H_2-ICE – A Zero-Impact Bridge to a Zero Emissions Future

SOUTHWEST RESEARCH INSTITUTE®

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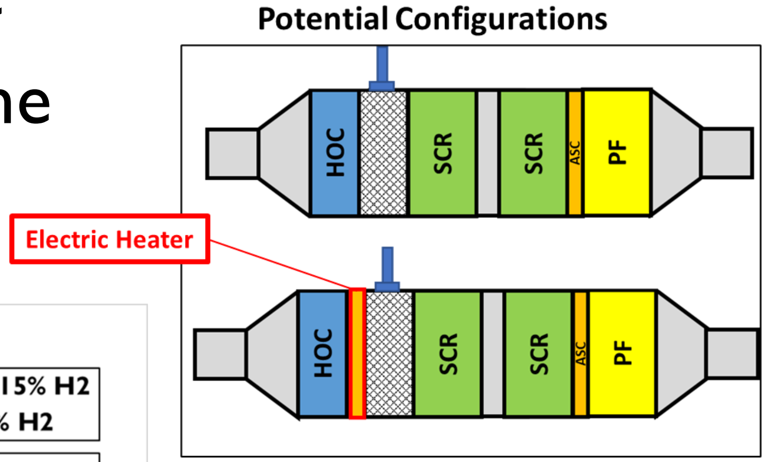
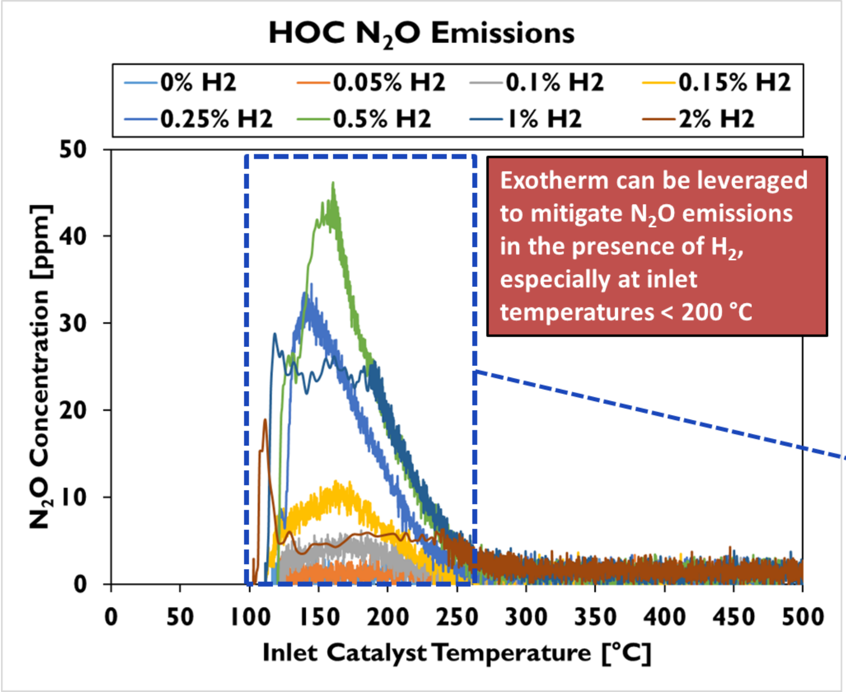
Executive Summary

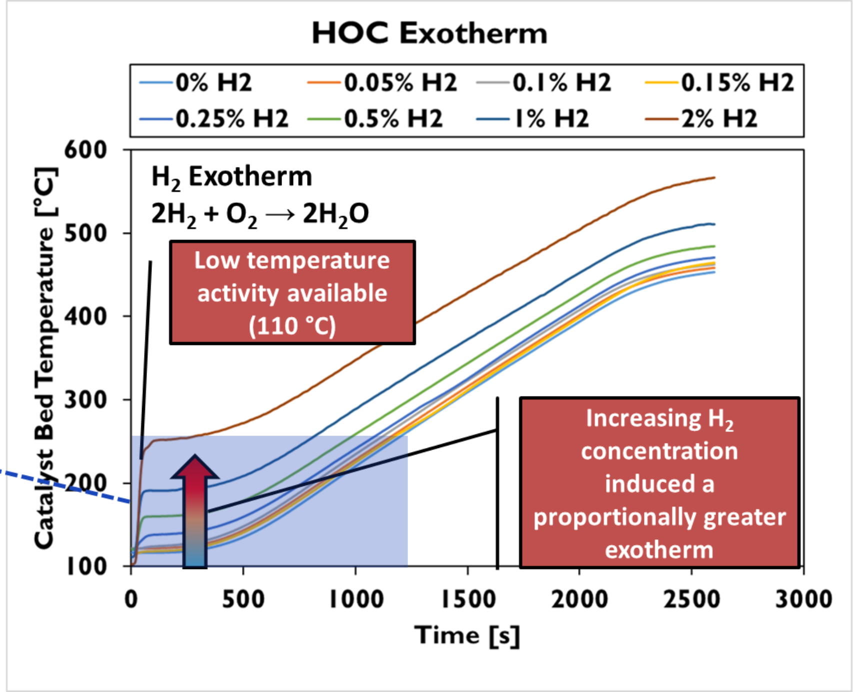
- Hydrogen-powered internal combustion engines offer a near-term solution to the challenges of decarbonizing sectors of the transportation industry that are less adaptable to electrification and offer a hedge against potential insurmountable challenges in mass-adoption of fuel cells
  - Immediate use of zero-carbon fuels
    - Built on existing industry infrastructure and ICE hardware
  - Ultra-low emissions of other greenhouse gasses
  - Ultra-low emissions of NO_X
  - Similar or better efficiency to fuel cells in the typical HD application operating range
- H_2-ICE combined with limited hybridization can yield even larger benefits
- At a minimum, H_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_2 production and filling stations

H_2-ICE "Other" GHG Emissions

Proper system design (control of H_2 slip and catalyst sizing/selection) will allow thermal management of the hydrogen exotherm to control N_2O emissions





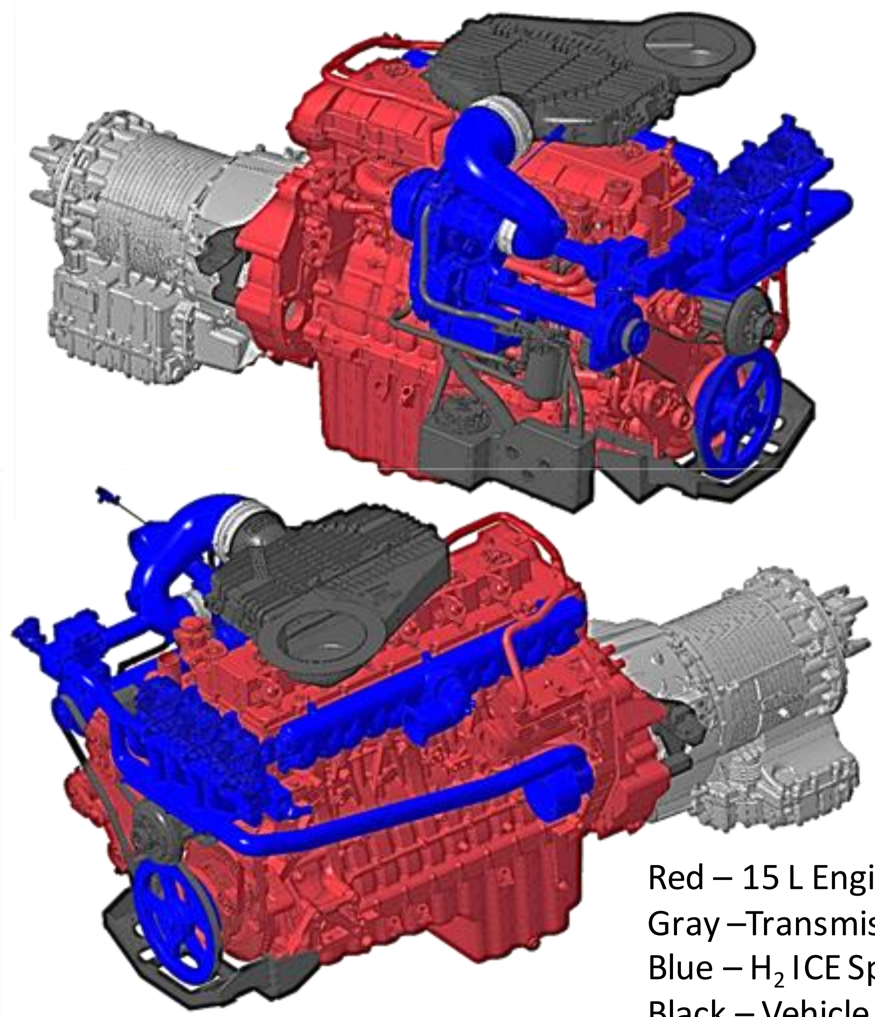


Exotherm also enables reduced cold-start emissions

SwRI's Joint Industry Program H_2-ICE

Demonstrating the ZEV Potential of an HD H_2 Application

- SwRI is building a demo vehicle that will
  - Have similar efficiency to diesel
  - Run on SI H_2
  - Have NOx emissions < 0.02 g/hp-h
- Most components carry-over from stock 15 L CNG application



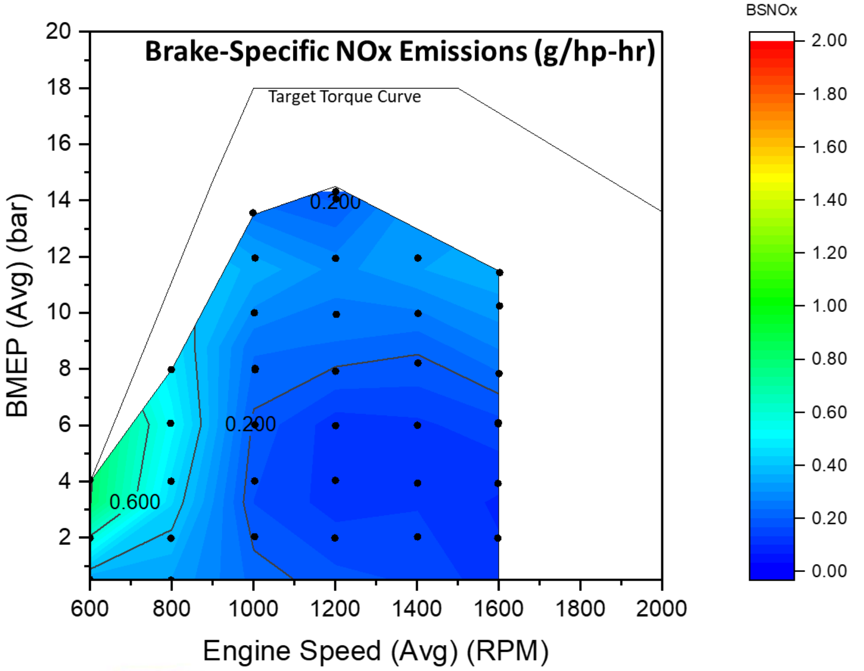
Red – 15 L Engine
Gray –Transmission
Blue – H_2 ICE Specific components
Black – Vehicle Specific Components

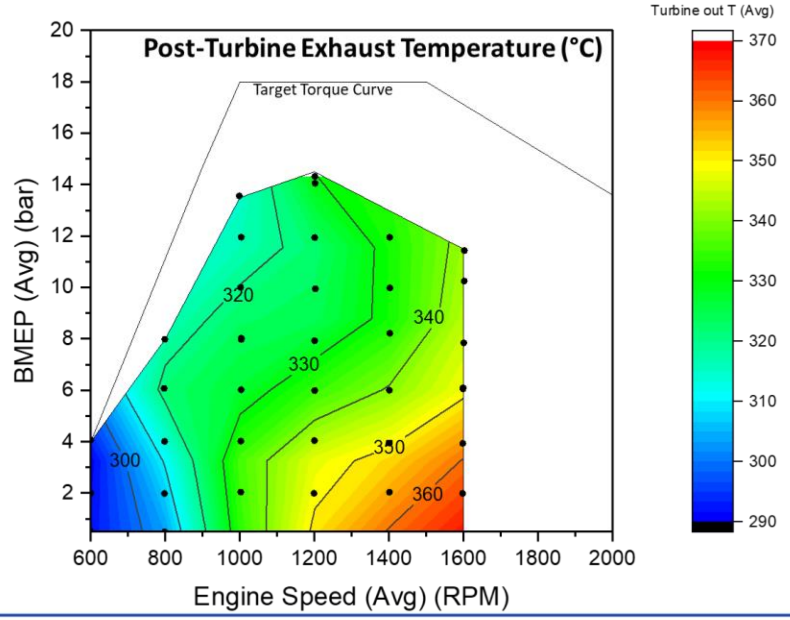
Membership Status

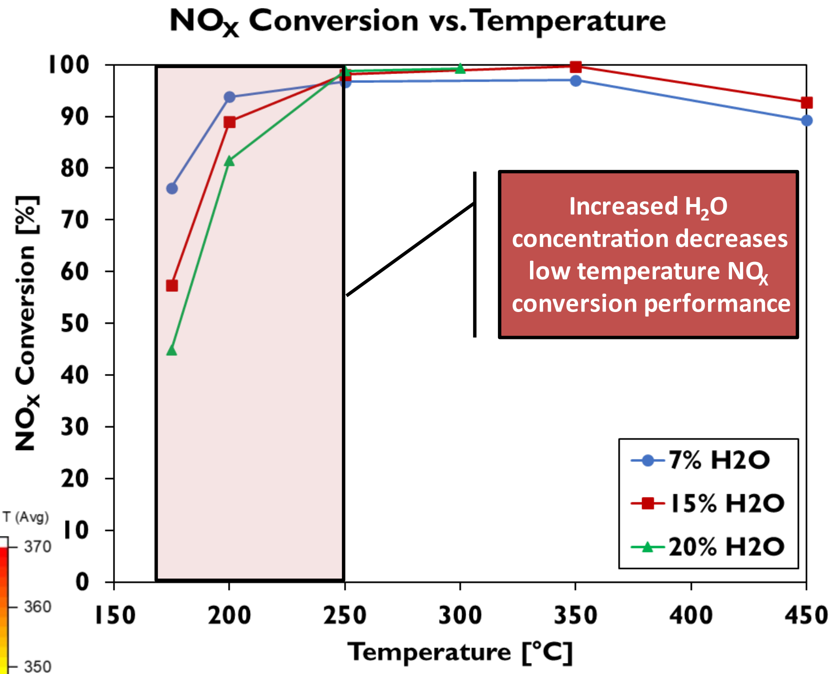
JCB
Allison Transmission
H_2 ICE ZERO CARBON FUEL ULTRA-LOW EMISSIONS
WOODWARD
Cummins
ExxonMobil
BOSCH
CATERPILLAR
MECA SUPPLYING CLEAN MOBILITY
aramco
FORVIA faurecia
DAIMLER TRUCK North America
MAHLE
SuperTurbo TECHNOLOGIES
Chevron
Oronite
Afton CHEMICAL
HD HYUNDAI INFRACORE
SwRI
PHINIA

H_2-ICE NO_X Control

- Steady-state, engine-out NO_X 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

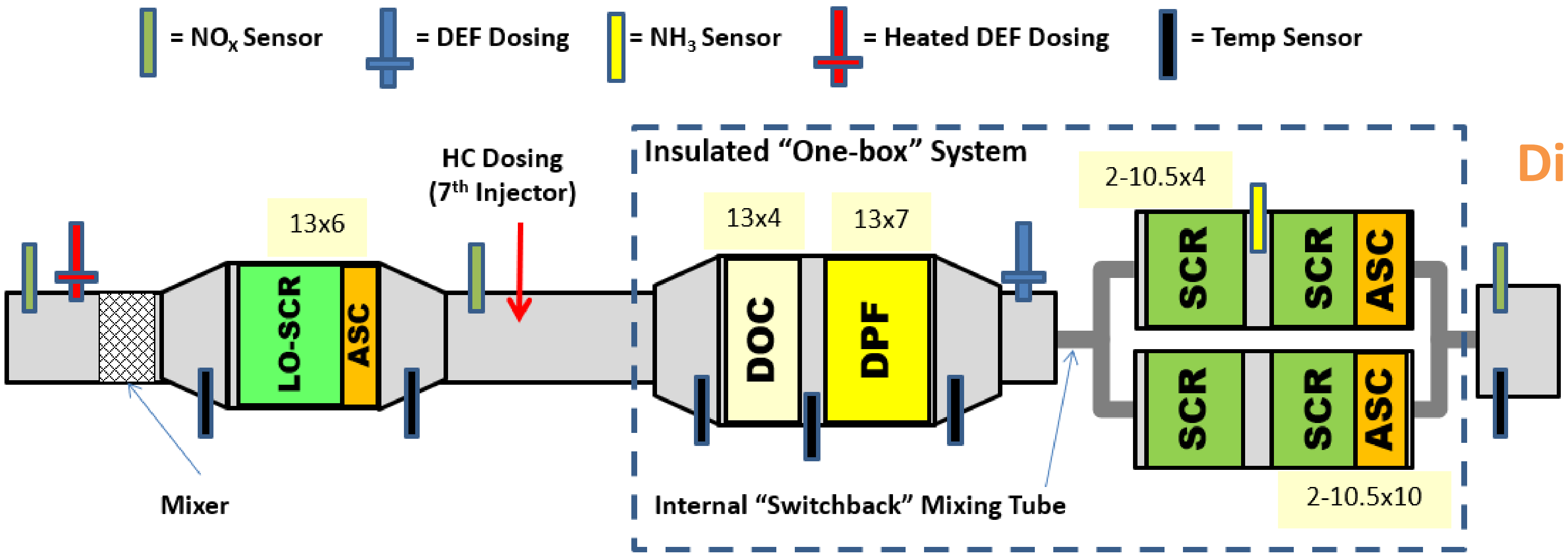




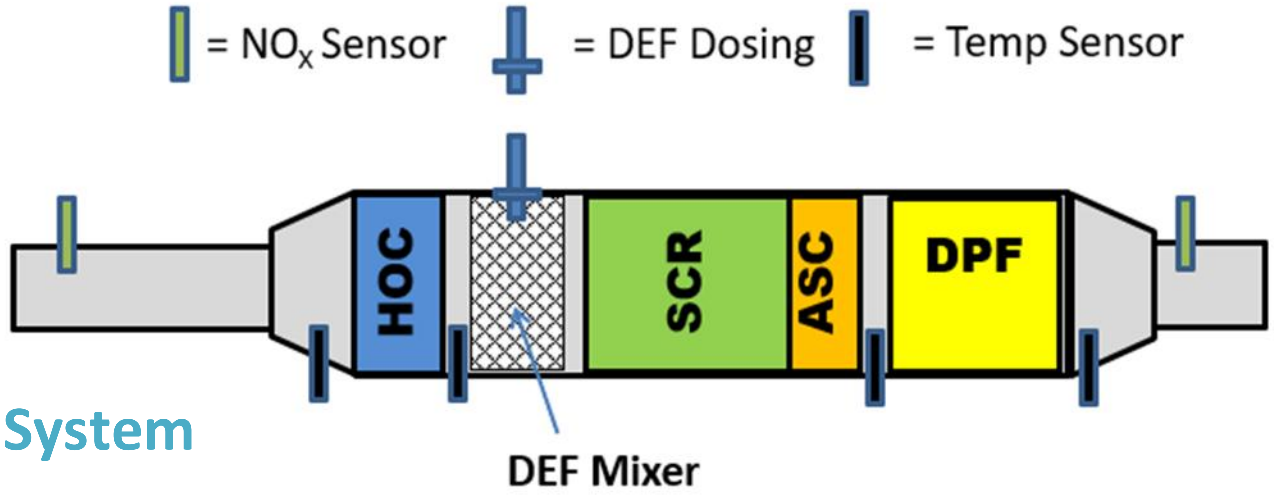


Catalysts based on 2027-intent diesel production parts. H_2-ICE exhaust presents fewer aging challenges – no concerns about full useful life performance.

H_2-ICE Aftertreatment – Comparison to Diesel AT

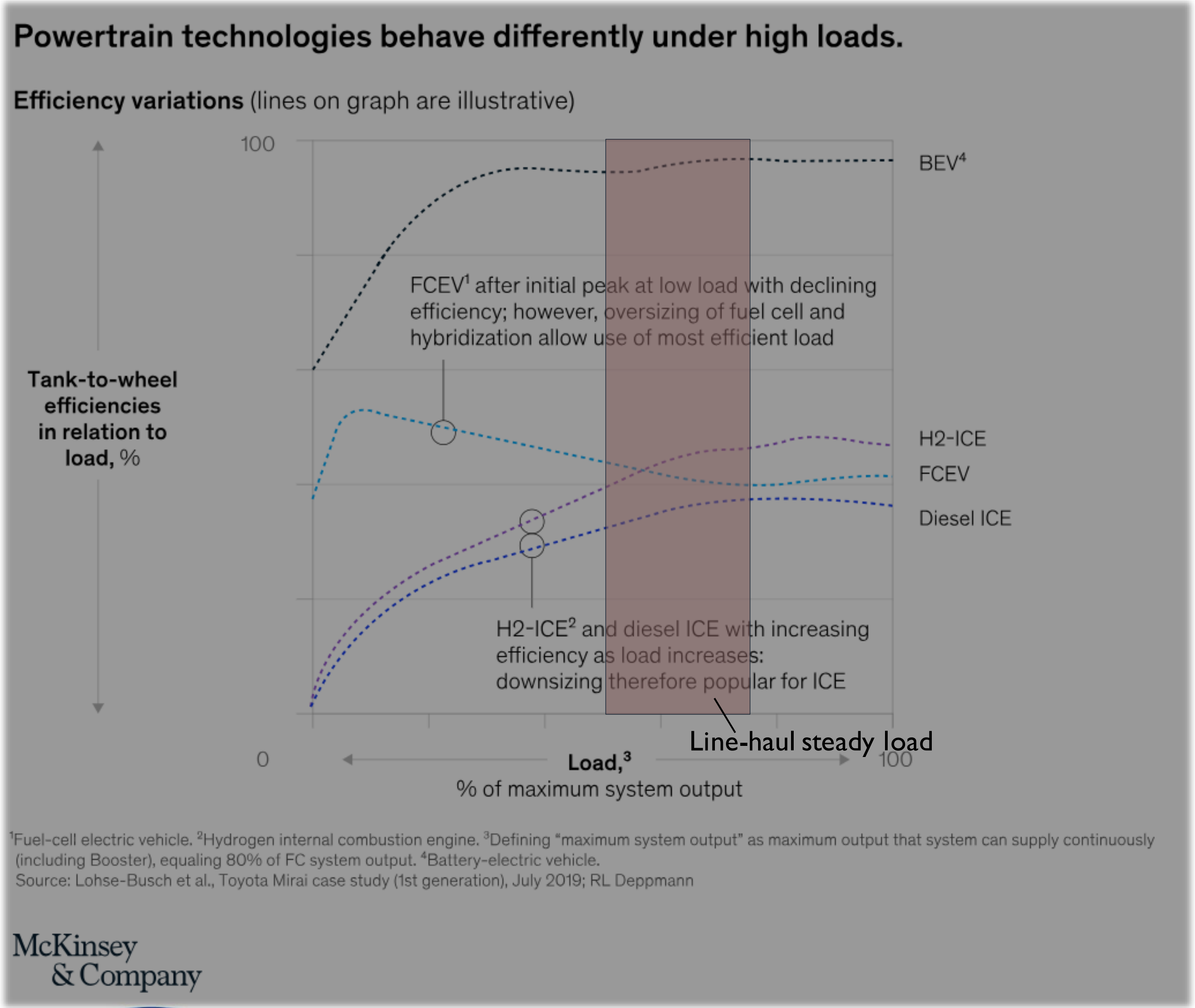


Diesel Low NO_X AT System



H2-ICE Low NO_X AT System

H_2-ICE vs. FC Truck Efficiency



- The relative performance between FCEV and H_2-ICE depends on application
  - Class 8 Line-Haul tends to run at 50-75% of peak and H_2-ICE will have similar H_2-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
    - H_2-ICE could be hybridized (at a lower cost compared to FCEV) to show same/similar vehicle fuel economy
  - H_2-ICE is more tolerant of impurities in the fuel supply and potentially able to use lower-cost grades of H_2

Image source: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-hydrogen-combustion-engines-can-contribute-to-zero-emissions

Wrap-Up

- H_2-ICE provides a cost-effective, zero-impact bridge between diesel ICE and H_2-FCEV
  - Immediate, large-scale reduction in GHG combined with ultra-low NOx emissions
  - Low impact on current ICE architecture
- H_2-ICE can provide important incentives for infrastructure investments to enable future FCEV applications
- Hybridized H_2-ICE can deliver the same, or better, fuel economy than a FCEV