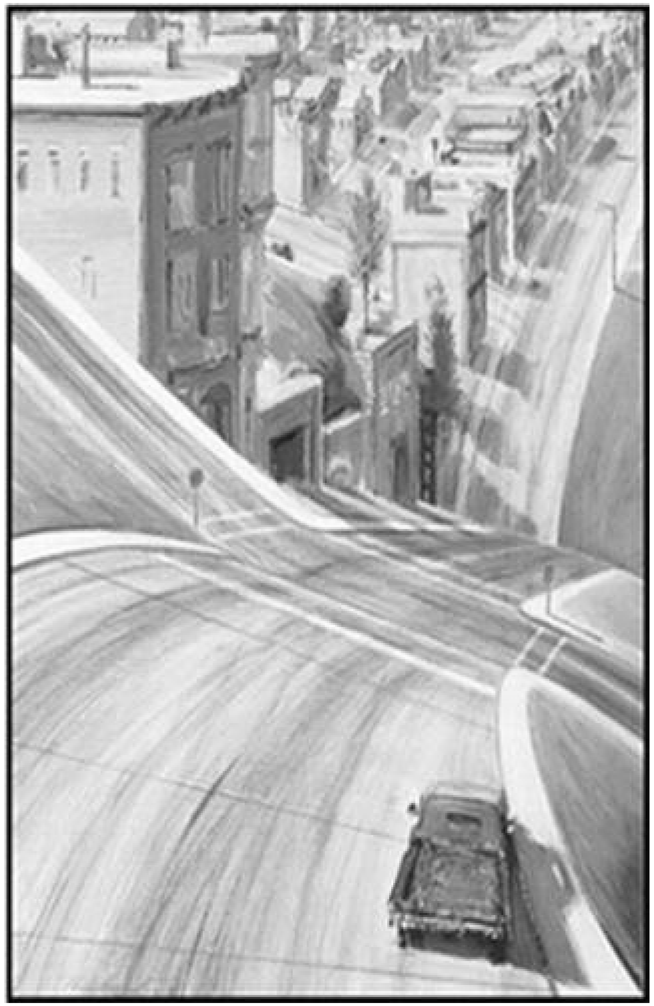
Institute of Transportation Studies
University of California, Davis



Hydrogen Enriched Natural Gas Technology

Marshall Miller

UC Davis

August 29, 2006

Outline

- Emissions regulations (Motivation)
- Hydrogen – Natural gas Blends description
- Competing Technologies / Technical Issues
- Data
- HCNG (defined later) Programs
- Codes and Standards
- Properties of HCNG
- Transition to future technologies
- Summary

Engine Emissions Regulations in US

- US Environmental Protection Agency (EPA) regulates engine emissions

- In California, California Air Resources Board (CARB) regulates engine emissions (stricter than US EPA)

- Both CARB and US EPA have proposed very strict heavy duty engine emissions for the near future (2007 and 2010).

CARB Transit Bus Emissions Standards

Year	HC	CO	NO_X	PM	Formaldehyde
1985-1986	1.3	15.5	5.1	NA	NA
1988-1990	1.3	15.5	6	0.6	NA
1991-1993	1.3	15.5	5	0.1	NA
1994-1995	1.3	15.5	5	0.07	NA
1996-2003	1.3	15.5	4	0.05	NA
2004-2006	2.4 (plus NO_X)	15.5	2.4 (plus NMHC)	0.05	NA
2007	0.05	5	0.2	0.01	0.01

Hydrogen / Natural Gas Blends

- Blends with < 20% hydrogen are called hythane®

  (a registered trademark of Hydrogen Components Inc.)
- Blends with > 20% hydrogen are called HCNG
- Hythane® NO_X reductions are limited to 30-50% but physical changes to bus are required
- HCNG must be used to reduce engine out emissions by > 50% (testing shows > 95% reductions from 2003 standard). Requires physical to engines.

Hythane® Programs

- Sunline Transit, CA USA has run hythane® buses since 2001 (L-10 buses)

- Recent program
  - 2003 Cummins Westport supplied two B gas plus engines (230 hp) to operate on hythane®
  - Buses ran ~ 30,000 miles

Future Hythane® Programs

- Westport will upgrade the 8.3 L C plus engine to hythane® as part of British Columbia's Hydrogen Highway program in Canada.
- Sunline transit has discontinued operating the B plus hythane® buses and plans to run C plus hythane® buses in the future.

Hythane® Data

- Testing shows ~ 50% reduction in NO_X from standard CNG.
- Hydrogen usage is ~ 1.25 kg H_2 / 100 km traveled.
- 15% reduction in storage capacity (energy stored) due to 20% H_2.

(SAE 2004-01-2956 : Hydrogen Blended Natural Gas Operation of a Heavy Duty Turbocharged Lean Burn Spark Ignition Engine)

HCNG Usage

- HCNG is a blend of hydrogen and natural gas with 21-50% by volume hydrogen.
- HCNG is blended, compressed and stored in the same container on-board the vehicle.
- With a properly tuned engines vehicles can achieve extremely low emissions and increases in thermal efficiency.

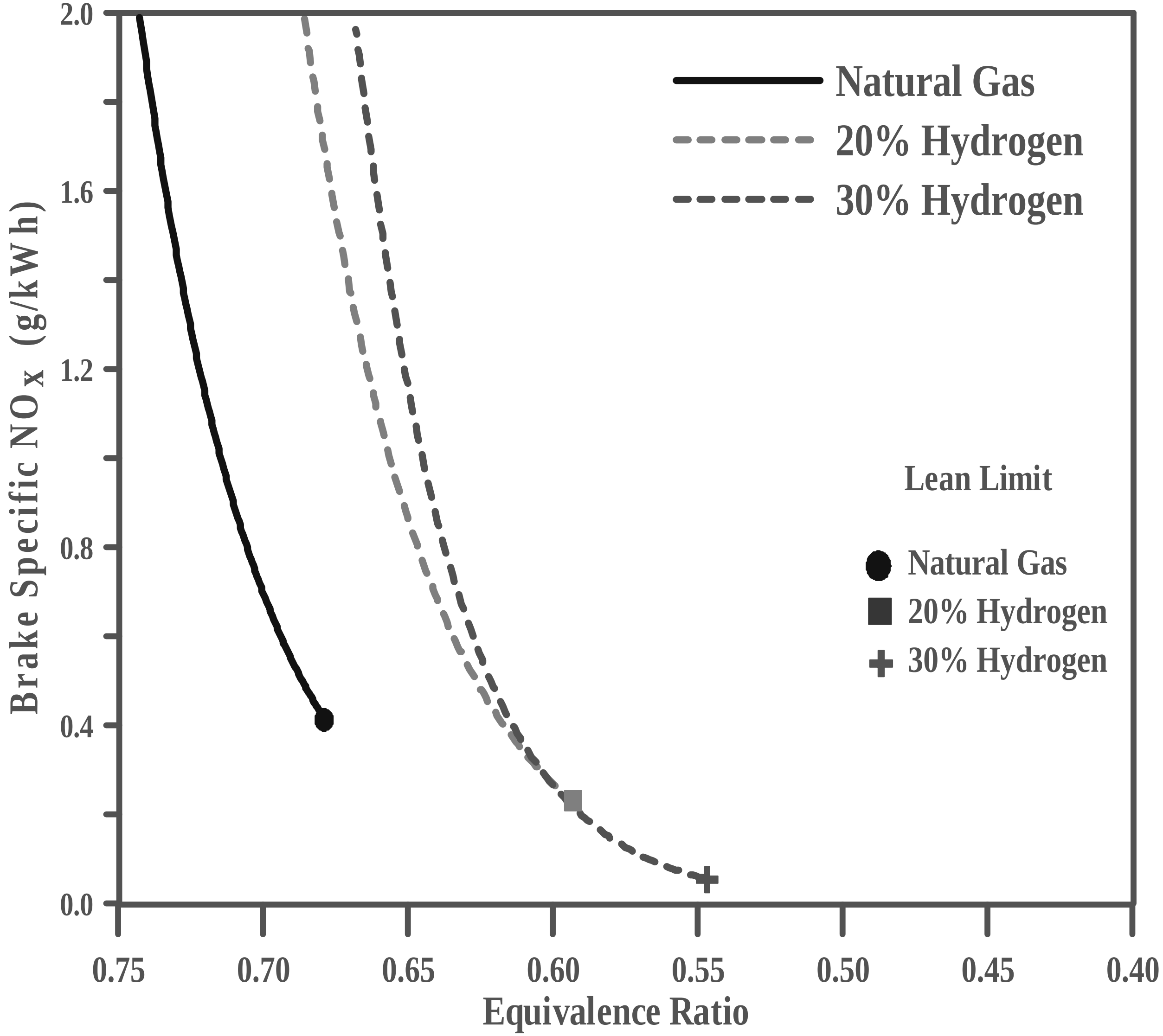
HCNG History

- Research on HCNG fuels was started in 1993 at the Florida Solar Energy Center by Kirk Collier and Neal Mulligan.
- The term HCNG was first coined in 1996 paper of Collier and Mulligan.
- Note: HCNG is sometimes used to refer to blends with < 20% hydrogen

How Does HCNG Achieve Low Emissions?

- HCNG engines operate with charge dilution (increased heat capacity of air-fuel mixture)
- Charge dilution can be lean burn (excess air) or EGR (Exhaust Gas Recirculation)
- HCNG engines operate in regimes that produce very low NO_x (lower combustion temperatures)
- Hydrogen in **H**CNG is the flame enhancer that promotes combustion with a large amount of charge dilution.

Why 30% Hydrogen?



What is “Correct” Hydrogen Percentage to Use?

- Increasing hydrogen %
  - Reduces NO_X
  - Reduces power (volume of fuel has lower energy content)
  - Increases cost (hydrogen costs more)
- 30% hydrogen
  - Reaches knee of NO_X curve
  - More hydrogen increases cost and requires extra design to recoup lost power

HCNG Applications

- Transit buses
- Medium duty trucks
- Light duty vehicles
  - Can reduce CO_2 emissions if renewable hydrogen is used
  - Can reduce natural gas usage
  - No benefit for emissions compared to conventional LDVs

Competing Technologies

- Battery electric and fuel cell vehicles
- Stoichiometric Natural Gas
- Diesel
- Gasoline Hybrid
- Hydrogen ICE Hybrid

Battery Electric and Fuel Cell Buses

- Battery Electric and Fuel Cell Buses can meet CARB 2007 and EPA 2010 standards
- Battery Electric Buses
  - Range is too short
  - Refueling times are too long
  - Not practical for transit
- Fuel Cell Buses
  - Buses are much too expensive (~3M $US)
  - Technology not yet mature

Stoichiometric Natural Gas

- Expected to have reduced fuel economy over lean burn
- Catalyst replacement durability/cost
- Excessive exhaust and catalyst heat
- Can meet pending emissions regulation

Diesel

- Not a direct path to hydrogen or fuel cells
- Engines have not met the pending 0.2 g/hp-hr NO_X standard, but PM traps and SCR (selective catalyst reduction with urea) is expected to meet regulations
- Engine manufacturers have stated that they will not have diesel engines capable of meeting the CARB 2007 standard before 2010

Gasoline Hybrid

- Additional cost over direct drive
- Additional training required
- Not a direct path to hydrogen or fuel cells
- Can meet pending regulation

Hydrogen ICE Hybrid

- Additional capital cost over direct drive
- Additional fuel cost over HCNG
- Additional training required
- Can meet pending regulation

Technical Challenges
HCNG

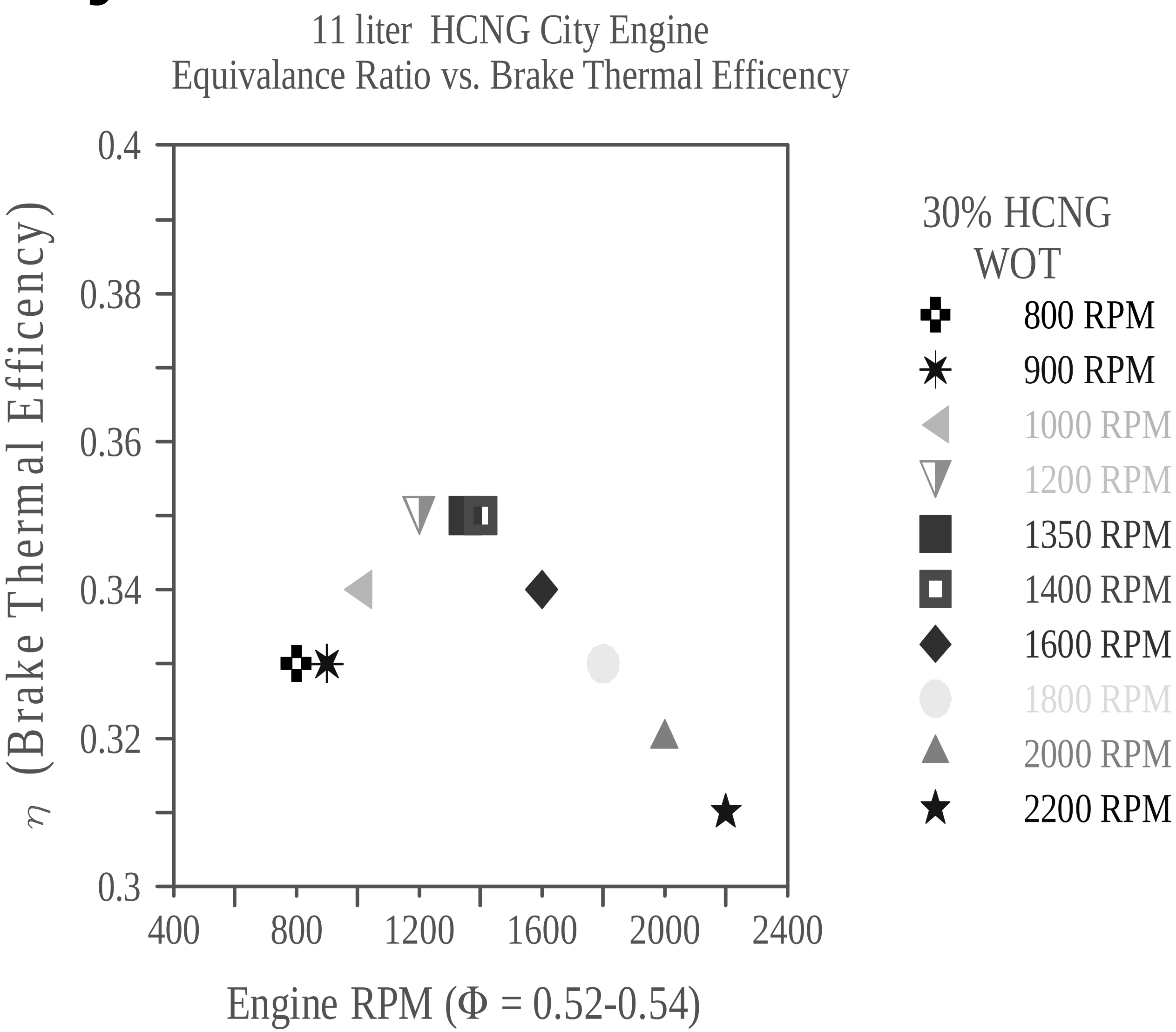
- Providing equivalent power for the specific application
- Low NO_X emissions require large amounts of charge dilution
- Lean Burn
  - Results in best fuel efficiency
- Full NO_X reduction potential requires quiescent combustion

Solutions to Technical Challenges HCNG

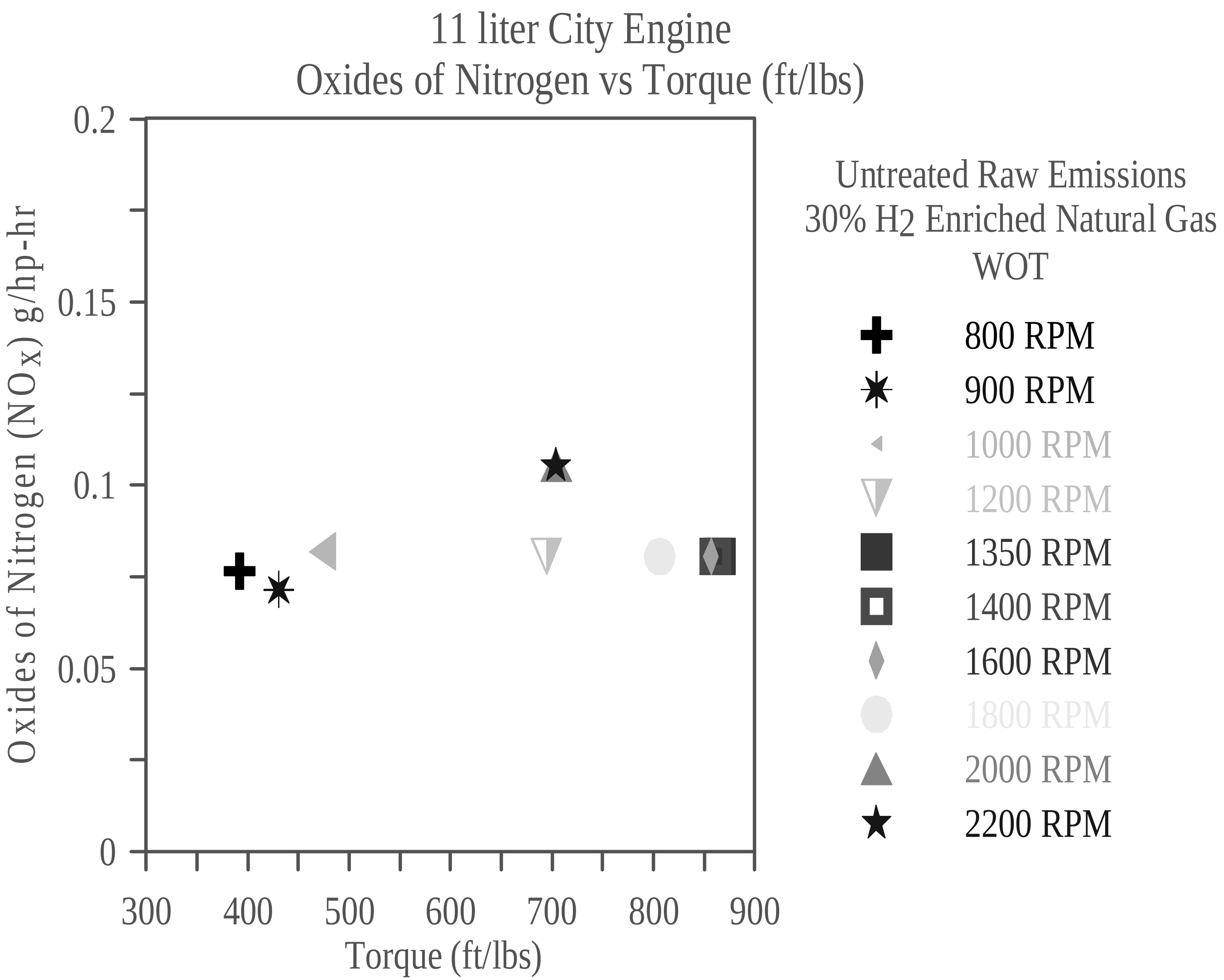
- Increase turbo-charging pressure to recuperate lost power

- Re-design cylinder heads for quiescent combustion and increased air flow. Present designs recoup all lost power.

Brake Thermal Efficiency



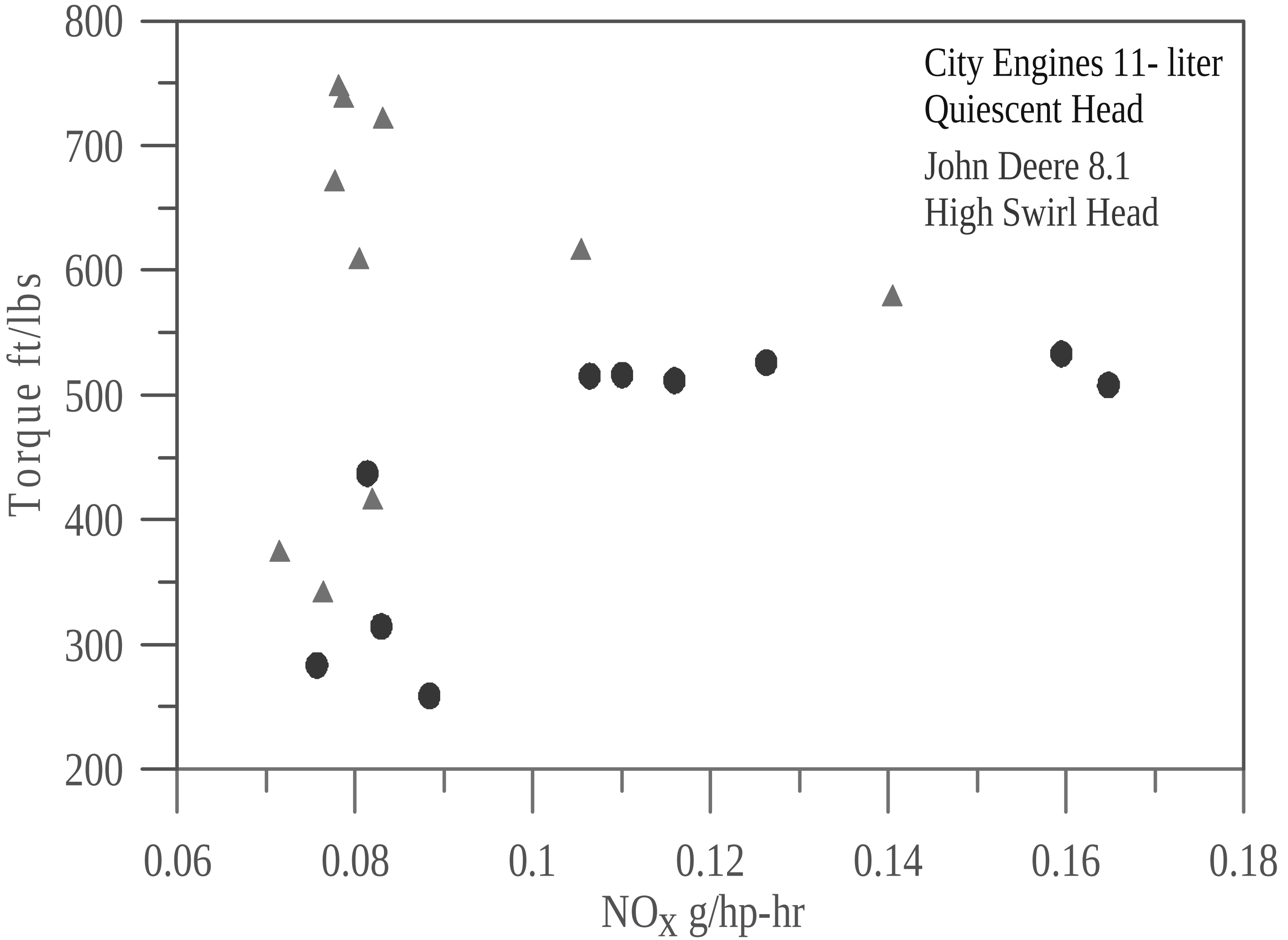
NO_X Emissions



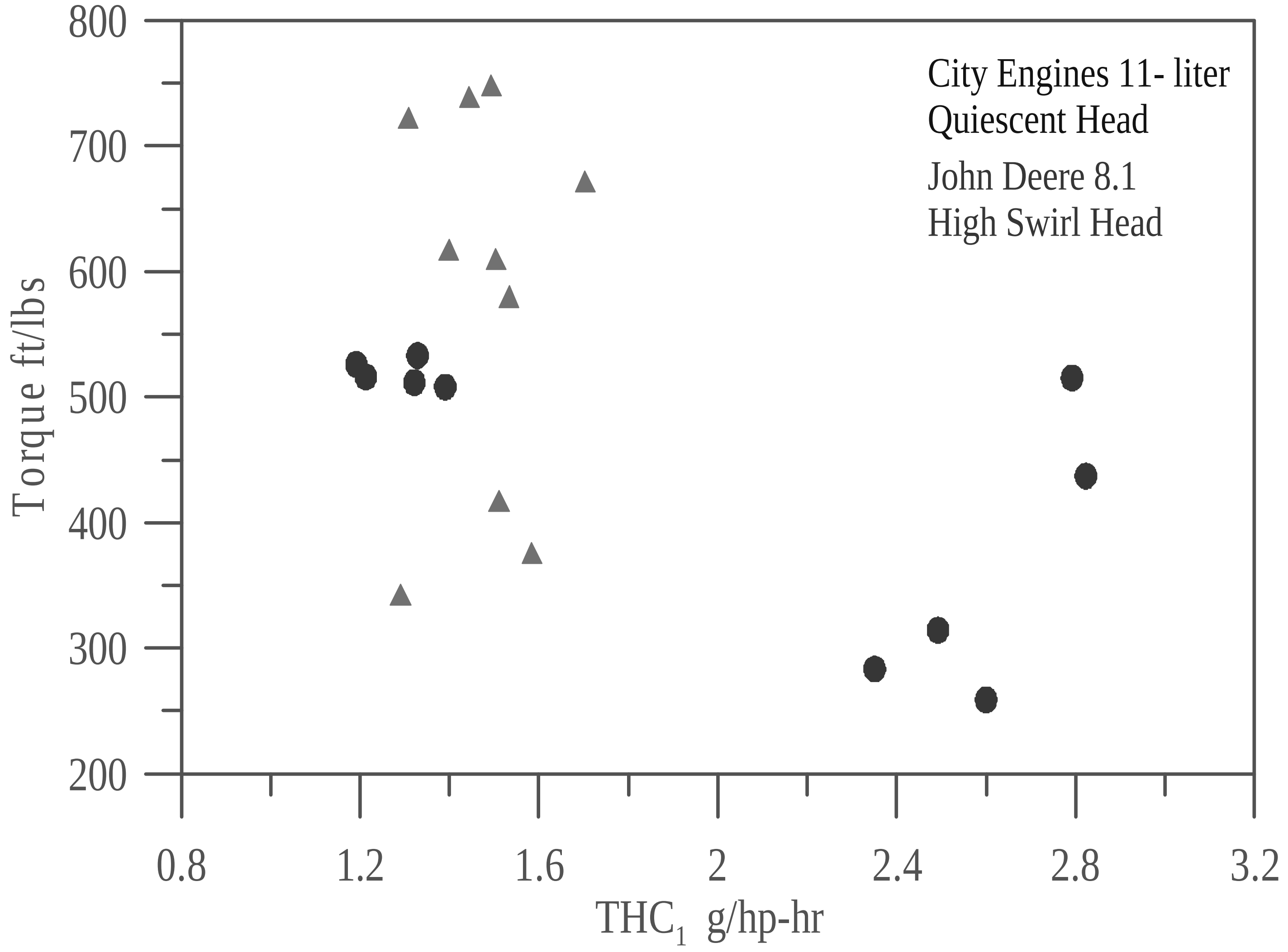
Quiescent Combustion

- Engines with both high swirl and low swirl cylinder heads have been modified to operate on HCNG fuel.
- Empirically, low swirl engines allow HCNG engines to operate with lower NO_X (not clear why this is so)
- Data in the following slides compare City Engines 11 L engine (low swirl) and John Deere 8.1 L engine (high swirl)

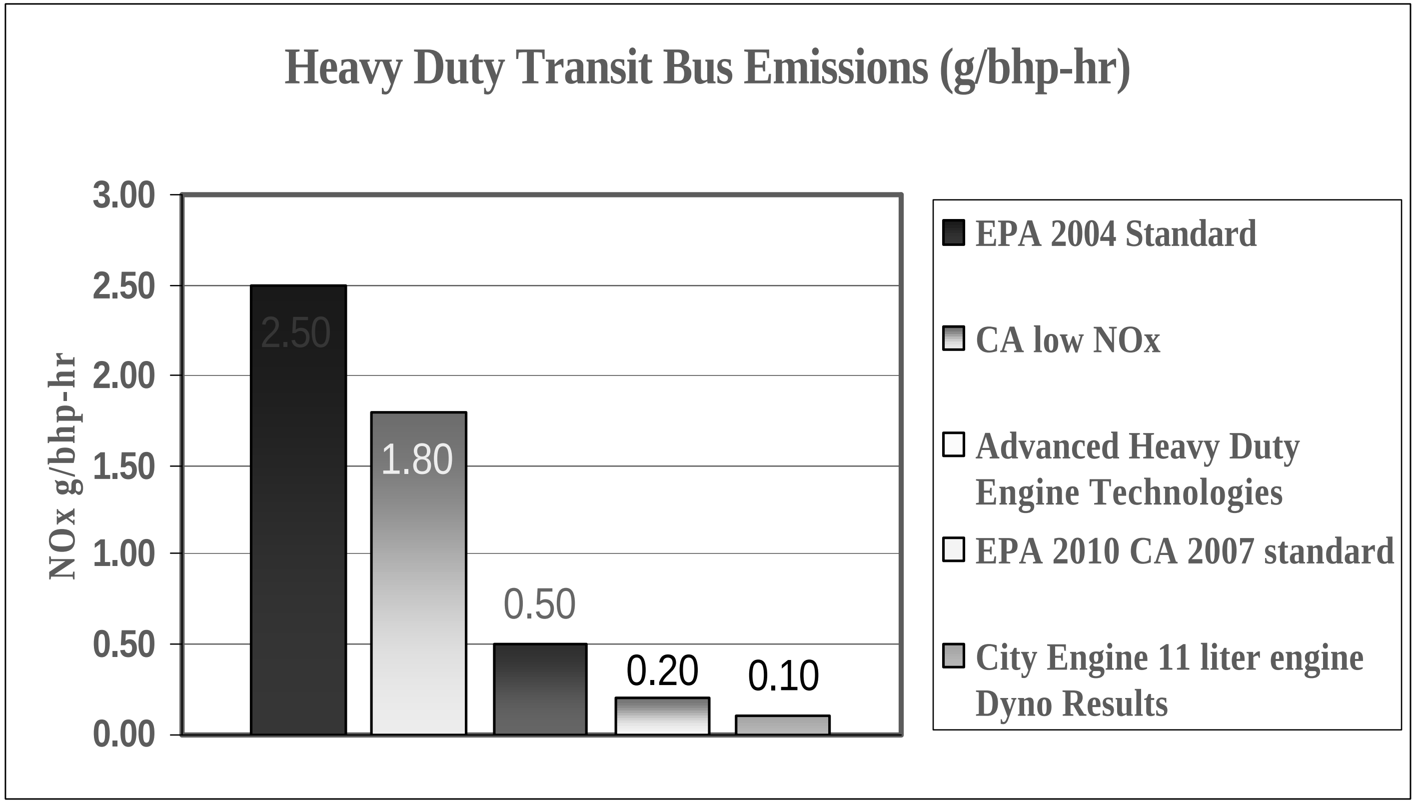
NO_X Comparison



Total Hydrocarbons Comparison



Transit Bus Emissions



HCNG Programs

- Las Vegas, NV USA
  - Program started 1999
  - 10 pickup trucks (F-150's) 5.4 L supercharged engine
- Penn State
  - Program starts 2006
  - Transit bus and van (5.4 L engine and Doosan 11 L (GE12TI)
- Canada
  - 2 pickup trucks running on 50% hydrogen HCNG

HCNG Programs

- UC Davis
  - Will run 2 transit HCNG buses
    - John Deere 8.1 L (high swirl)
    - Doosan 11 L (low swirl)
  - Station Infrastructure
    - Supports 3600 psi HCNG and 5000 psi hydrogen
    - 1500 gallon Cryogenic tank storage for LH_2
    - Natural gas and hydrogen blended at high pressure at the fueling pump

HCNG Bus

Cryogenic Tank

Hydrogen Series 100 Dispenser

HCNG Dispenser

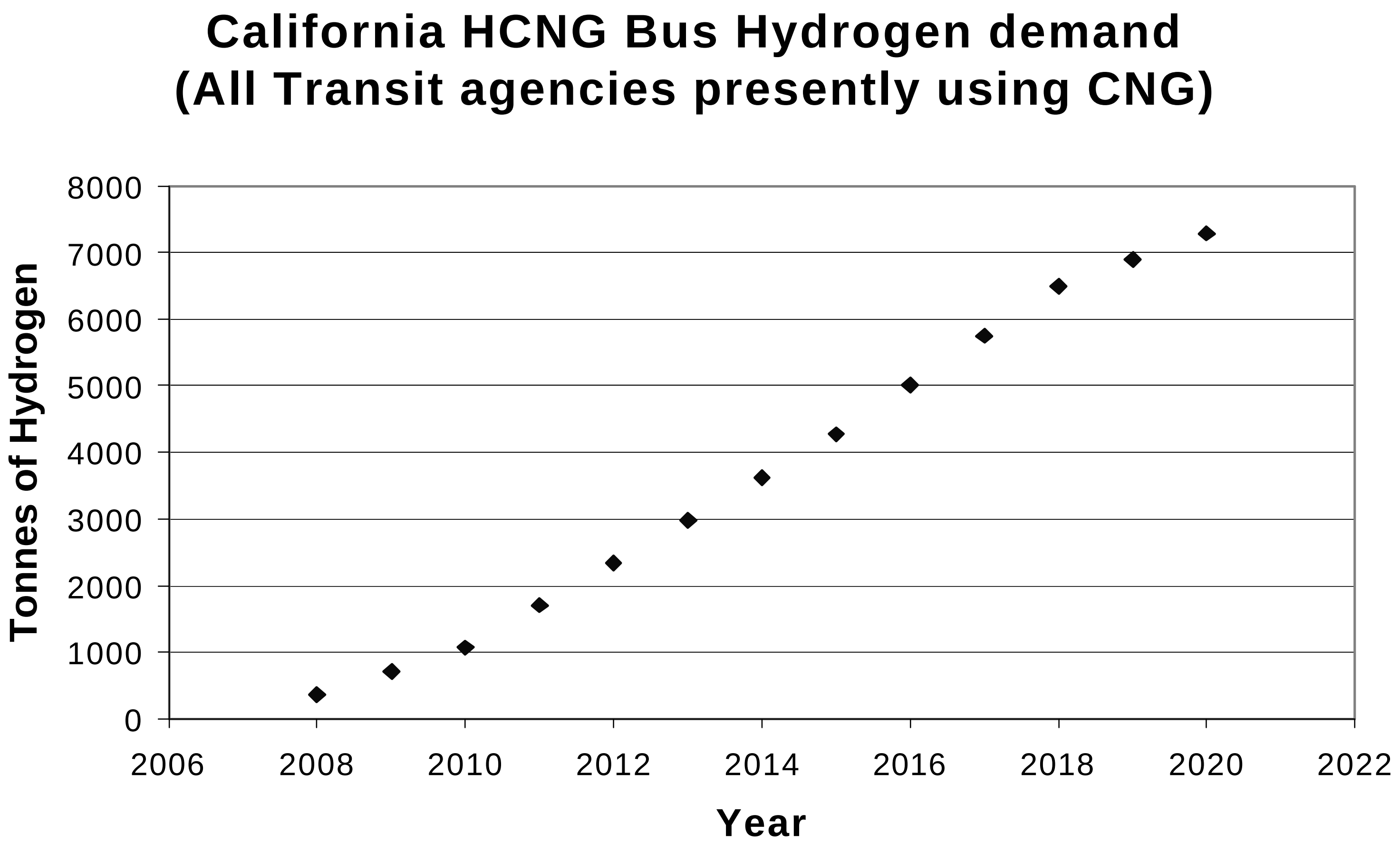
Codes and Standards (C&S)

- There are C&Ss in place for industrial natural gas use, natural gas fueling stations, and natural gas vehicles.
- There are some C&Ss for hydrogen stations and vehicles. Others are being written
- There are no C&Ss for HCNG.
- In US HCNG programs have used the natural gas and hydrogen C&Ss to permit stations

US Codes and Standards (C&S)

- NFPA (National Fire Protection Association) 52 presently covers CNG and hydrogen fueling stations. Blends with < 20% hydrogen by volume are treated identically to CNG.
- SAE J2600 defines hydrogen nozzle standard. No such standard for HCNG. We use OPW LK3600 which is non-interchangeable with J2600 nozzles.
- Bus storage tanks identical to CNG tanks.
- More work necessary to define C&S for HCNG.

Hydrogen Usage (Tonnes/ year)



Calculated Properties of 30% HCNG

- 817 btu/ft^3 HHV (higher heating value)
- 737 btu/ft^3 LHV (lower heating value)
- 0.0458 lbs/ft^3 Density
- 122 ft^3 of HCNG = 1 therm or 100K btu' s
- 147 ft^3 of HCNG = 1 Gallon of Gasoline
- 170 ft^3 of HCNG = 1 Gallon of Diesel
- Flammable limits; 4.65% $_{lower}$ 19.7% $_{upper}$

30% HCNG energy storage at pressure

psig	GH_2 BTU/ft^3	NG BTU/ft^3	Total BTU/ft^3
500	3590	23195	26785
1000	7077	49382	56459
1500	10749	75495	86244
2000	14537	101359	115896
2500	18368	126884	145252
3000	22176	152012	174188
3500	25900	176657	202557
4000	29492	200663	230155
4500	32917	223767	256684

Partial pressure of hydrogen and natural gas in 30% HCNG

psig	GH_2 pp psig	NG pp psig
500	154	346
1000	322	678
1500	501	999
2000	687	1313
2500	878	1622
3000	1069	1931
3500	1259	2241
4000	1444	2556
4500	1623	2877

HCNG Buses
(Transition Strategy)

- Present transit: Diesel fleets with CNG fleets growing
- Present Problems: emissions, global warming gases, imported fuel dependence
- Future Solution: Hydrogen fuel cell buses
- Problems
  - 2 new technologies: Fuel cells and Hydrogen Infrastructure
  - high cost, fuel cell reliability questions

HCNG Buses
(Transition Strategy)

- How do we get from the present to Hydrogen fuel cell buses?
- HCNG fleets
  - significantly reduce emissions
- Hydrogen infrastructure
  - Transit agencies can prepare for introduction of fuel cell buses when they are both affordable and available

Stationary HCNG Engines

- HCNG engines can provide stationary power for various applications
- Landfills store waste materials and emit significant amounts of natural gas.
- Proposals to utilize landfill gas and add hydrogen to produce a clean burning power source and reduce landfill emissions
  - Reform landfill gas to hydrogen?
  - Landfill gases contain sulphur and Siloxane. These can be problems for engines and reformers.

Summary

- Proposed US heavy duty emissions standards for near future are VERY strict
- Only Stoichiometric CNG and HCNG are practical options for transit buses
- HCNG is economically competitive with Stoichiometric CNG and paves the way toward a hydrogen based future with fuel cell vehicles