Hybrids Trend Overview

- **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

# Natural Gas Fuelled Hybrids (includes Hydraulic Hybrids)

TECHOLOGY

**Stage 1 – Current Status**
*Limited fleet trials of NG-hydraulic hybrid refuse trucks*

**Stage 1 performance goals may include:**
- 22-38% GHG-C02 reduction (and petroleum reduction)

**Stage 1 Applications:**
New York Sanitation NG hybrid refuse truck demo

Economic goals
Technical characteristics

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**Natural Gas Hydraulic Hybrid Technology**
**Stage 1 Parallel**
Limited Feet Trials (Autocar & Parker Hannifin)

**Hydraulic hybrid economic goals:**
- 5 year payback without incentives in refuse;

**Hydraulic hybrid performance goals may include:**
- 10-25% fuel economy improvement for parallel system;
- 4-5X brake life
- Increased productivity (e.g., stops per day in a refuse truck)

**Hydraulic hybrid technical capabilities may include:**
- Regenerative braking system only
- Axial piston pump/motor with single speed gearbox (parallel)
- Bladder accumulator (steel)

**Stage 2**
**Stage 2 builds off Stage 1...**
*More commercial offerings, full deployment of NG-hydraulic hybrid refuse trucks, potential for hybrid-electric refuse applications, mild-hybrid trucks in other applications*
**Stage 2 performance goals may include:**
- NG hybrid 27-54% GHG-C02 reduction, 100% petroleum reduction)
- Increased low-speed torque in hybrid system (beyond conventional hybrid design) to compensate for lower torque NG engines

**Stage 2 economic goal:** 3-5 year payback, accounting for non-fuel savings in these specific applications (fuel savings ROI alone may not get economic model to work); benefits include productivity gains (more stops per hour) and maintenance savings (significant brake job cost savings)
**Stage 2 technical characteristics may include:**
- NG hybrid refuse truck with right sized NG tanks and battery storage or hydraulic storage
- Mild hybrid & high electrification in bus or truck
- Opportunities for down-sized engines

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**Natural Gas Hydraulic Hybrid Technology**
**Stage 2 Series, Enhanced Parallel and Dual Mode (Power Split)**

**Stage 2 economic goals:**
- 3 year payback (mature) without incentives in refuse

**Stage 2 performance goals may include:**
- 35-100% fuel economy improvement
- Significantly longer brake life (up to 4-5X in refuse, lower in less aggressive drive cycles)
- Also targeting trials in package delivery vehicles, yard hostlers, and city transit buses

**Stage 2 technical capabilities may include:**
- Full Series: no mechanical connections between engine and wheels
- Dual mode series hydraulic hybrid at low speed, switches to mechanical transmission at highway speed
- Parallel: improved transmission efficiency and system integration
- Potential for engine off operation
- OBD Compliant



**2014** **2016** **2018** **2023**

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

- Weigh in on CNG engine OBD compliance Issues
- Consider funding demonstrations of hydraulic-hybrid technology in new applications areas such as transit

# Policy/Other

POLICY / OTHER

**Current Status and Near-Term Trends**

**FEDERAL**

*Mandates/regulations*

- Development of NHTSA/EPA Phase 2 fuel economy standards

*Incentives*

- FTA research grants
- DOE EERE funding
- FTA MAP-21 NOLO deployment funding
- Development of next-gen MAP-21 program (2015-2019)

*Other relevant federal issues*

- RIN/LCFS credits for RNG
- Systemwide NG leakage studies

**STATE/LOCAL**

*Mandates/regulations*

- CARB voluntary low-NOx standards
- Zero-emission bus regulation under review – how will this affect potential of NG range-extenders?
- California cap-and-trade funds for heavy-duty transportation
- Potential for Calif. carbon tax – how will it affect cap & trade revenues?
- SJVAPCD/SCAQMD NOx standards

*Incentives*

- CEC/PIER program $3M NG hybrid development program for trucks
- CEC NGV incentive program for trucks
- CEC Biofuel and RNG demo programs in development
- Continuation of AB 118 funding for demos

*Other relevant state/local issues*

- CPUC determination of RNG pipeline injection
- AB 118 funding for infrastructure
- CARB undergoing planning on their sustainable freight strategy
- POLA/POLB roadmapping and planning for zero-emission freight corridor

**Mid-Term Trends**

**FEDERAL**

- Adoption of NHTSA/EPA phase 2 GHG/mileage standards – will require better vehicle/engine design optimization
- MAP-21 may include GHG performance-based metrics
- 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?
- 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

**STATE/LOCAL**

- CARB voluntary GHG regulations adopted
- Zero-emission bus regulations implemented
- Cap and trade revenues used for transportation
- 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
- CARB ultra-low NOx voluntary standards adopted
- CPUC regulations on pipeline injection of RNG – will this bring better access by producers ?
- Will CPUC bring consistency to fuel quality standards (possibly higher methane numbers)?
- How will the settlement of California OBD issues affect AFVs?
- Passage of AB 8 will bring more funds for more infrastructure, vehicles & the development of RNG
- Port zero-emission freight corridor implementation



**2013** **2018** **2023**

# Recommendations for Policy

- Support use of CA cap-and-trade funds for NG vehicle & infrastructure development
- Insure that NHTSA/EPA Phase 2 fuel economy standards give fair recognition to natural gas
- Track and weigh in on federal & state RIN/LCFS proceedings to promote greater use of RNG and to mitigate risk for producers
- Track and weigh in on CPUC proceedings re: pipeline injection of RNG
- Weigh in on systemwide NG leakage studies
- Monitor & contribute to issues affecting NG engine OBD compliance issues
- Work to encourage CEC to make NG truck incentives more transparent by adopting HVIP-like voucher structure

# Technology Trends by Heavy-Duty Application

- **Transit**: early adopter of NG; moving toward implementation of zero- and near zero-emission solutions such as NG range-extenders & 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 extenders
- **Local/regional delivery**: currently untapped market; good candidate for 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

NG Engine Technology

Range Extended EV & Hybrid Vehicles

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Pathways by Vehicle Application

## By Application Type

### Buses

**Current Status**
- Primarily using CNG
- Adequate onboard storage capacities
- Large-scale fueling operations required
- Primarily using 8.9L, may see some 11.9L engines
- Manufacturers: New Flyer, NABI, Gillig, Novabus, El Dorado, Designline might reenter market with turbine electric

**Projected Trends**
- Zero emissions bus regulations will drive the use of hydrogen battery electric buses (up to 15% per year new purchases)
- Opportunity exists for a NG range extender drive system ( CARB Open to this under ZEB regulations)
- Likely early deployment of near zero emissions (8.9liters) due to municipal fleet rules by SCAQMD
- Opportunity for very Mild Hybridization

### Refuse

**Current Status**
- 75-100 DGE onboard CNG storage is typical, could use 50-60 DGE in some apps
- Placement of tanks/increased storage sometimes an issue
- Some LNG applications
- New deployments of hydraulic hybrids
- Mostly utilizing 8.9L but 11.9L will make inroads
- Excellent application for time-fill
- Autocar/Cummins Westport Class 7 cab-over-chassis
- Manufacturers : Autocar, Crane Carrier, Freightliner, Kenworth, Mack

**Projected Trends**
- Anticipate growing use of RNG -excellent application due to proximity of fuel source, i.e. Waste Management & Republic Services.
- Increasing use of LNG though CNG stays dominant
- More NG/hydraulic hybrid combos as well as a potential for Hybrid Electric combos due to productivity gains associated with the technology

### Port Drayage

**Current Status**
- Use of NG picked up in 2011-2013 due to incentives but will flatten out due to significant early turnovers driven by CARB regulations
- Using CNG & LNG via POLB/POLA clean trucks program
- Limited need for range and HP-
- Mostly utilizing 8.9L but 11.9L will make inroads
- Manufacturers : Freightliner, Volvo, Kenworth, Peterbilt, Navistar

**Projected Trends**
- Growing interest will re-occur in CNG
- Zero Emission Zone at POLA/POLB will drive new range-extender NG + fuel cell –battery dominant solutions
- H2 + BEV could compete

### Regional /local Delivery

**Current Status**
- Primarily using CNG
- Main alternative competitors are hybrid & BEV
- Mostly utilizing 8.9L now but 11.9L will make inroads
- Manufacturers : Freightliner, Volvo, Kenworth, Peterbilt, Navistar

**Projected Trends**
- Potential for very mild NG hybrids
- NG/BEV range extenders could compete
- Opportunity for LNG infrastructure to support local use of NG Pipeline
- Need to further develop innovative CNG storage for less space and shorter tractors on regional trucks

### Over the Road Trucks

**Current Status**
- Best application for LNG due to need for longer range
- Still captive to infrastructure availability
- 15L HPDI current best fit but should be able to handle 13L & 15L SI
- Manufacturers : Freightliner, Kenworth, Volvo

**Projected Trends**
- DME use
- Aerodynamics/light-weighing
- Increased range for CNG



**2013** **2018** **2023**

# Recommendations by Application

## Transit Buses

- Build partnerships and encourage development of NG-turbine range extender electrified drivelines to provide NG option for California Zero Emission Bus regulations
- Work with MTA and others to become early adopter of low-NOx NG engines to secure early beachhead market for low NOx engine makers
- Work with technology partners to develop ultra-mild hybrid/electrified accessory NG driveline to drive down GHGs from conventional NG buses

# Recommendations by Application

## Refuse Collection

- Weigh in with CEC on PIER 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

# Recommendations by Application

## 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 to determine funding interest

# Recommendations by Application

## 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

# Recommendations by Application

## 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

- Detailed engine/driveline technology descriptions and an assessment of their potential emissions & $CO_2$ improvements
- CALSTART analysis of future paybacks for range extended electric drayage trucks

# 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, $CO_2$ 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 $CO_2$ 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 ($CO_2$ 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 2nd 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

 

# 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 |
| **Waste Heat Recovery** | 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 $CO_2$ emissions |
| | 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 $H_2$) with higher calorific energy content and combusting this syngas in the cylinder, which then permits ignition of leaner mixtures due to the $H_2$ content in the syngas, thus enabling lower NOx emissions |
| **Emissions Treatment** | 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 $CO_2$ emissions |
| | 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 $CO_2$ 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 $N_2$ 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 $N_2$ over a reduction catalyst during rich operations (Can be attained by injecting fuel into exhaust or via in cylinder injection strategies) |

Source: Ricardo Analysis, Public Domain

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

RICARDO

## 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 ($CO_2$ 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 ($CO_2$ 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 ($CO_2$ 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 ($CO_2$ 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 ($CO_2$ emissions) |

Source: Ricardo Analysis, Public Domain

# Engine air System and combustion technology assessment for NOx and $CO_2$ reductions on natural gas engines

RICARDO

## Technology Capabilities Assessment – (1/4)

Before 2023 | 2023 - 2032

| Sub System | Technology | Est. Tailpipe NOx (g/hp-hr) Reduction From Base EPA 2010 | | Est. Engine Level $CO_2$ Reduction | |
|---|---|---|---|---|---|
| Air System | Miller & Atkinson Cycles | 10% - 30% | • Est. based on larger off highway gas engines; when coupled with 2 stage turbocharging systems, upper limits could be attained | 3% - 15% | • Combination of variable valve timing + lift and optimized turbocharging |
| | Camless Engine | Up to 30% to 40 % | • Est. based on claims from efforts in R&D stage and can vary based on trapped EGR and overall valve train, air system strategies | 5% - 20% | • Est. based on claims from efforts in the R&D stage currently |
| Combustion | HCCI | 75% - 90% | • HCCI expected to be more of a NOx reduction tool | 5% - 25% | • 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 |
| | Pre-Chamber Spark Ignited (Lean burn) | 20% - 25% | • Based on est. from large off highway gas engines; overall reduction could be higher when combined w/ EGR, boosting, suitable ignition systems | 4% - 18% | • Based on est. from large off highway gas engines and current on highway pre chamber systems being developed |
| | Stratified Charge / Lean Burn | 20% - 70% | • Assumes using lean burn or stratified charge near the natural gas flammability limit with suitable ignition system to achieve upper ends of NOx reduction potential | 5% - 40% | • 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. |

Source: Ricardo Analysis, Public Domain

 

# Engine design, heat recovery and ignition system technology assessment for NOx and $CO_2$ reductions on natural gas engines

RICARDO

## Technology Capabilities Assessment – (2/4)

Before 2023 | 2023 - 2032

| Sub System | Technology | Est. Tailpipe NOx (g/hp-hr) Reduction From Base EPA 2010 | | Est. Engine Level $CO_2$ 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 NOx reduction by increasing PCP is due to overall engine downsizing and associated fuel consumption benefits, which translates into a g/mile NOx benefit | 1% - 3% | • Increased PCP's through higher compression ratio, BMEP's |
| Waste Heat Recovery | Thermo-Chemical Recuperation | 40% - 80% | • $H_2$ 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 $CO_2$ emissions with exhaust gas TCR that creates $H_2$ rich intake fuel |
| Ignition System | Improved Ignition | Up to 70% | • Laser ignition in R&D phase has shown up to 70% NOx reduction capability | 8% - 40% | • Laser ignition and plasma ignition have shown up to 30% to 40% efficiency improvement |

Source: Ricardo Analysis, Public Domain

# Engine emissions reduction technology assessment for NOx and $CO_2$ reductions on natural gas engines

## Technology Capabilities Assessment – (3/4)

Before 2023 | 2023 - 2032

| Sub System | Technology | Est. Tailpipe NOx (g/hp-hr) Reduction From Base EPA 2010 | | Est. Engine Level $CO_2$ Reduction | |
|---|---|---|---|---|---|
| Emissions Treatment | Steam/Water Injection | 10% – 40% | • NOx reduction varies depending on mechanism employed – Fumigation vs. in cylinder injection | (2%) - 1% | • Small penalties have been recorded in some cases with $H_2O$ injection |
| | Exhaust Gas Recirculation[1] | 30% - 80% | • Increasing EGR by 5 to 20% points on a 2010 gas engine could yield ~30 to 80% lower tailpipe out NOx emissions vs. 2010 | 1% - 5% | • Typical $CO_2$ benefits gained by being able to advance injection timing at same NOx level or by improving knock limit |
| | Selective Catalytic Reduction (Lean Burn Only) | 50% - 80% | • Improving SCR NOx 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 NOx vs. 2010 | 1% - 3% | • Overall $CO_2$ benefit with improved SCR will be limited due to lower tailpipe out NOx targets desired and already high SCR conversion efficiencies |
| | Non Selective Catalytic Reduction (3 way cat.) | 60% – 80% | • Improving TWC NOx conversion eff. on a 2010 stoichiometric gas engine from current ~95% avg. to 98% to 99% will yield ~60 to 80% lower tailpipe out NOx vs. 2010 | 1% - 2% | • Overall $CO_2$ benefit with improved TWC will be limited due to lower tailpipe out NOx targets desired and already high TWC conversion efficiencies |
| | Lean NOx Trap (Lean Burn Only) | 25% - 50% | • Improving LNT NOx 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 NOx vs. 2010 | 3% - 4% | • Overall $CO_2$ benefit with improved LNT will be ~3% - 4% due to lower tailpipe out NOx targets desired and overall lower current NOx conversion efficiencies |

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

Source: Ricardo Analysis, Public Domain

 

# Engine vehicle level technology assessment for NOx and $CO_2$ 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 $CO_2$ Reduction | |
|---|---|---|---|---|---|
| Vehicle System | Aerodynamics | 2% - 28% | • Est. based on lower engine power needs; tractor and trailer optimized for low $C_d$ (outfitted with multiple drag reduction devices) to attain upper end of NOx reduction potential | 2% – 28% | • Tractor and trailer optimized for low $C_d$ (outfitted with multiple drag reduction devices) to attain upper end of $CO_2$ reduction potential |
| | Lower Rolling Resistance | 1% - 6% | • Est. based on lower engine power needs; ~1% $CO_2$ reduction per 5% decrease in rolling resistance and a 30% rolling resistance reduction target | 1% – 6% | • Est. ~1% $CO_2$ reduction per 5% decrease in rolling resistance and a 30% rolling resistance reduction target |
| | Lower Weight | 1.5% - 6% | • Est. based on lower engine power needs; est. ~0.5% $CO_2$ reduction per 1000 lb. weight reduction for a 10% – 15% overall weight reduction target | 1.5% - 6% | • Est. ~0.5% $CO_2$ reduction per 1000 lb. weight reduction for a 10% – 15% overall weight reduction target |
| Powertrain | Hybridization | 5% - 30% | • Est. based on lower engine power needs | 5% - 30% | • Overall $CO_2$ benefit sensitive to drive cycle and chosen technology |
| Waste Heat Recovery | Rankine Cycle | 2% - 8% | • Est. based on lower engine power needs | 2% - 8% | • Overall $CO_2$ benefit sensitive to drive cycle |
| Friction and Parasitics | Reduced accessory load | 1% - 3% | • Through load dependent deployment of pumps and/or by electrification | 1% - 3% | • Through load dependent deployment of pumps and/or by electrification |
| | Reduced friction | 0.5% - 3% | • Combined impact of lubricants, ring pack design, advanced bearings etc. | 0.5% - 3% | • Combined impact of lubricants, ring pack design, advanced bearings etc. |

Source: Ricardo Analysis, Public Domain

 

# PROMISE of Payback

- Initial analysis shows the promise of acceptable ROI, but needs more study – verify assumptions and estimates
- CNG REEV, then FC REEV, then BEV esp. for short routes

Summary of Business Case Analysis Results

Source: CALSTART

| | Total Range (ZE Range) | Daily Driving | Simple Payback Period (years) | Incentive for 5-year Payback Period | 10-yr. O&M savings | 2020 Truck Incremental Cost ($ per truck) | Infrastructure Cost ($ per truck) |
|---|---|---|---|---|---|---|---|
| #1 BEV | 100 (100) | 100 | 17 | $87,708 | $67,798 | $100,000 | $25,000 |
| #2L CNG REEV Low Utilization | 200 (50) | 100 | 13 | $42,983 | $43,051 | $60,000 | $8,400 |
| #2H CNG REEV High Utilization | 200 (50) | 200 | 7 | $20,692 | $74,507 | $60,000 | $8,400 |
| #3L Fuel Cell REEV Low Utilization | 200 (200) | 100 | 16 | $23,808 | $14,907 | $31,500 | $3,350 |
| #3H Fuel Cell REEV High Utilization | 200 (200) | 200 | 10 | $17,142 | $19,879 | $31,500 | $3,350 |

# Appendix – Stakeholders Engaged for this Study

| | |
|---|---|
| Adsorbed Natural Gas Products, Inc. | Robert Bonelli |
| American Gas Alliance | Katherine Clay |
| Autocar | Trevor Bridges |
| Brayton Energy | Jim Kesseli |
| California Natural Gas Vehicle Coalition | Tim Carmichael |
| Capstone | Steve Gillette |
| Chesapeake Energy | Sarie Joubert |
| Chesapeake Energy | Tim Denny |
| Clean Energy | Mike Eaves |
| Cummins Westport | Charlie Ker |
| Cummins Westport | Mustafa Kamel |
| Cummins Westport | Scott Baker |
| E-Controls | Kenon Guglielmo |
| Freightliner Trucks | Greg Treinen |
| Freightliner Trucks | Brian Daniels |
| Gas Technology Institute | William Liss |
| Gas Technology Institute | Tony Lindsey |
| Kenworth | Kevin Baney |
| Lincoln Composites | Jack Schimenti |
| Mack Trucks | Roy Horton |
| Natural Gas Vehicles America | Rich Kolodziej |
| Oberon Fuels | Rebecca Boudreaux |
| Paccar, Inc. | Graham Weller |
| Peterbilt | Frank Schneck |
| Quantum Technologies | David Mazaika |
| Sturman Industries | Joe Vollmer |
| Trillium CNG | Bill Zobel |
| University of Missouri | Peter Pfeiffer |
| Volvo Trucks | Sam McLaughlin |
| Ward Alternative Energy | Paul Nelson |
| Waste Management | Chuck White |
| Westport Technologies | Tahra Jutt |
| Westport Technologies | Valerie Parr |
| Westport Technologies | Mark Dunn |
| Westport Technologies | Patric Oulette |

# Possible Next Steps

- Marine & rail pathways
- CalHEAT Advisory Committee Review
- Industry outreach via technology forum
- RNG roadmap
- CEC NG-hybrid solicitation
- Other issues