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Results of Research Engine and Vehicle Drive Cycle Testing during Blended Hydrogen/Methane Operation

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NHA Annual Hydrogen Conference 2007
San Antonio/Texas

March 19th – 22nd 2007

DOE-Sponsors: Lee Slezak, Gurpreet Singh

U.S. Department of Energy

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- Argonne's Hydrogen Engine Approach
- Comparison of fuel properties
- Research engine testing
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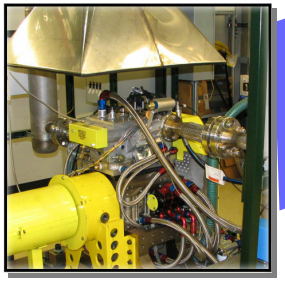
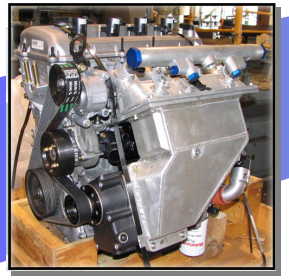
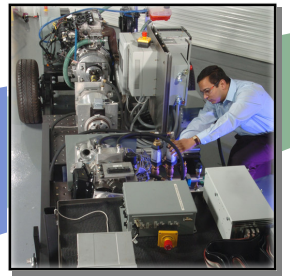
  - Combustion analysis
  - Efficiency evaluation
  - NO_x emissions results
- Vehicle Drive-Cycle testing
  - Vehicle specifications
  - Fuel economy comparisons
  - Emissions results
- Summary and conclusions

Motivation for blend testing
Pros and cons

- Blending hydrogen with methane reduces the demand for hydrogen
- Hydrogen offers unique combustion properties even in blended operation
- Improved on-board storage density

- Addition of methane causes formation of greenhouse gas emissions (CO_2)
- Running on hydrogen/methane blends results in formation of regulated emissions other then NO_x

Argonne's Hydrogen Engine Approach
Moving from Single-Cylinder Research to On-Road Application

- **DOE-Targets:**
  45 % BTE
  0.07 g/mile NO_x

Comparison of fuel properties
Liquid versus gaseous fuels

Parameter	Symbol	Unit	Diesel	Gasoline	Methane	H_2
Density	ρ	kg/m^3	830[I]	730-780[I]	0,72[I]	0,089[I] 71[II,III]
Stoichiometric air demand	L_{St}	kg_{air}/kg_{fuel}	14,5	14,7	17,2	34,3
Lower heating value	H_u	MJ/kg_{Kst}	42,5	43,5	50	120
Mixture calorific value[V]	H_G	MJ/m^3	3,83 3,83	3,82 3,82	3,4 3,76	3,2 4,53
Boiling temperature[III]	$T_{Boiling}$	°C	180-360	25-215	-162	-253
Ignition limits[IV]		Vol-% λ	0,6-5,5 0,5-1,3	1,0-7,6 0,4-1,4	5,3-15 0,7-2,1	4-76 0,2-10
Minimum ignition energy[III,IV,V]	$E_{Ignition}$	mJ	0,24	0,24	0,29	0,02
Self-ignition temperature	$T_{Ignition}$	°C	approx. 250	approx. 350	595	585
Diffusion coefficient[I,IV]	D	m^2/s	-	-	$1,9 \times 10^{-6}$	$8,5 \times 10^{-6}$
Quenching distance[III,IV,VI]		mm		2	2,03	0,64
Laminar flame speed[IV,V]	v_{lam}	cm/s	40-80	40-80	40	200
Carbon content	C	Mass-%	86	86	75	0

[I] at 1,013 bar und 0 °C [II] at –253°C [III] at 1,013 bar [IV] in air [V] λ=1 [VI] at 20°C

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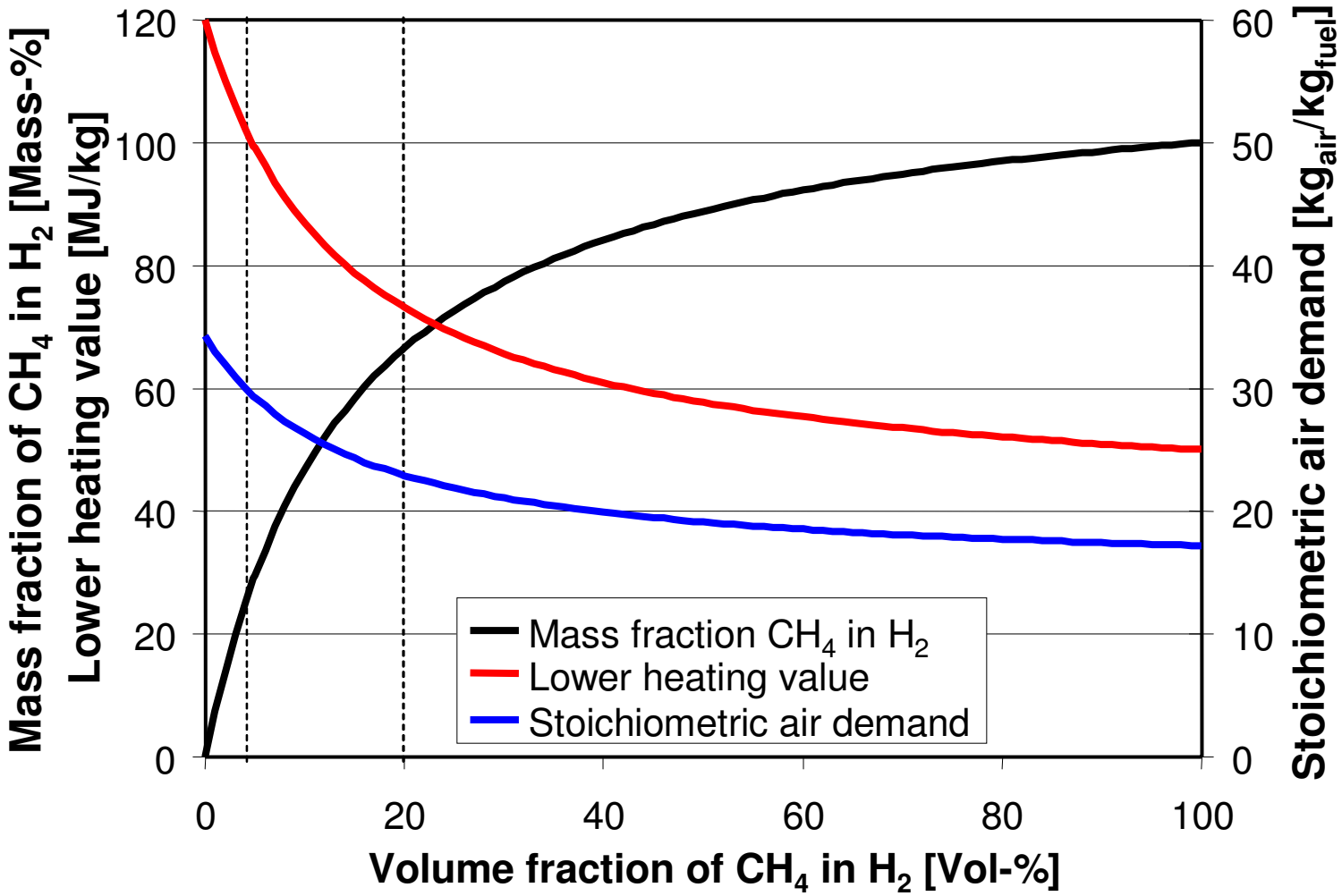
On-board storage

Lean operation

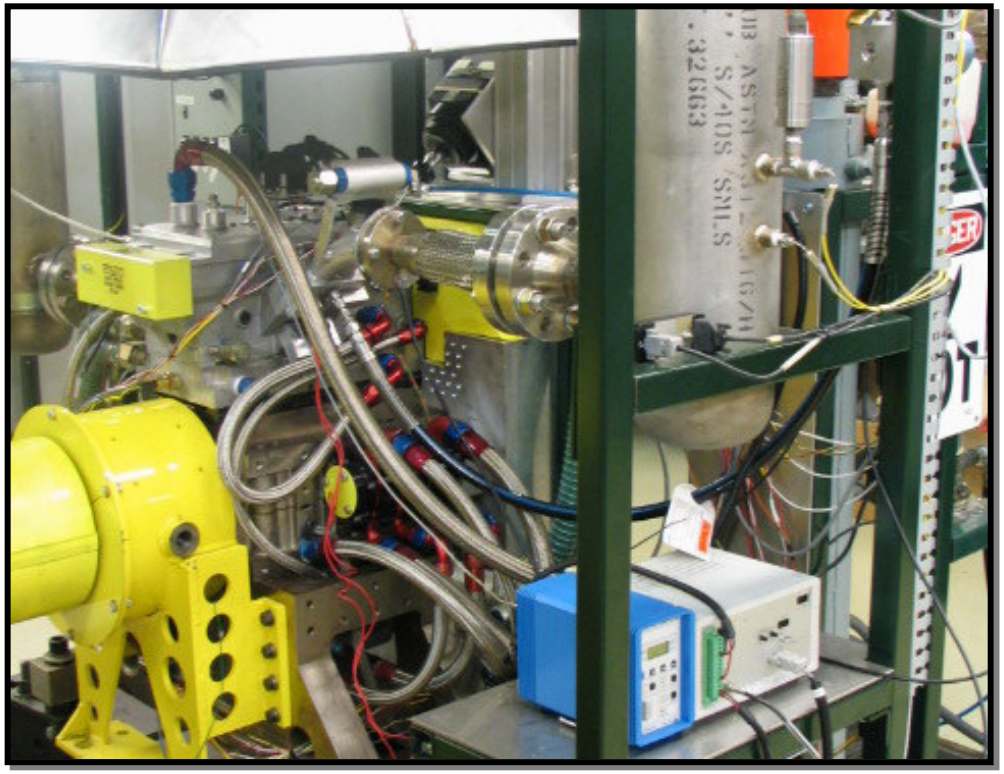
Combustion speed

Emissions

Effect of blending hydrogen with methane
Fuel properties

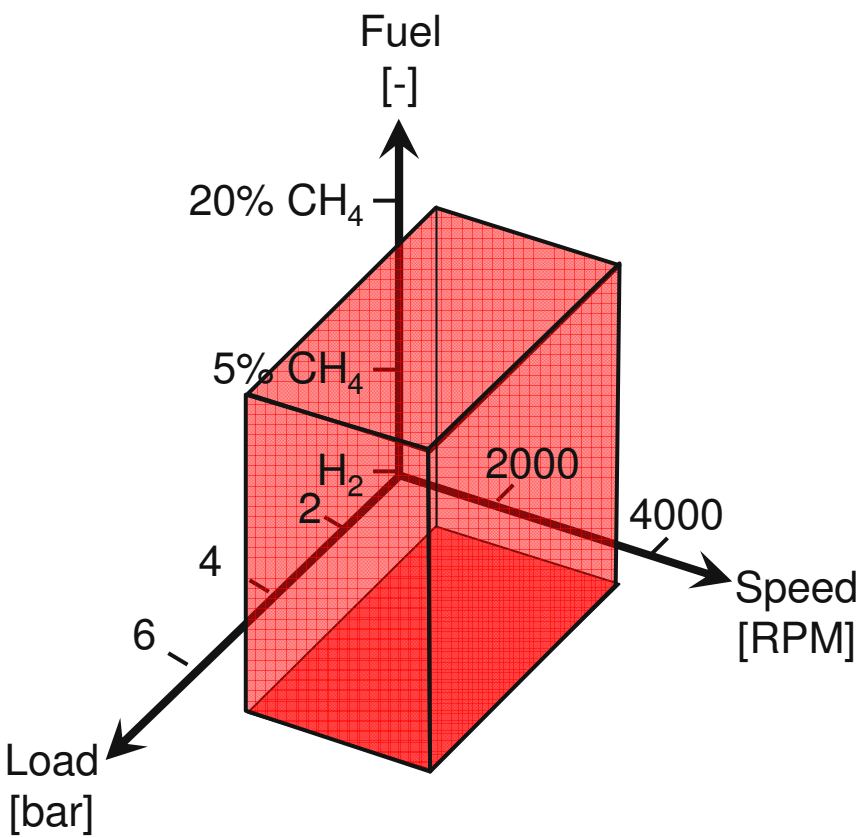


Experimental setup
Single cylinder research engine



- 0.5 liters displacement
- Bore / stroke: 89 / 79.6 mm
- Max. speed: 6000 RPM
- 4-valve DOHC configuration
- External supercharger and air-heater
- Hydrogen fueling modes:
  - Port injection
  - Direct injection

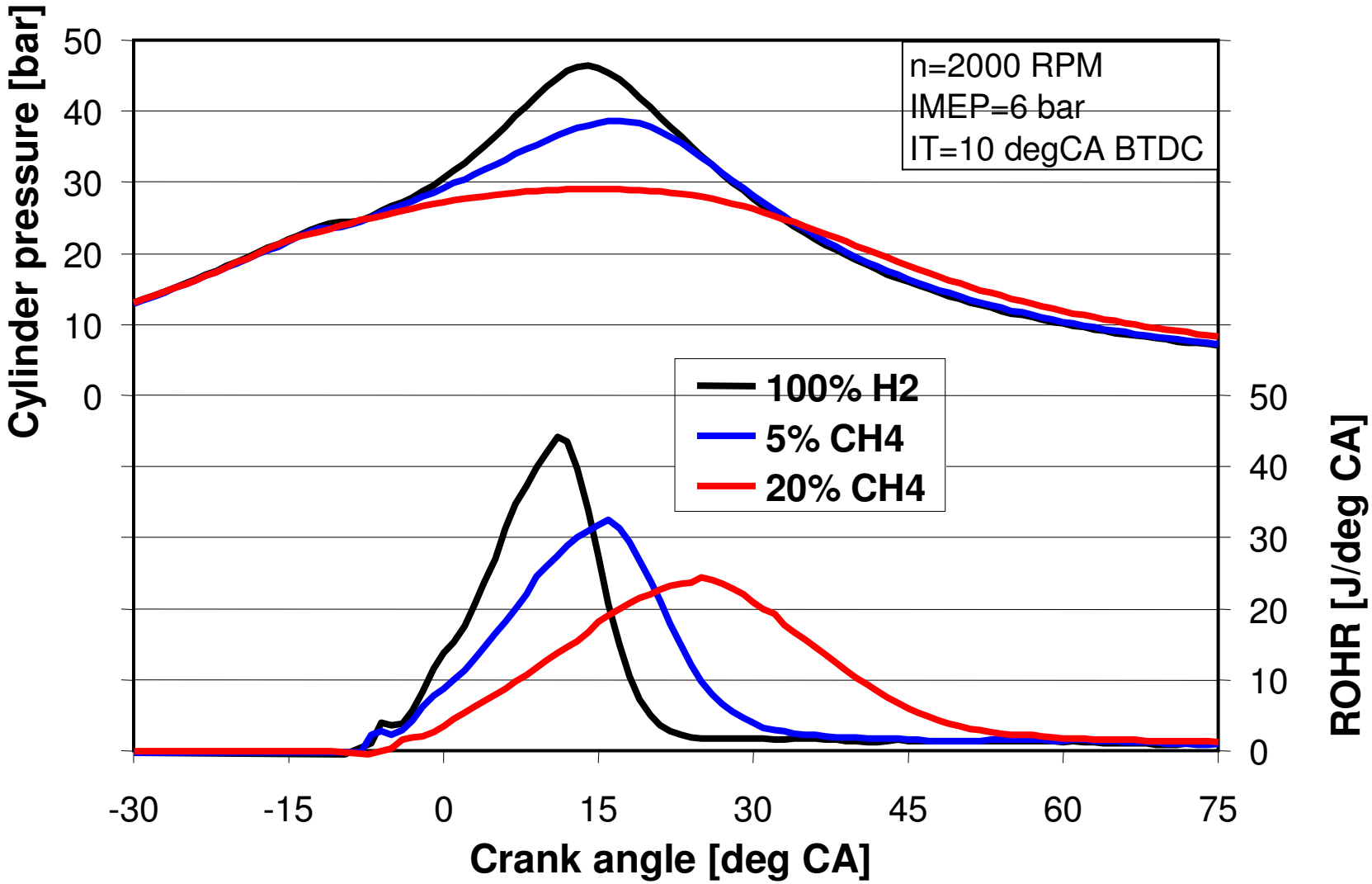
Test program
Single cylinder research engine



- Fuels tested
  - Pure hydrogen (H_2)
  - 5% methane in hydrogen (5% CH_4)
  - 20% methane in hydrogen (20% CH_4)
- Speeds tested
  - 2000 RPM
  - 4000 RPM
- Loads tested
  - 2, 4 and 6 bar IMEP
  - Unthrottled (lean) operation

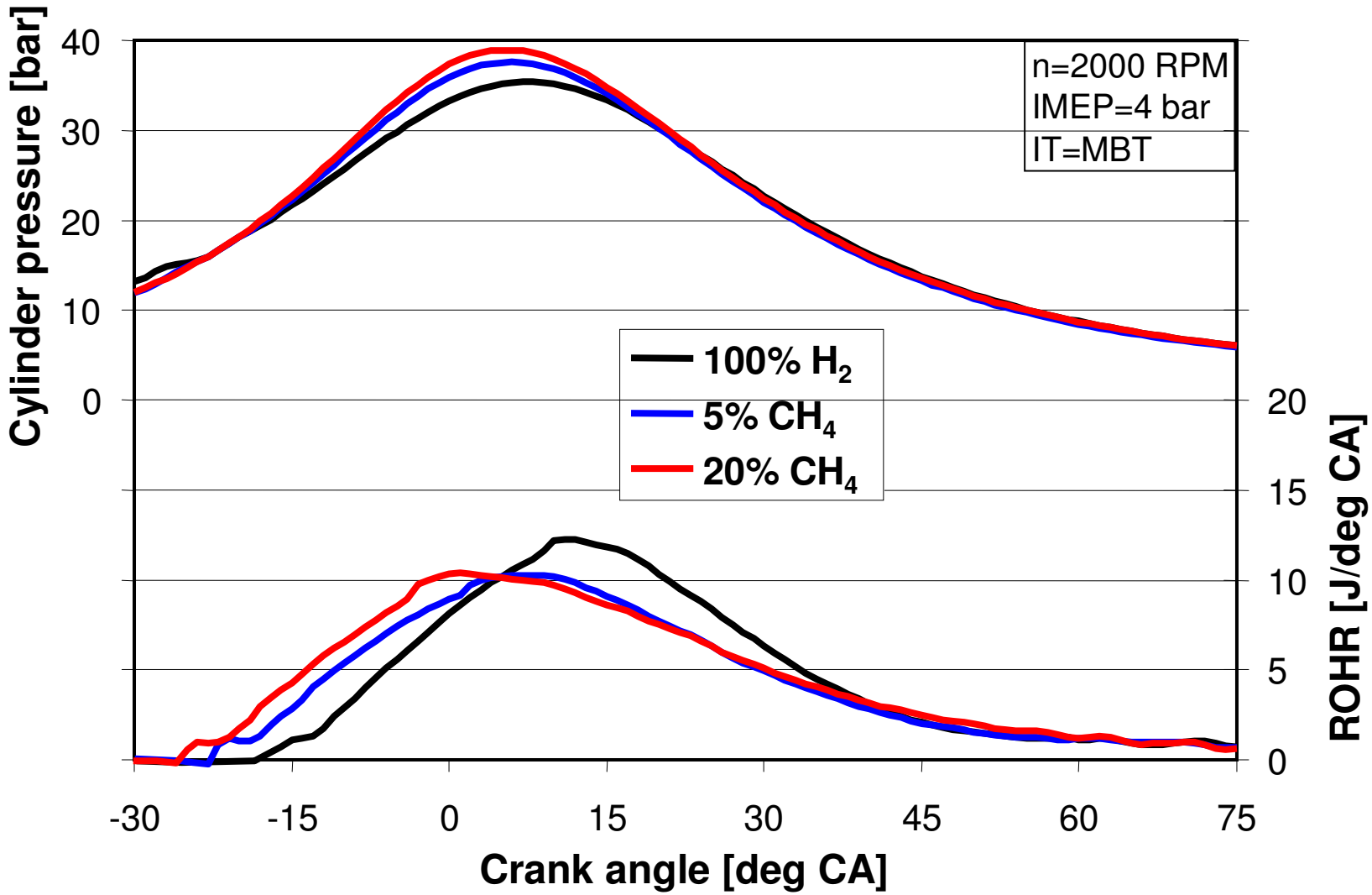
Pressure traces and rate of heat release

Lower flame speed of methane causes longer combustion duration

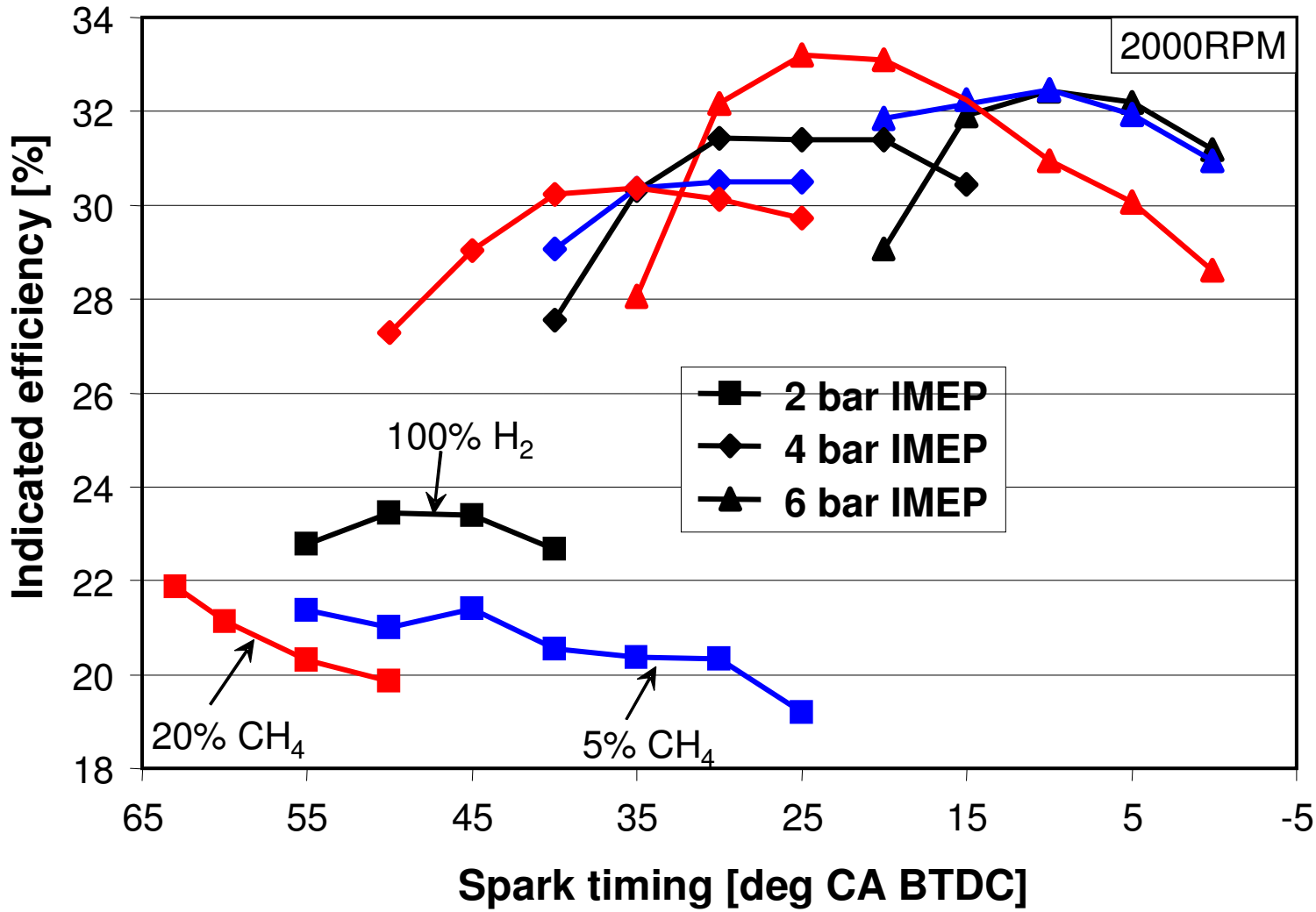


Pressure traces and rate of heat release

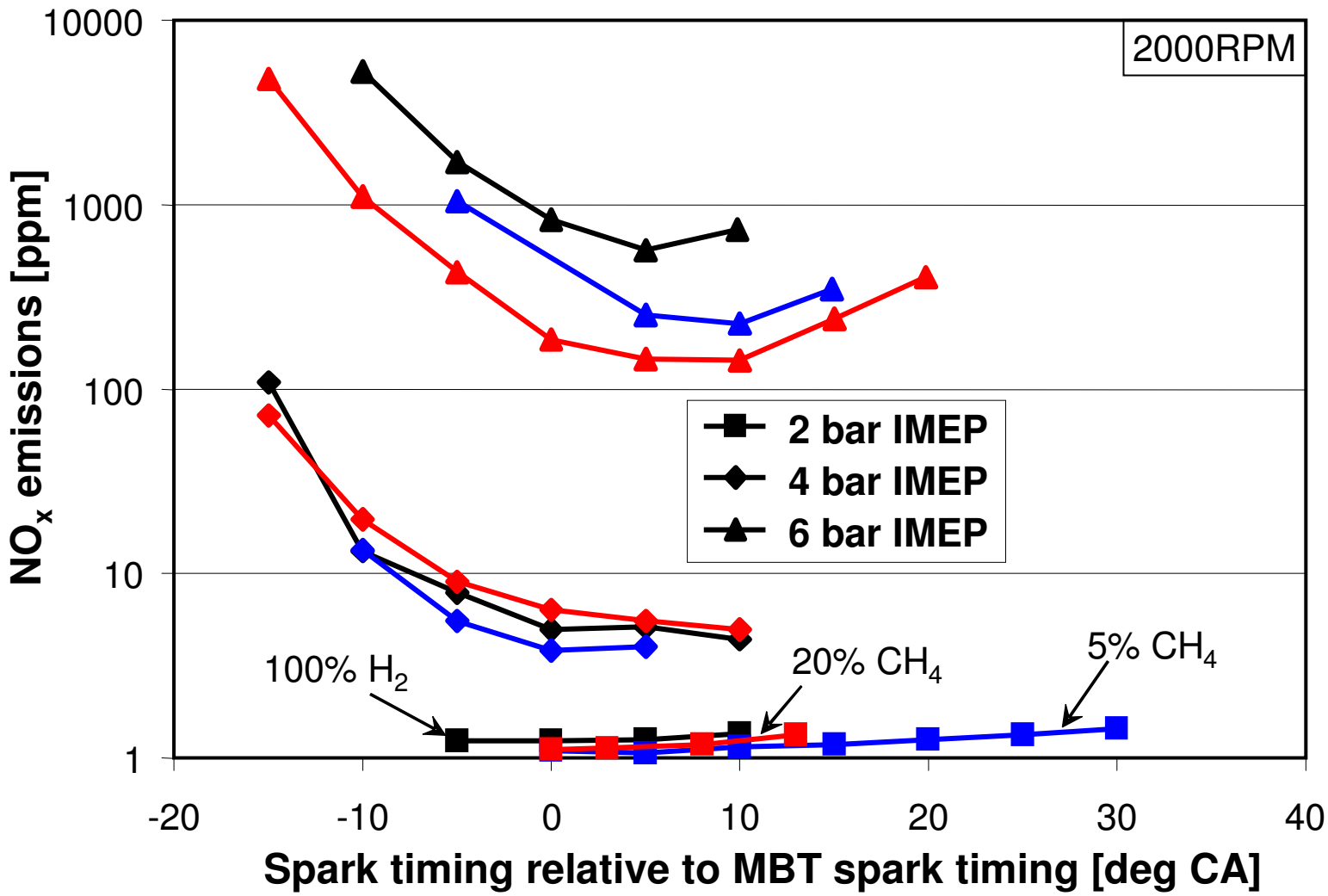
Partially compensate able by earlier spark timing



Research engine results
Indicated efficiency



Research engine results
NO_x emissions

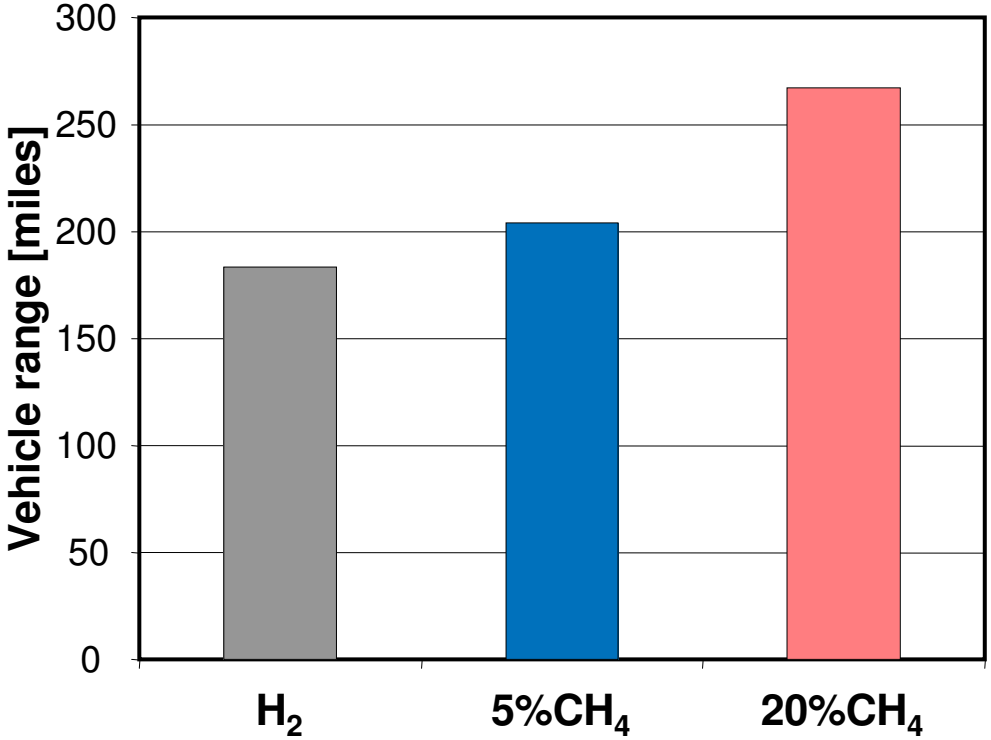


Hydrogen/methane blend vehicle testing

Vehicle details on the eTec / Roush H_2 Silverado

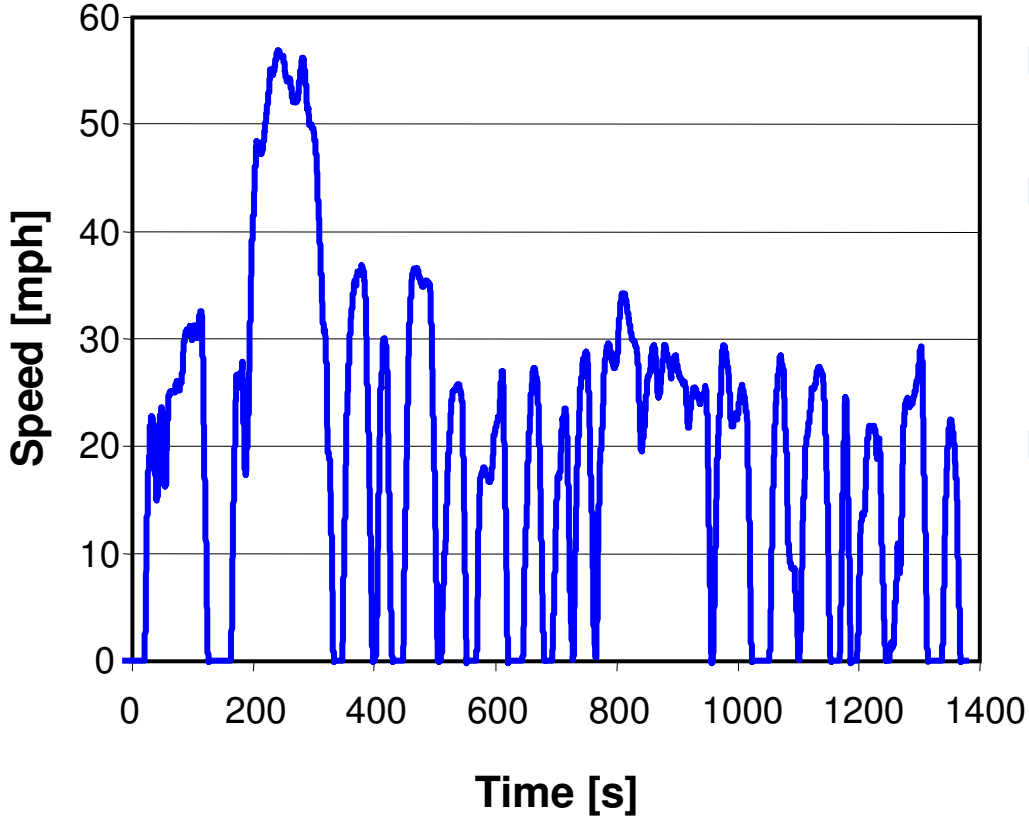
Standard features	
Seat positions	6
Engine	6.0l V8
Transmission	4 speed automatic
Drive	2 wheel
Vehicle modifications	
Supercharged and intercooled	
Powertrain control system custom calibrated for H2 Fuel	
Compressed Hydrogen with electronic fuel injection	
Three 150 liter tanks Type 3 (aluminum lined, carbon-fiber reinforced) 350 bar (5000 psi) storage pressure	
10.5 kg (10.5 gge) usable fuel	
Standard 350 bar fueling nozzle (SAE J2600)	
Weight and dimensions	
Curb Weight (est.)	6,625 lbs.
GVWR	8,600 lbs.
Wheelbase	153 in

Hydrogen/methane blend vehicle testing
Comparison of storage capability



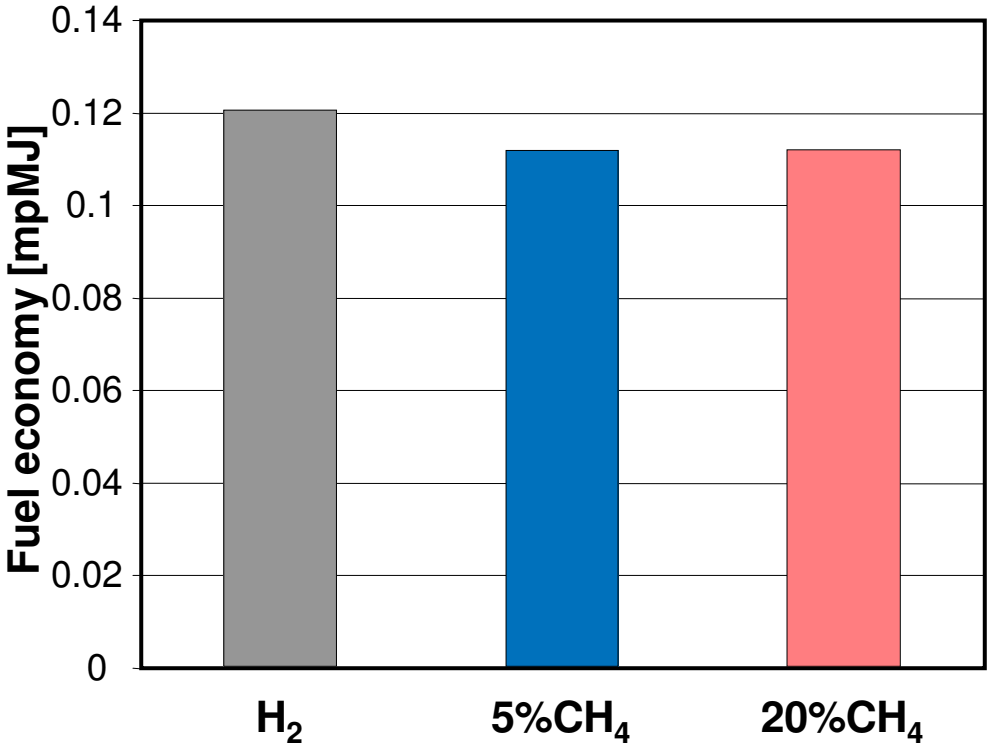
- 11% increase in stored energy with 5% methane in hydrogen
- 46% increase in stored energy with 20% methane in hydrogen

Test program
Hydrogen/methane blend vehicle testing



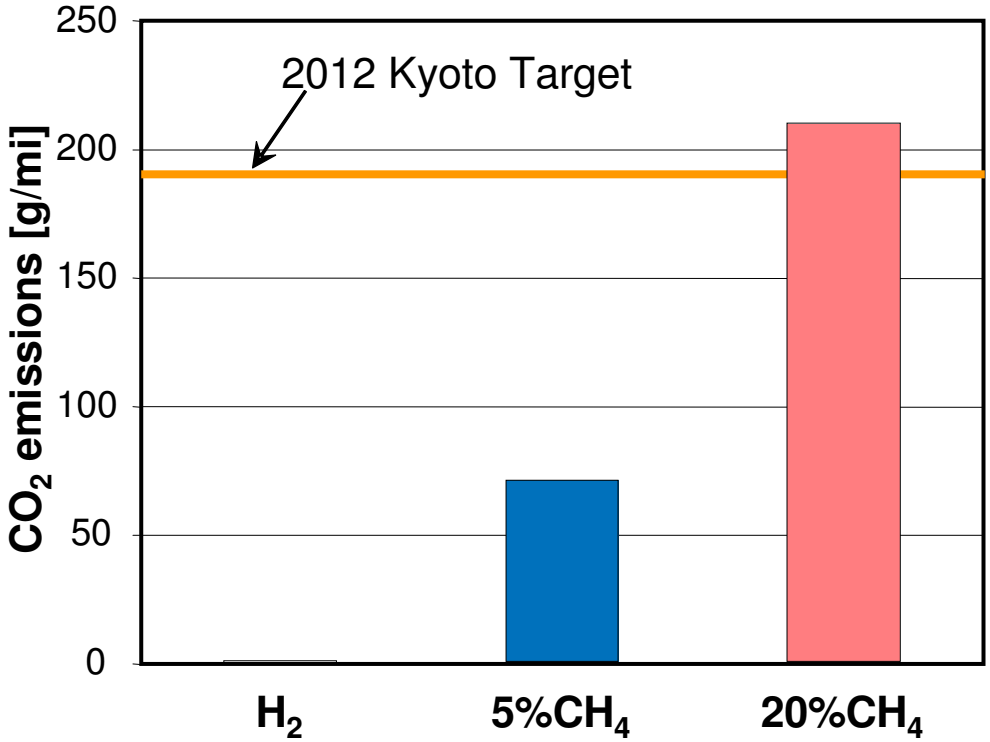
- Engine calibration
  - Constant air/fuel ratio (Φ~0.5)
- Fuels tested
  - Pure hydrogen (H_2)
  - 5% methane in hydrogen (5% CH_4)
  - 20% methane in hydrogen (20% CH_4)
- Drive cycles FTP-72 (UDDS)
  - 12.07 km (7.5 mi)
  - frequent stops
  - maximum speed 91.2 km/h (56.7 mi/h)
  - average speed 31.5 km/h (19.6 mi/h)

Hydrogen/methane blend testing
Vehicle results – Fuel consumption



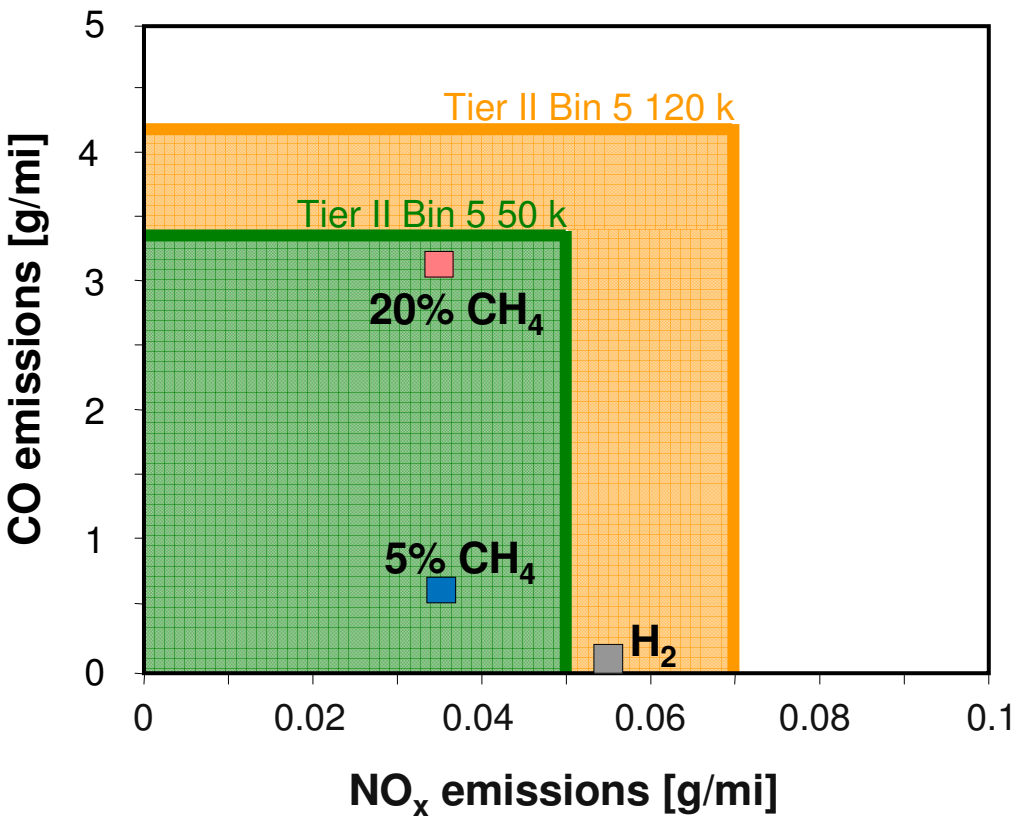
- Fuel economy in operation on pure hydrogen slightly higher (due to optimization and faster combustion)
- 0.12 mpMJ equals to about 19 mpg gasoline equivalent

Hydrogen/methane blend testing
Vehicle results –CO_2



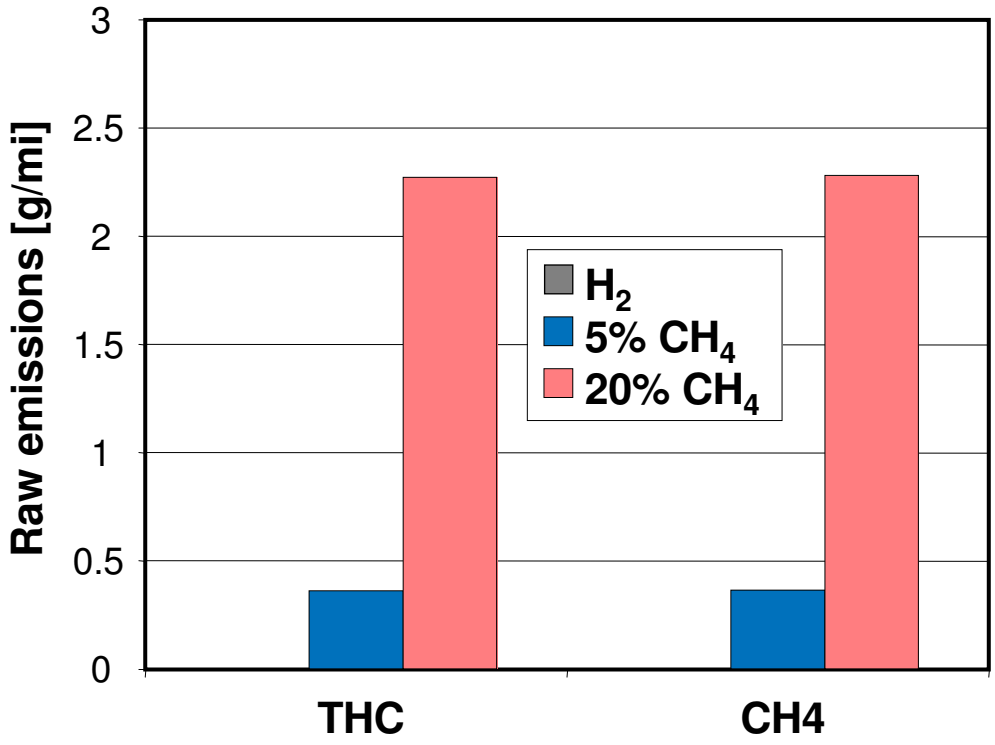
- Virtually no carbon dioxide emissions in pure hydrogen operation
- Even 20% blend almost meets 2012 Kyoto Target

Hydrogen/methane blend testing
Vehicle results – Limited emissions



- NO_x emissions are virtually the only limited emissions component in pure hydrogen operation
- NO_x emissions decrease with increased amount of methane in the mixture (as seen in engine experiments)
- CO in the range of federal regulations
- No catalyst used

Hydrogen/methane blend testing
Vehicle results – Limited emissions



- Hydrocarbon emissions increase dramatically with increased amount of methane in the blend
  - NMHC (calculated) close to zero
- No catalyst used

Summary and conclusion

- Blending hydrogen with methane can effectively reduce the hydrogen demand
- Slower combustion speed of blends compared to pure hydrogen can be partially compensated for with spark timing adjustment
- Blending significantly increases the vehicle range
- Reduction of NO_x emissions with increased amount of methane in the blend
- Tier II Bin 5 emissions regulations can be met without aftertreatment

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