H$_2$-ICE – A Zero-Impact Bridge to a Zero Emissions Future

SOUTHWEST RESEARCH INSTITUTE®

Dr. Terry Alger
Executive Director, Sustainable Energy and Mobility
Executive Summary

- Hydrogen-powered internal combustion engines offer a near-term solution to the challenges of decarbonizing sectors of the transportation industry that are less adaptable to electrification and offer a hedge against potential insurmountable challenges in mass-adoption of fuel cells
  - Immediate use of zero-carbon fuels
    - Built on existing industry infrastructure and ICE hardware
  - Ultra-low emissions of other greenhouse gasses
  - Ultra-low emissions of NO\textsubscript{X}
  - Similar or better efficiency to fuel cells in the typical HD application operating range

- H\textsubscript{2}-ICE combined with limited hybridization can yield even larger benefits

- At a minimum, H\textsubscript{2}-ICE offers a bridge technology between today’s diesel ICE trucks and future FCEV trucks – get low-GHG trucks to market faster and provide a market to attract infrastructure investment for H\textsubscript{2} production and filling stations
H₂-ICE “Other” GHG Emissions

Proper system design (control of H₂ slip and catalyst sizing/selection) will allow thermal management of the hydrogen exotherm to control N₂O emissions.

Exotherm can be leveraged to mitigate N₂O emissions in the presence of H₂, especially at inlet temperatures < 200 °C.

Exotherm also enables reduced cold-start emissions.

\[ 2H_2 + O_2 \rightarrow 2H_2O \]

Low temperature activity available (110 °C)

Increasing H₂ concentration induced a proportionally greater exotherm
SwRI’s Joint Industry Program H₂-ICE
Demonstrating the ZEV Potential of an HD H₂ Application

- SwRI is building a demo vehicle that will
  - Have similar efficiency to diesel
  - Run on SI H₂
  - Have NOx emissions < 0.02 g/hp-h
- Most components carry-over from stock 15 L CNG application

Red – 15 L Engine
Gray – Transmission
Blue – H₂-ICE Specific components
Black – Vehicle Specific Components

Membership Status

SwRI's Joint Industry Program H₂-ICE
**H₂-ICE NOₓ Control**

- Steady-state, engine-out NOₓ emissions < 1.0 g/hp-hr combined with turbine-out temperatures > 300 °C full-map → catalyst efficiency > 98%
- Engine can be expected to have certification emissions levels near 0.01 g/hp-hr with **no / minimal margin**
- Aftertreatment will retain oxidation catalyst and particulate filter to ensure tailpipe emissions remain below 2027 regulated levels

**Catalysts based on 2027-intent diesel production parts. H₂-ICE exhaust presents fewer aging challenges – no concerns about full useful life performance.**
H₂-ICE Aftertreatment – Comparison to Diesel AT

Diesel Low NOₓ AT System

H₂-ICE Low NOₓ AT System
**H₂-ICE vs. FC Truck Efficiency**

Powertrain technologies behave differently under high loads.

- **Efficiency variations** (lines on graph are illustrative)

**Tank-to-wheel efficiencies in relation to load, %**

- **H₂-ICE**
- **FCEV**
- **Diesel ICE**

**Load, % of maximum system output**

- **H₂-ICE**
- **diesel ICE**

**H₂-ICE** and diesel ICE with increasing efficiency as load increases; downsizing therefore popular for ICE

*Line-haul steady load*

- **FCEV** after initial peak at low load with declining efficiency; however, oversizing of fuel cell and hybridization allow use of most efficient load

**BEV**

- **H₂-ICE**
- **FCEV**
- **Diesel ICE**

**H₂-ICE vs. FC Truck Efficiency**

- The relative performance between FCEV and H₂-ICE depends on application
  - Class 8 Line-Haul tends to run at 50-75% of peak and H₂-ICE will have similar H₂-to-wheel efficiency
  - Class 7/8 Vocational has a mix of long idle times and operation at peak torque for each start. FCEV has an advantage at light load but a disadvantage at high torque.

- **NOTES:**
  - Some of the FCEV advantage in vehicle FE is due to the hybridized powertrain
    - H₂-ICE could be hybridized (at a lower cost compared to FCEV) to show same/similar vehicle fuel economy
  - H₂-ICE is more tolerant of impurities in the fuel supply and potentially able to use lower-cost grades of H₂

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Wrap-Up

- $\text{H}_2$-ICE provides a cost-effective, zero-impact bridge between diesel ICE and $\text{H}_2$-FCEV
  - Immediate, large-scale reduction in GHG combined with ultra-low NOx emissions
  - Low impact on current ICE architecture
- $\text{H}_2$-ICE can provide important incentives for infrastructure investments to enable future FCEV applications
- Hybridized $\text{H}_2$-ICE can deliver the same, or better, fuel economy than a FCEV