A Technical Review of Hydrogen-Fueled Internal Combustion Engines

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H_2ICEs: A bridge to the hydrogen economy

- **Technology is available today and economically viable in the near-term.**
- **Number of test/demo vehicles: Ford, BMW among others (see below).**
  - demonstrated efficiencies in excess of today's gasoline engines.
  - operate cleanly (NO_x is the only emission pollutant)
- **Fewer constraints concerning H_2 storage compared to fuel cells.**
  - relative ease of a dual-fuel option (H_2/gasoline).
  - impurities are a non-issue

H_2 properties relevant to ICEs

Property	Gasoline	CNG	Hydrogen
flammability limits (ϕ)	0.7–4	0.4–1.6	0.1–7.1
laminar flame velocity (m/s) ‡	0.37–0.43	0.38	1.85
research octane number	91–99	140	> 120
adiabatic flame temp. (K)‡	2580	2214	2480
autoignition temp. (K) ‡	550	723	858
stoichiometric volume fraction (%)	≈ 2†	9.48	29.53
minimum ignition energy‡	0.24	0.28	0.02
quenching distance (mm) ‡	≈ 2	2.1	0.64
lower heating value (MJ.kg)	44.79	45.8	119.7
heat of combustion (MJ/kg_{air}) ‡	2.83	2.9	3.37

† gasoline vapor, ‡ stoichiometric mixture

wide flammability range (ultra-lean operation)

high flame speeds (good stability)

high compression ratios with improved thermal efficiency

air displacement effects

propensity to preignite

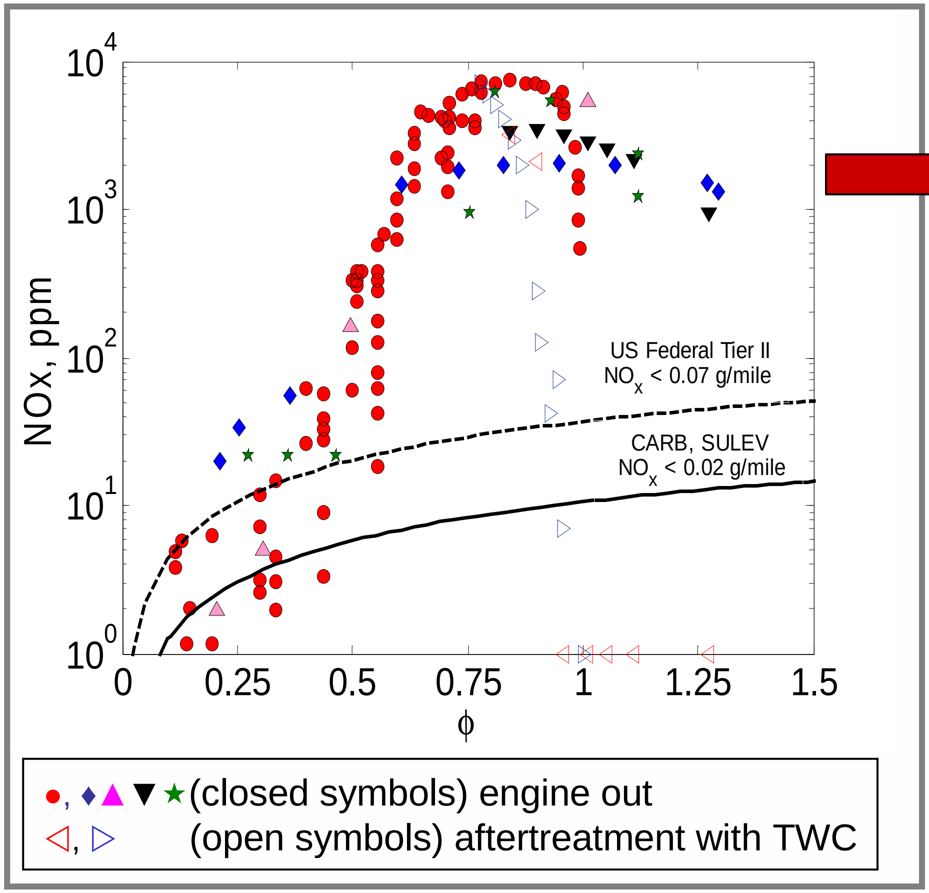
thin thermal boundary layers

favorable
unfavorable

The unique combustion properties of hydrogen can be beneficial at certain engine operating conditions and pose technical challenges at other engine operating conditions.

Present Day H_2ICEs: Emissions

- **Cold-start is a non-issue (gaseous fuel)**
- **NO_x is the only non-trivial engine-out emission pollutant**
  - statement ignores the upstream emissions in producing hydrogen



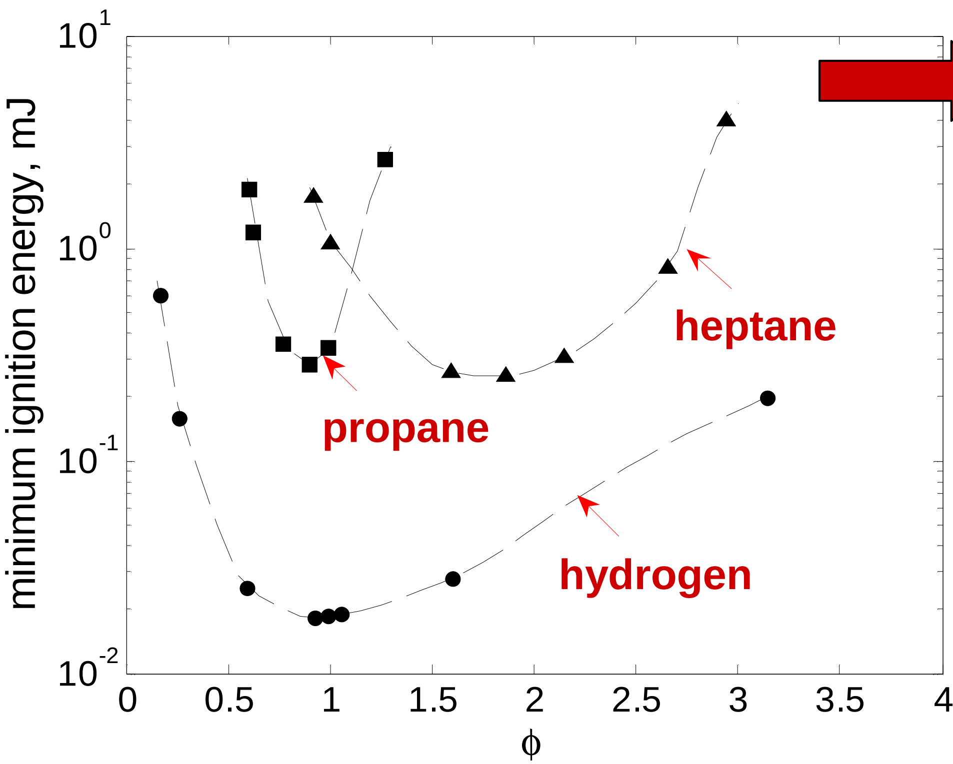
Satisfy SULEV regulations

- operate ultra-lean ($\phi < 0.45$).
- operate at stoichiometry ($\phi = 1$) with 3-way catalyst (TWC)

Aim of the next few slides is to illustrate the fundamental and practical obstacles related to SULEV operating strategies in conventional PFI-H_2ICEs.

Preignition in H_2ICEs

Preignition:
Ignition of the fuel/air mixture before the spark plug fires. Ignition sources include engine hot spots, oil contaminants, and others. Produces engine knock-like effects than can lead to engine damage.



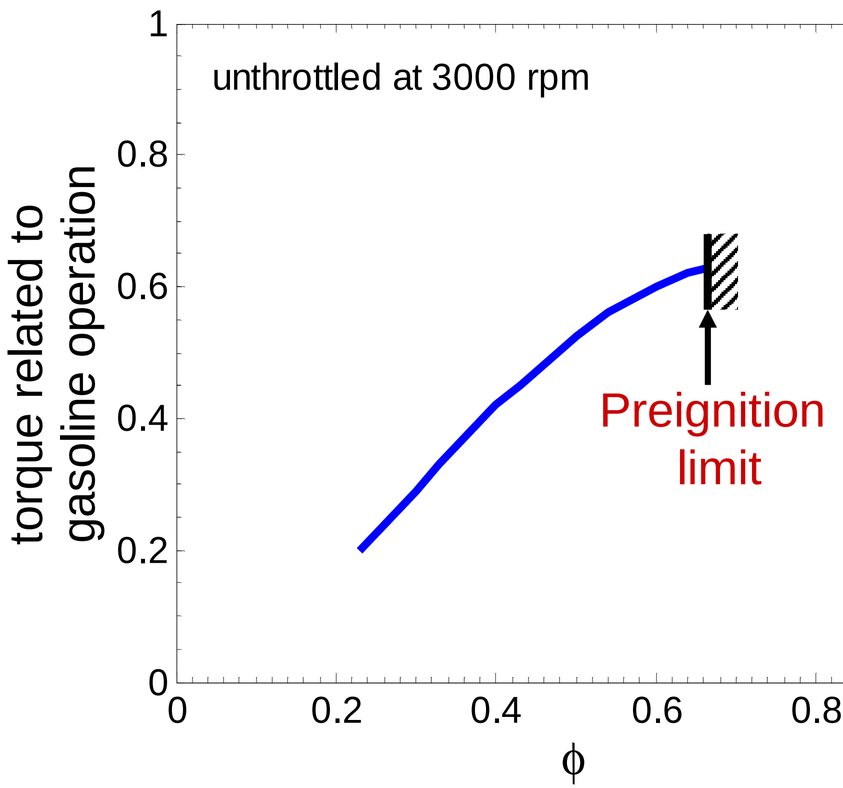
H_2 is predisposed to preignition

Conventional port-fuel-injection (PFI) H_2ICEs fueled by compressed hydrogen gas are most susceptible to preignition.

In practical applications, it is very difficult to operate a PFI-H_2ICE at or near ϕ = 1

Limiting Effects of Preignition

In practice, to avoid preignition the engine is operated lean. Consequently, engine torque (and power) is significantly reduced.



Profound effects on SULEV operating strategies:

- **Stochiometric operation with aftertreatment.**

→ **region is inaccessible.**

- **Continuous ultra-lean operation (no aftertreatment)**

→ **torque (power) is very low**

Demonstrates a need for advanced H_2ICEs and SULEV operating strategies

Advanced H_2ICEs and SULEV Strategies (1)

Continuous ultra-lean (ϕ < 0.45) operation with improved power densities

pressure boosting (turbo or SC) → H_2ICE-electric hybrid

Ford H_2ICE Focus

SC 2.3L I4-engine
Fuel economy: 37 miles/kg

Emissions: SULEV or better

Ford H_2ICE-450 shuttle

SC 6.8L V10-engine
Fuel economy: 7 miles/kg

Emissions: SULEV or better

Ford H_2RV

SC 2.3L I4-engine
30 HP Electric Motor
Fuel economy: 45 miles/kg

Emissions: SULEV or better

Advanced H_2ICEs and SULEV Strategies (2)

Accessible stochiometric (ϕ = 1) operation with aftertreatment

liquid hydrogen fueling

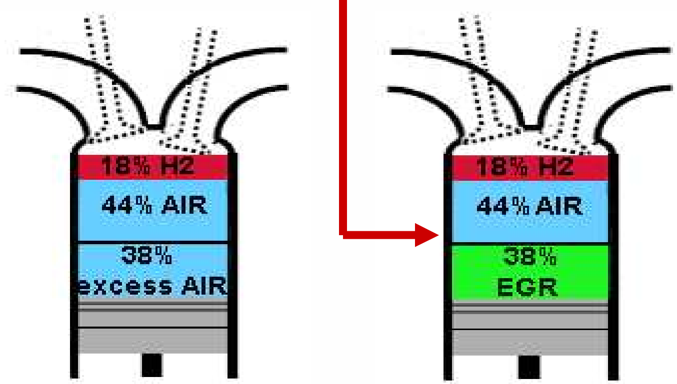
cold mixture prevents preignition and allows ϕ = 1 operation

direct injection DI-H_2ICE

injection timing is optimized (delayed) to prevent preignition and allow for ϕ = 1 operation

exhaust gas dilution (EGR)

lean-burn conditions are diluted with EGR such that ϕ = 1 (no excess oxygen)



ϕ = 0.6 (excess air)

ϕ = 1.0 (EGR dilution)

Advanced H_2ICEs and SULEV Strategies (3)

BMW 745h

Multi-mode strategies → BMW 745h → liquid hydrogen fueling

- low engine load → **ultra-lean (ϕ < 0.45) operation**
- medium engine load → exhaust gas dilution (EGR) → **stochiometric (ϕ = 1) operation with aftertreatment**
- high engine load → **stochiometric (ϕ = 1) operation with aftertreatment**

4.4L V8-engine
Fuel economy: 25 miles/kg → **Emissions: Significantly below SULEV**

Advanced H_2ICEs and SULEV Strategies (4)

Ford H_2ICE Focus

Multi-mode strategies

low engine load

medium engine load

high engine load

ultra-lean (ϕ < 0.45) operation

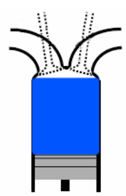
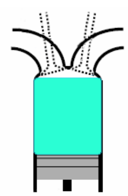
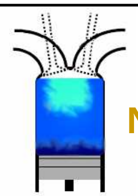
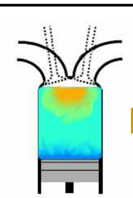
pressure boosting supercharger

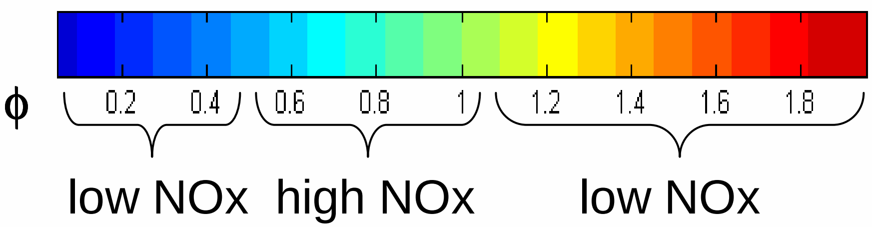
Lean ($\phi \approx 0.7$) operation Lean NOx trap (LNT)

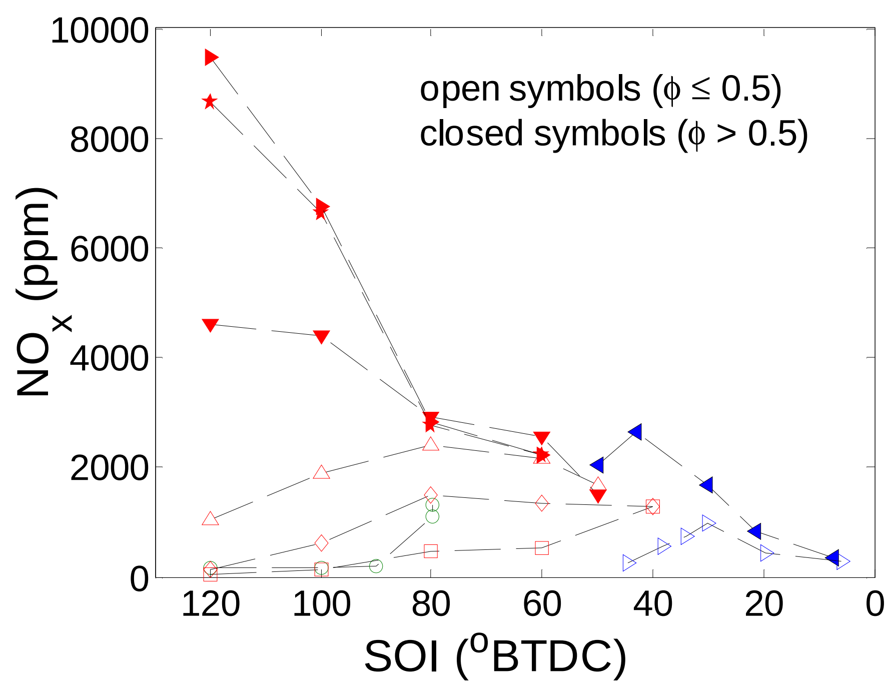
Emissions: Significantly below SULEV

Mixture Stratification with Direct Injection

Create a stratified H_2/air mixture to reduce emissions and improve efficiency.

Mixture formation	ϕ = 0.3	ϕ = 0.8
well-mixed		
stratified	 NOx ↑	 NOx ↓





Mixture inhomogeneities →

Advanced H_2ICEs and SULEV Strategies (5)

Multi-mode strategies → direct injection hydrogen fueling

- **idle** → **stratified ultra-lean (ϕ < 0.2) operation**
- **low engine load** → **ultra-lean (ϕ < 0.45) operation**
- **medium engine load** → **stratified lean (0.45 ≤ ϕ < 1) operation with LNT aftertreatment**
- **high engine load** → **stratified stochiometric (ϕ = 1) operation with aftertreatment**

Very high efficiency (BTE > 45%)

Emissions: Significantly below SULEV

Summary

- Significant advancements in the development of the H_2ICE over the last decade.

- Several H_2ICE powered vehicles with demonstrated emissions significantly below SULEV regulations.

- Good prospects for increased efficiencies, high power density and reduced emissions with hybridization, multi-mode operating strategies and advancements in ICE design and materials.