

Lower NOx Heavy-Duty Natural Gas and Other Alternative Fuel Engines Technology Assessment

September 2, 2014
Sacramento, California

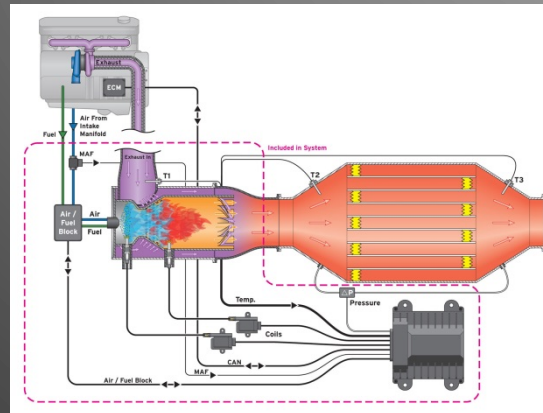
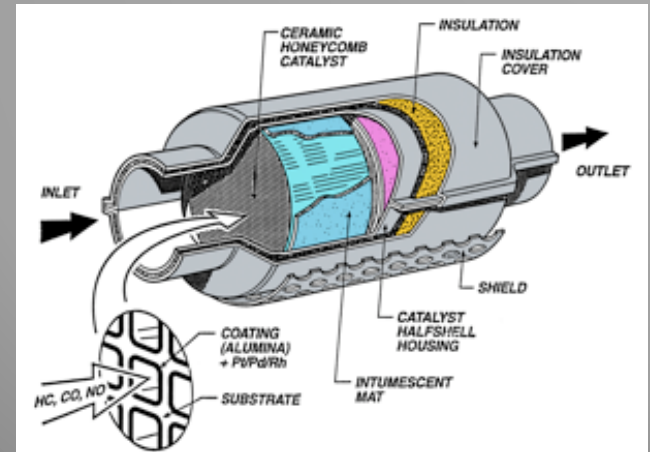
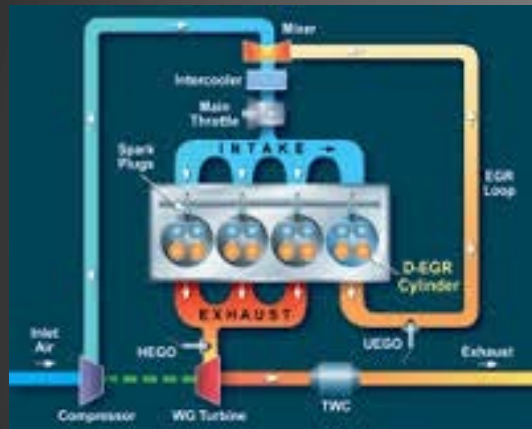
California Environmental Protection Agency

 **Air Resources Board**

Overview

- ▶ Technologies Evaluated
- ▶ Deployment Challenges and Issues
- ▶ Current Projects
- ▶ Other Alternative Fuels
- ▶ Contacts

Technologies Evaluated



Woodward Emissions Control Systems

Current NO_x Control Technology for Natural Gas Vehicles

- ▶ 2010 heavy-duty engine NO_x standards:
 - 0.20 g/bhp-hr
- ▶ Stoichiometric engine with three-way catalyst (TWC)
- ▶ Cooled exhaust gas recirculation (EGR)

Technologies Evaluated

- ▶ Advanced Engine Control Technologies
 - Port Fuel Injection
 - Advanced Air to Fuel Ratio Control
 - Cooled EGR
 - Dedicated EGR
 - Faster Light-off
- ▶ Advanced Aftertreatment Technologies
 - Advanced TWC
 - Close-coupled Light-off
 - Ammonia Slip Catalyst

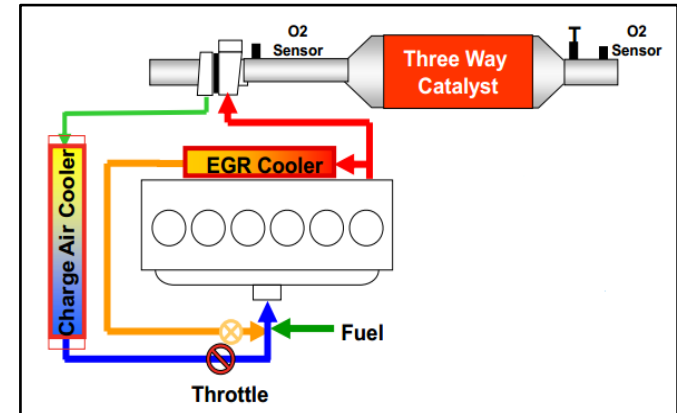
Advanced Engine Control Technologies

- ▶ Port Fuel Injection
 - Provides homogeneous charge, enabling higher compression ratio, increasing efficiency
 - Technology readiness: in demonstration
- ▶ Advanced Air to Fuel (A/F) Ratio Control
 - Improve A/F ratio control to maximize catalytic converter efficiency
 - Use of more accurate zirconia-based wideband O₂ sensor
 - Technology readiness: in demonstration

Advanced Engine Control Technologies

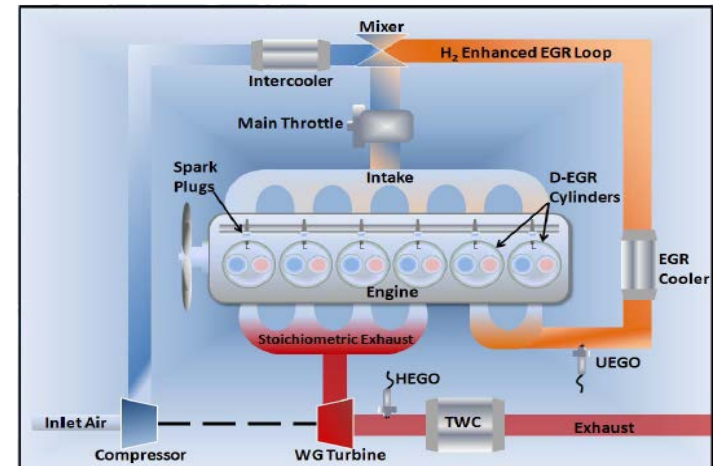
► Cooled EGR

- Redirect part of exhaust to intake air and EGR cooler
- Reduce engine combustion temperature, reducing NO_x
- Technology readiness: in production



► Dedicated EGR

- Operate one or more cylinders in rich mode
- Route rich exhaust to intake manifold of the lean burn cylinders
- Increase CO, H₂ to other cylinders, improving methane combustion
- Increased EGR, reducing NO_x
- Technology readiness: pilot



Advanced Engine Control Technologies

▶ Faster Light-off Strategies

Warm up TWC more quickly for efficient reduction of NO_x

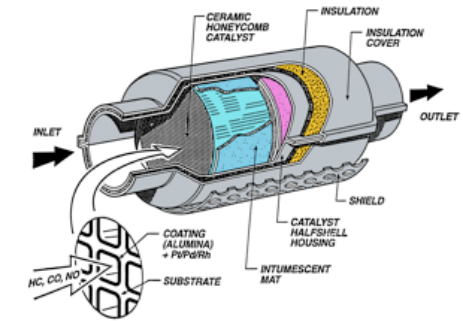
- Turbocharger Bypass
- High Engine Idle Speed
- Retarded Ignition Timing
- Rich and Lean Cylinders

▶ Technology readiness: in demonstration

▶ Above strategies may increase fuel consumption

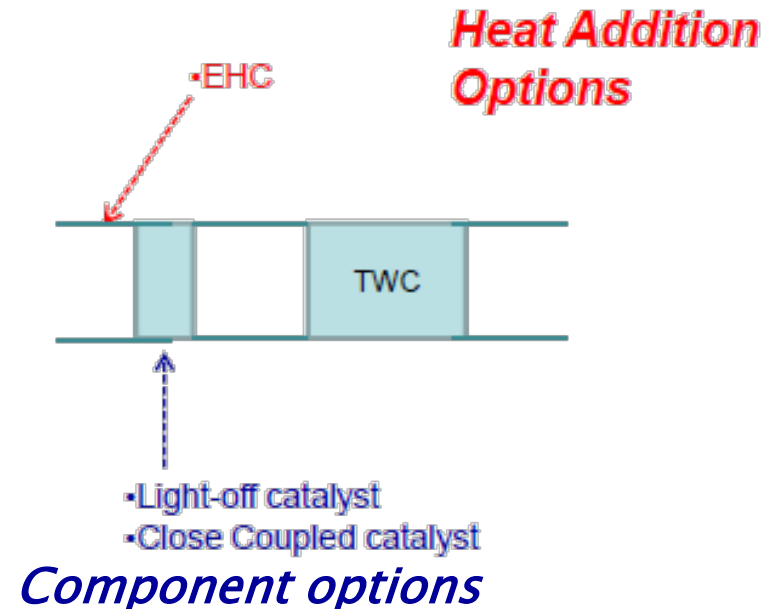
Advanced Aftertreatment Control Technologies

- ▶ Advanced Three Way Catalyst
 - Catalyst Formulation
 - Substrate Design
 - High Oxygen Storage Material
 - Substrate Coating Process
 - Exhaust System Thermal Management
- ▶ Technology readiness: in demonstration

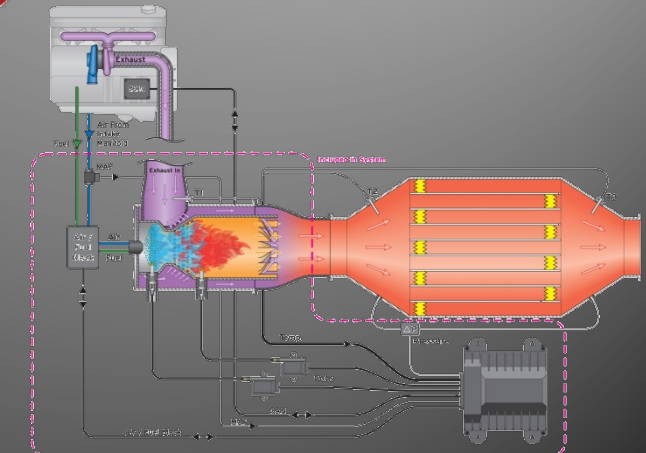
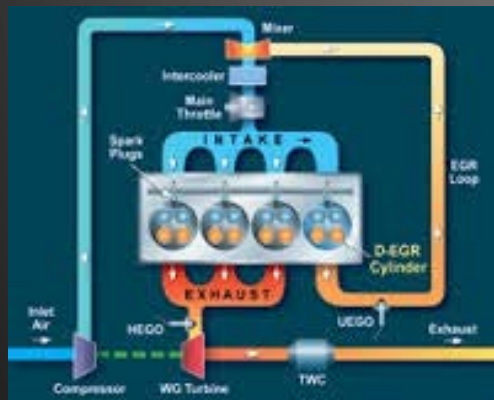
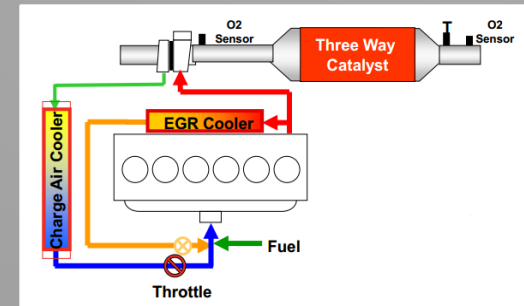
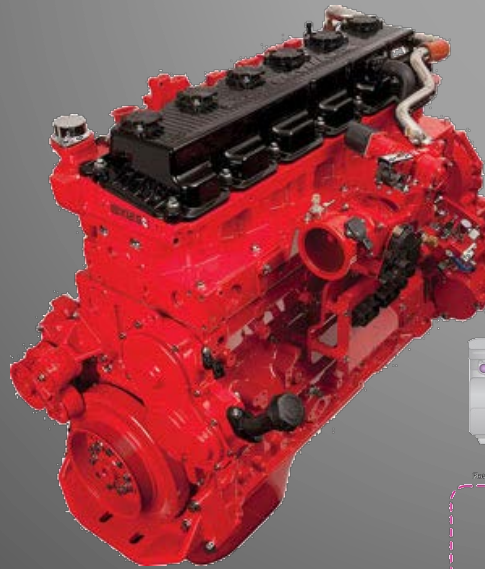
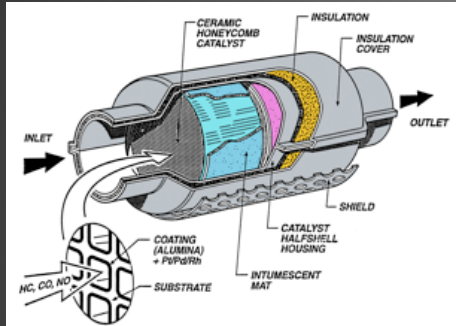


Advanced Aftertreatment Control Technologies

- ▶ Close Coupled Light-Off
 - TWC located near engine exhaust valves to reduce heat loss and accelerate catalyst heating
- ▶ Ammonia Slip Catalyst
 - Controls NH_3 emissions to below 10ppm in exhaust
- ▶ Package under study in ARB/SwRI project



Approaches to NOx Control

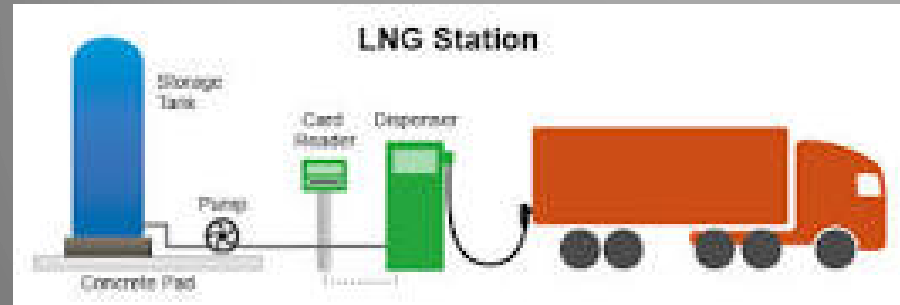
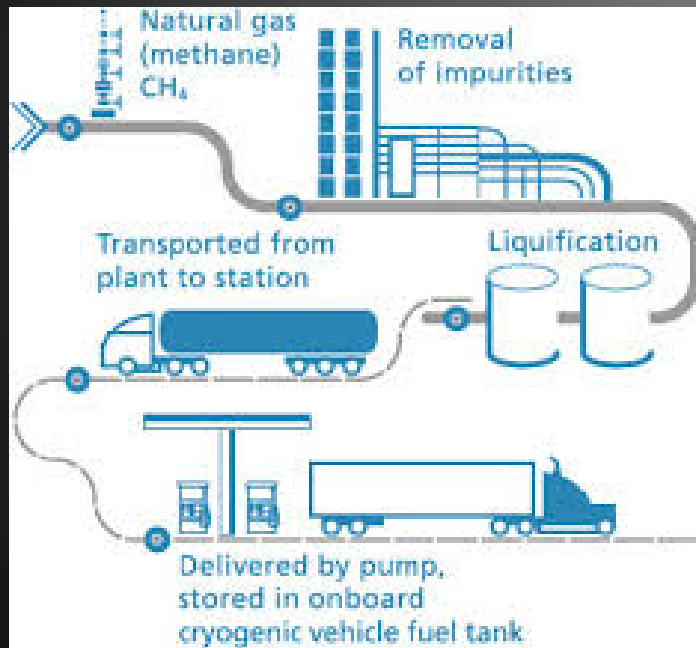


Woodward Emissions Control Systems

Low-NOx Standard

- ▶ ARB adopted optional low NOx standard
- ▶ ARB funding research to demonstrate feasibility
 - 0.02 g/bhp-hr
- ▶ Systems integration is critically important
 - Engine management and aftertreatment system control needs to accommodate engine use variability for in-use performance and emissions control
 - Address in-use emissions to ensure standards are achieved in real world

Deployment Challenges/Issues



Natural Gas vs Diesel Trucks

► Advantages over diesel

- Lower PM emissions, does not require DPF
- NO_x aftertreatment with TWC, no SCR required
- Price of natural gas lower than diesel
- Price at the pump per diesel gallon equivalent less impacted by NG market fluctuations than diesel

► Disadvantages

- Lower energy density – lower range per fueling
- Increased weight due to heavier fuel tanks
- Limited product (power/torque) offerings
- Fuel economy lower by 10% to 15%

Natural Gas vs Diesel Trucks (cont'd)

- ▶ Incremental capital cost (including tank package) \$30,000 to \$80,000^a
 - Tank package ~65% of the incremental cost
- ▶ Incremental maintenance cost: 1–2 cents/mile^b
- ▶ With current low natural gas prices, the payback period is between 3 to 6 years^c
 - As demand increases, incremental cost of natural gas vehicle is expected to decrease, resulting in a shorter payback period

^aTIAX Natural Gas Vehicle Market Analysis, TIAX, 2012

^bTransport Topics Special Report, 12/2013

^cBased on CNG: \$2.43/DGE; LNG:\$2.97/DGE; Diesel \$4.10/gal

Deployment Challenges

- ▶ Refueling infrastructure
 - Limited reach and number of publically accessible refueling stations
 - 490 CNG stations
 - 57 LNG stations
 - 7000+ Diesel stations (for comparison)
 - resulting in a shift or day operation range per fuel charge
- ▶ Methane as a greenhouse gas

Distribution of Natural Gas Fueling Stations



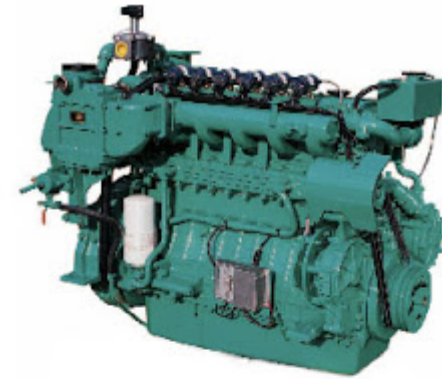
Publically Accessible Natural Gas Stations (Heavy Duty)

- CNG (490)
- LNG (57)

Methane Emissions

- ▶ Atmospheric Methane Global Warming Potential
 - 21 times that of CO₂ (100 year horizon)
 - Average lifetime 12 years
- ▶ EPA inventory: 6.186 million metric tons of methane annually by natural gas systems^a
- ▶ HD GHG Phase 1, methane FTP tail pipe limits:
 - 0.10 g/bhp-hr (same as diesel)
- ▶ Natural gas engine methane emissions often much higher than diesel engines'

Current Projects



Current Projects – Engine/Vehicle

- ▶ South Coast AQMD, NREL and SwRI to develop a low NO_x natural gas engine
 - Project started: 2006
 - Convert 11L Doosan Infracore lean-burn engine to 11L stoichiometric engine
 - Will include advanced ignition system, cooled EGR, dedicated EGR, optimized in-cylinder geometry
 - Target 0.05 g/bhp-hr NO_x, 15% reduction in CO₂ emissions from 2010 diesel engines
 - Engine development nearing completion
 - Test to be conducted on articulated tandem bus by end of 2015

Current Projects – Engine/Vehicle

- ▶ South Coast AQMD (SCAQMD), Cummins Westport and Cummins Inc.
 - Project started: 2013
 - Develop ultra-low NOx emission 8.9L and 15L natural gas engines
 - Target 0.02 g/bhp-hr NOx
 - Test system durability through engine to vehicle chassis integration
 - Integrated project to be placed in commercial service for one year and performance evaluated
 - Project completion by end of 2016

Current Projects – Engine/Vehicle

- ▶ ARB, SwRI to demonstrate maximum NO_x reduction possible from 11L heavy-duty natural gas engine
 - Project Started: 2013
 - Will use engine tuning practices, thermal management and aftertreatment strategies
 - Target NO_x emissions 0.02 g/bhp-hr with minimal or no GHG penalty
 - Project completion by mid-2016

Current Projects – Fueling Infrastructure

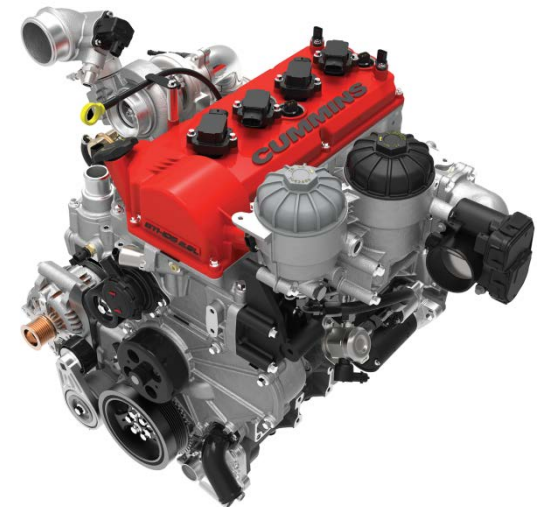
- ▶ SCAQMD project installs new LNG station in Las Vegas
 - Project started: 2009
 - Joint project between SCAQMD, UPS, Eastern Sierra Regional Clean Cities Coalition, Southern California Clean Cities Coalition
 - Creates LNG corridor from South Coast region to Salt Lake City
 - Publicly accessible LNG station in Las Vegas
 - Objective: extend Interstate Clean Transportation Corridor throughout western US

Other Alternative Fuels



Other Alternative Fuels: E85

- ▶ Fuel blend consisting of 85% ethanol, 15% gasoline by volume
- ▶ Ultra-Low Carbon Powertrain Program (ETHOS)
 - Cummins project, in partnership with CEC
 - Development of 2.8L E85 downsized engine
 - Power: 250hp; Torque: 450lb-ft, 4 Cylinders
 - Targeted for Class 4-6 vehicles
 - Integrated stop-start system
 - CO₂ reduction from lower carbon fuel
 - 10-20% with CA-grown corn ethanol
 - Vehicle Demonstration
 - 2000 miles completed on two test routes



Other Alternative Fuels: DME

- ▶ Dimethyl Ether (DME) is a synthetic fuel manufactured from syngas generated from natural gas or biomass.
- ▶ Stored as liquid under moderate pressure in steel tank, not cryogenic
- ▶ Volvo D13–DME engine
 - Compression ignition, 425hp, 1750 lb–ft
 - No DPF needed
 - Road–tested, about 650,000 highway miles
 - Limited production beginning 2015



Conclusions and Contacts



Success with Natural Gas Fueling

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Conclusion

- ▶ Optimistic natural gas engines can meet a 0.02 g/bhp-hr standard, relatively quickly
 - Current NOx certification levels with conventional TWC: 20% to 75% below 0.2 g/bhp-hr
- ▶ Research in progress to demonstrate low NOx emissions
- ▶ Vehicle cost, refueling Infrastructure, and methane emissions still impact the adoption of natural gas engines
- ▶ Other alternative fuels, such as E85 and DME, can also reduce GHG emissions while keeping criteria emissions low

Contacts

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- ▶ Submit comments by Oct. 1 to:
<http://www.arb.ca.gov/msprog/tech/comments.htm>