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

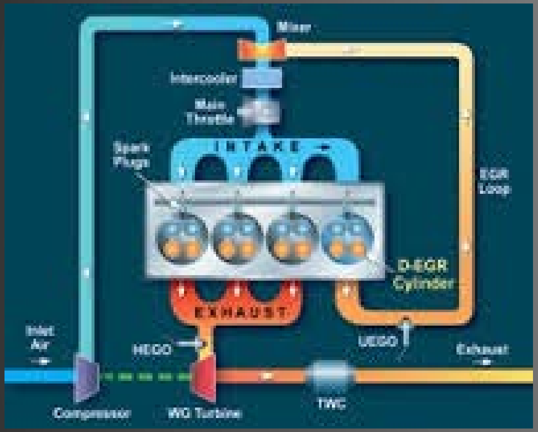
September 2, 2014
Sacramento, California

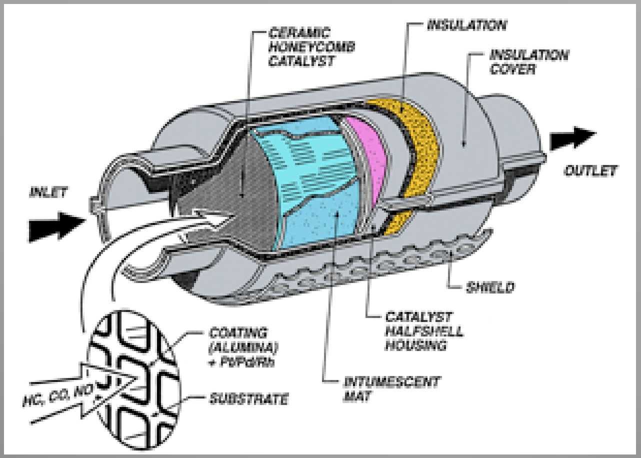
California Environmental Protection Agency
Air Resources Board

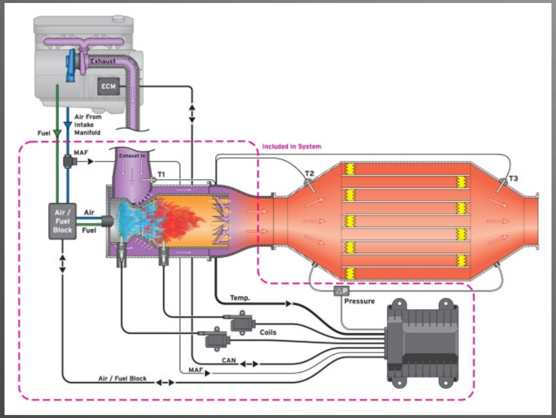
Overview

- 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 NOx standards:
  - 0.20 g/bhp-hr
- Stoichiometric engine with three-way catalyst (TWC)
- Cooled exhaust gas recirculation (EGR)

Technologies Evaluated

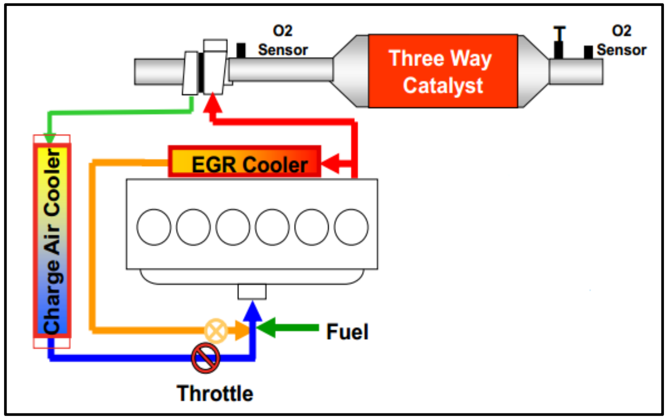
- Advanced Engine Control Technologies
  - Port Fuel Injection
  - Advanced Air to Fuel Ratio Control
  - Cooled EGR
  - Dedicated EGR
  - Faster Light-off
- Advanced Aftertreatment Technologies
  - Advanced TWC
  - Close-coupled Light-off
  - Ammonia Slip Catalyst

Advanced Engine Control Technologies

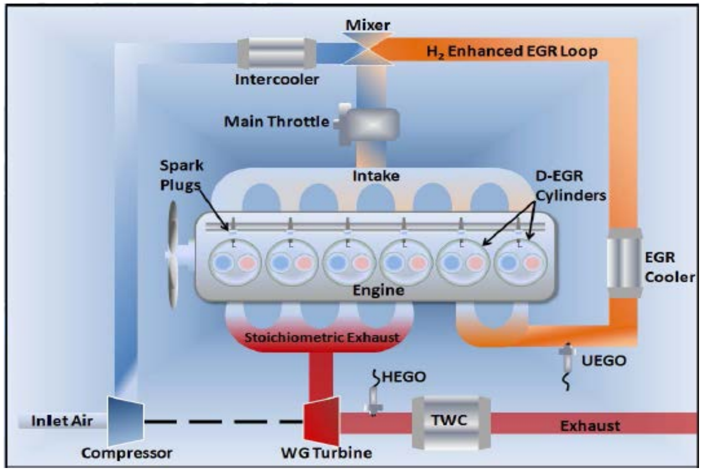
- Port Fuel Injection
  - Provides homogeneous charge, enabling higher compression ratio, increasing efficiency
  - Technology readiness: in demonstration
- Advanced Air to Fuel (A/F) Ratio Control
  - Improve A/F ratio control to maximize catalytic converter efficiency
  - Use of more accurate zirconia-based wideband O_2 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, H_2 to other cylinders, improving methane combustion
  - Increased EGR, reducing NO_X
  - Technology readiness: pilot



Advanced Engine Control Technologies

- Faster Light-off Strategies

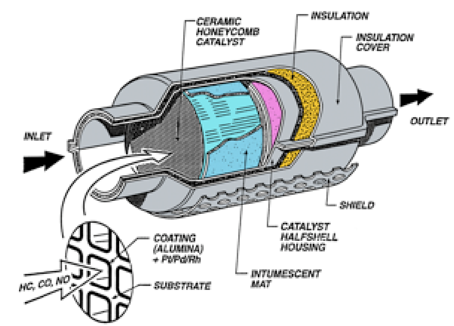
  Warm up TWC more quickly for efficient reduction of NO_X

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

- Technology readiness: in demonstration
- Above strategies may increase fuel consumption

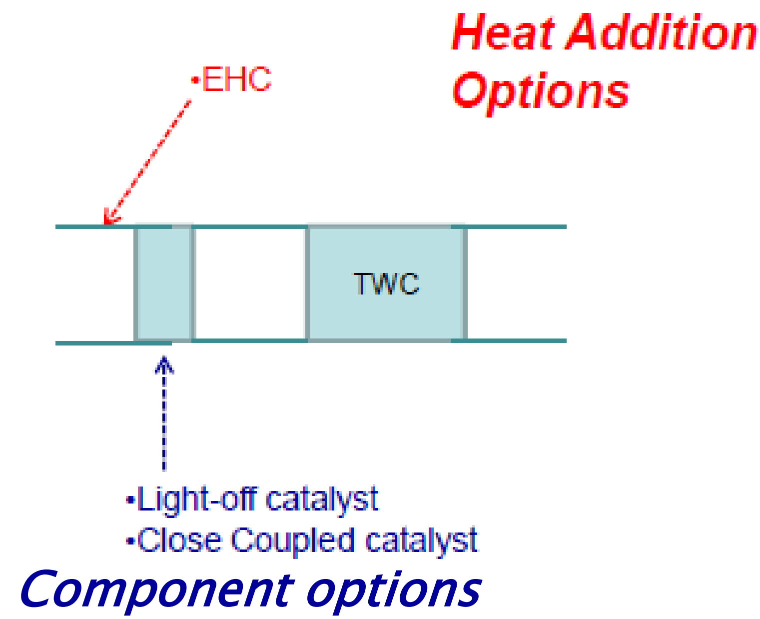
Advanced Aftertreatment Control Technologies

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

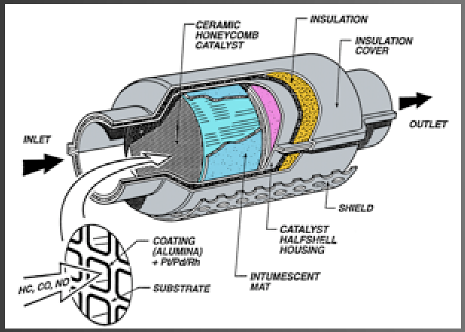


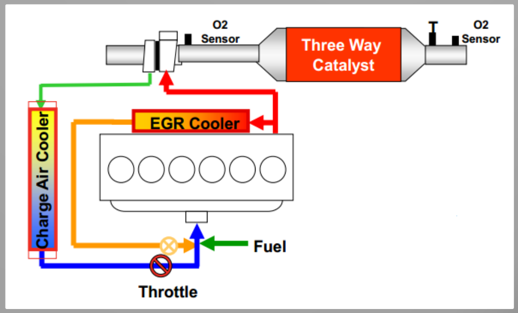
Advanced Aftertreatment Control Technologies

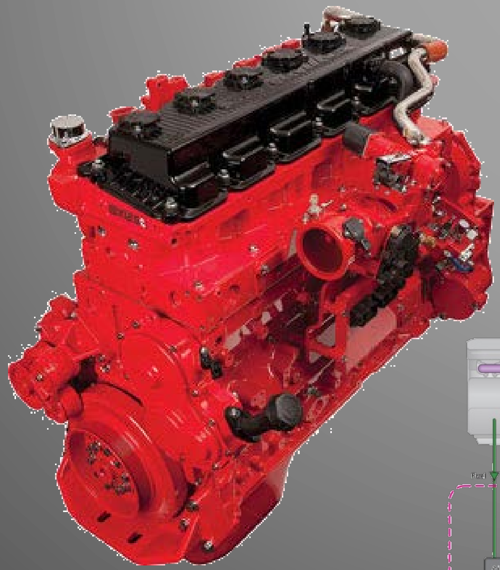
- Close Coupled Light-Off
  - TWC located near engine exhaust valves to reduce heat loss and accelerate catalyst heating
- Ammonia Slip Catalyst
  - Controls NH_3 emissions to below 10ppm in exhaust
- Package under study in ARB/SwRI project

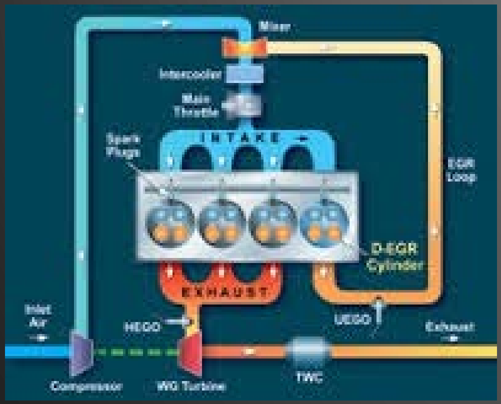


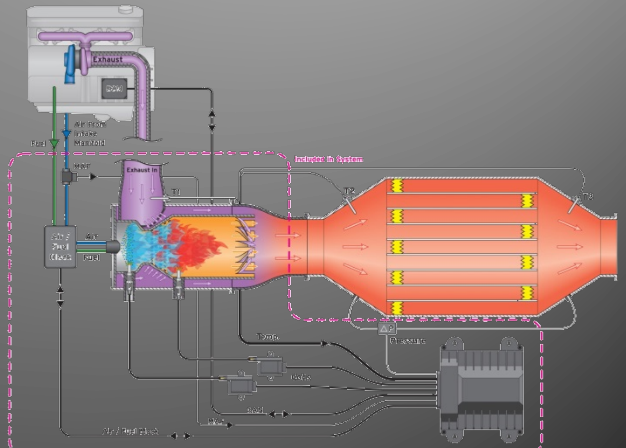
Approaches to NOx Control









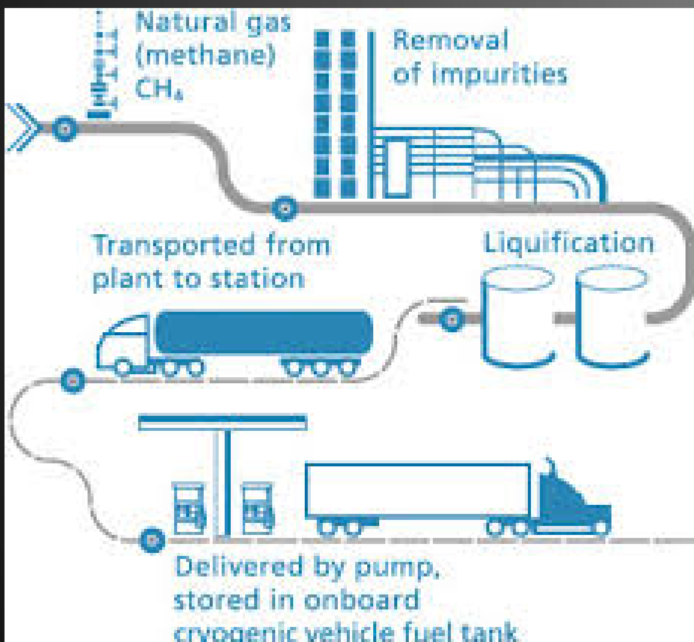


Woodward Emissions Control Systems

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

[a]TIAX Natural Gas Vehicle Market Analysis, TIAX, 2012
[b]Transport Topics Special Report, 12/2013
[c]Based 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 CO_2 (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'

[a]Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2012, EPA 430-R-14-003, April 2014

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 CO_2 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

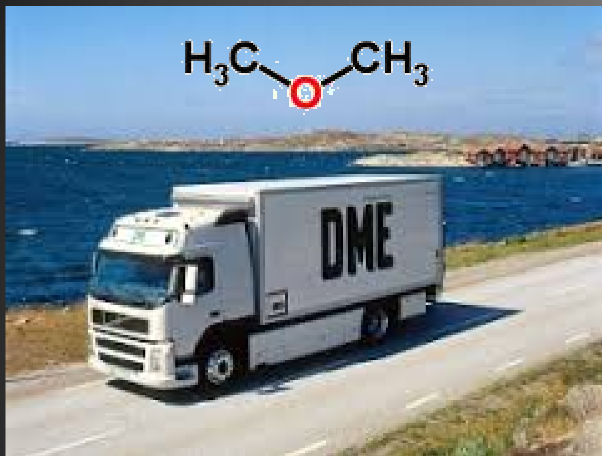
Current Projects – Engine/Vehicle

- 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
  - CO_2 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

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