Opportunity for Hydrogen Engines in Heavy-Duty Trucking

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Emission Control Technologies 2024

New Delhi, India

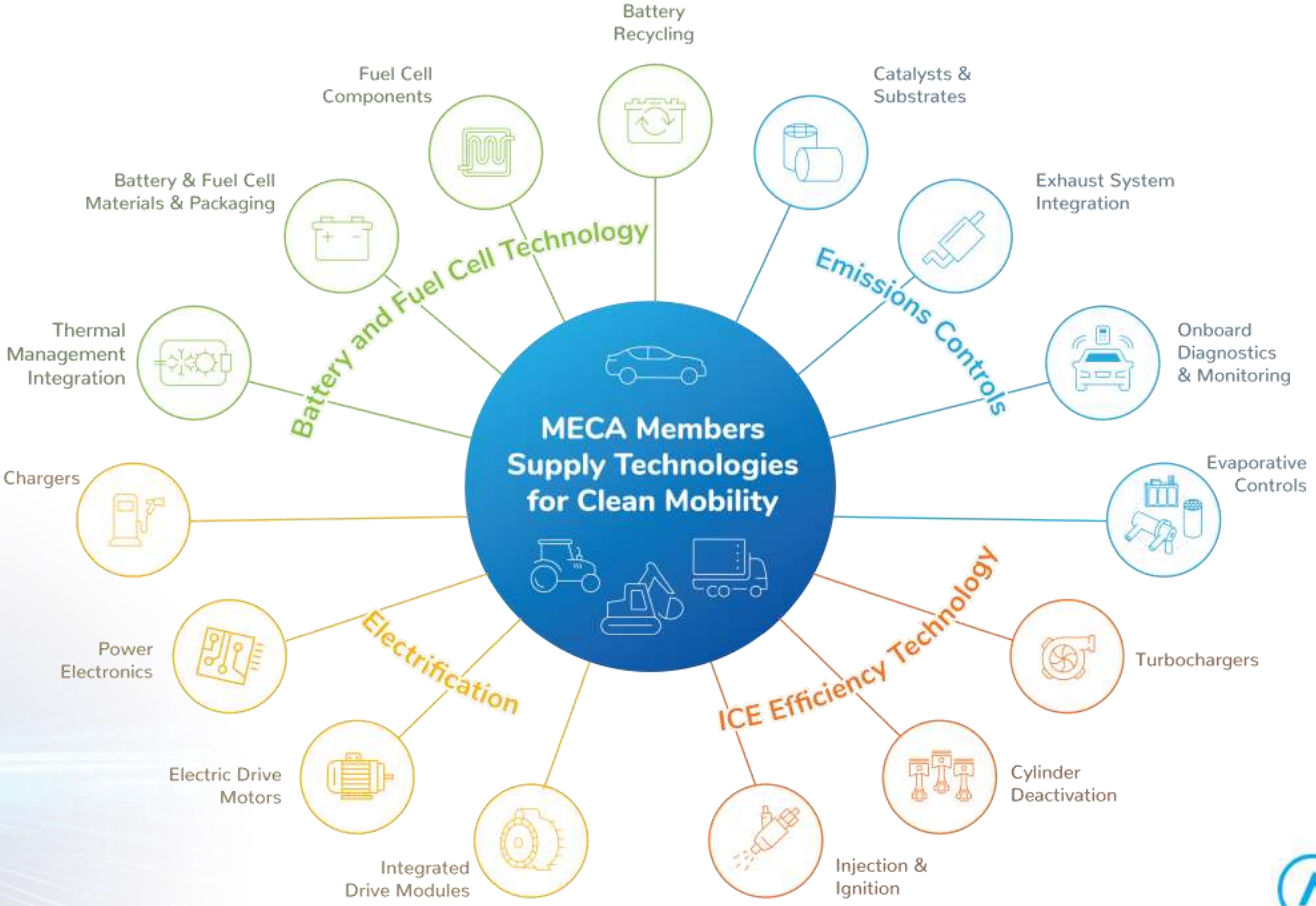
SUPPLYING CLEAN MOBILITY

Outline

Hydrogen engine's role in meeting climate and air quality goals

Engine and aftertreatment technology

Role of Government Policies



MECA Members Supply Technologies for Clean Mobility

Battery and Fuel Cell Technology

Thermal Management Integration

Battery & Fuel Cell Materials & Packaging

Fuel Cell Components

Battery Recycling

Emissions Controls

Catalysts & Substrates

Exhaust System Integration

Onboard Diagnostics & Monitoring

Evaporative Controls

ICE Efficiency Technology

Turbochargers

Cylinder Deactivation

Injection & Ignition

Electrification

Integrated Drive Modules

Electric Drive Motors

Power Electronics

Chargers

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Hydrogen Engine's Role in Meeting Climate and Air Quality Goals

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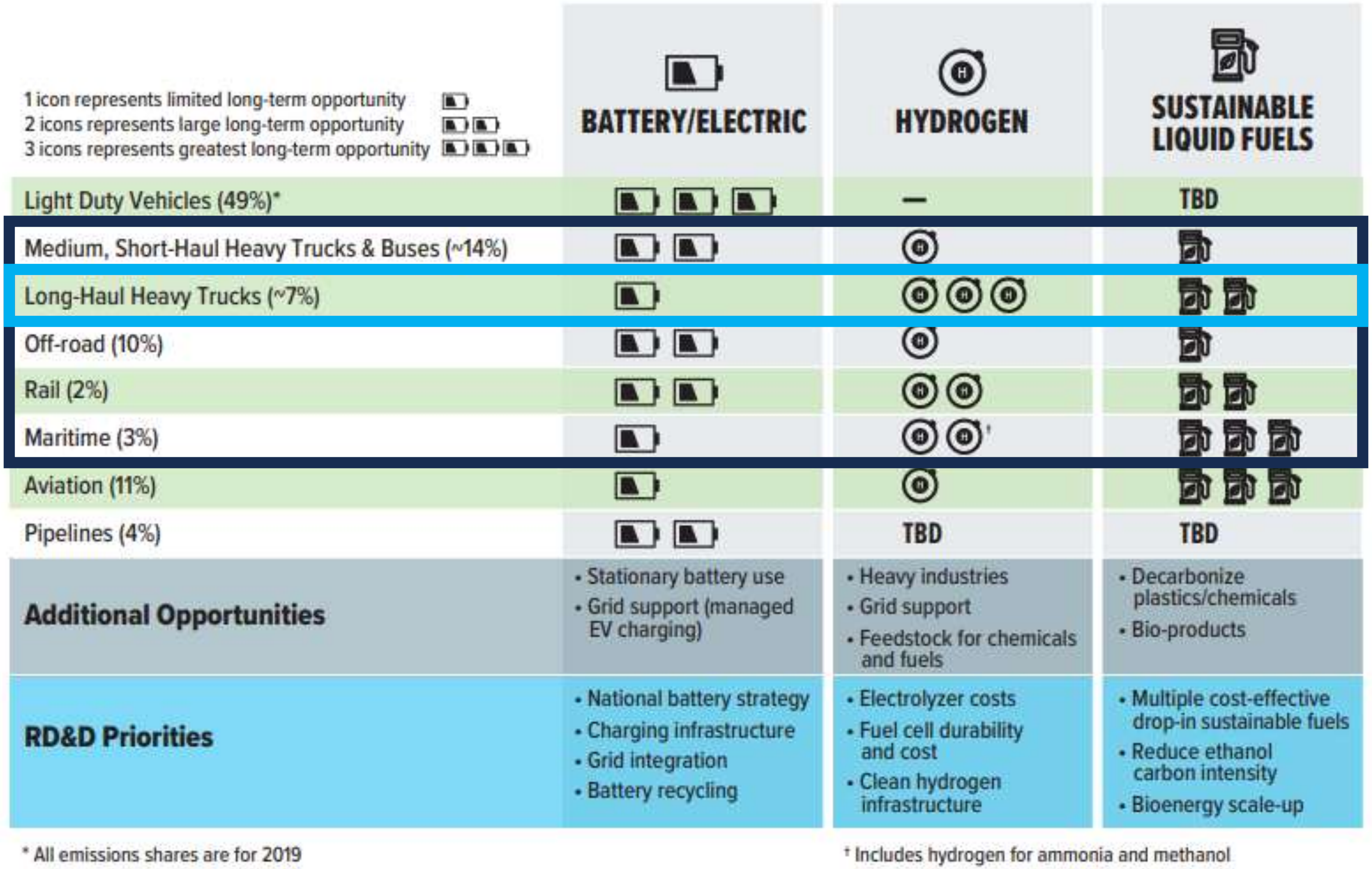
US National Blueprint for Transportation Decarbonization



1 icon represents limited long-term opportunity 🔋
2 icons represents large long-term opportunity 🔋🔋
3 icons represents greatest long-term opportunity 🔋🔋🔋

	BATTERY/ELECTRIC	HYDROGEN	SUSTAINABLE LIQUID FUELS
Light Duty Vehicles (49%)*	🔋🔋🔋	–	TBD
Medium, Short-Haul Heavy Trucks & Buses (~14%)	🔋🔋	Ⓗ	⛽
Long-Haul Heavy Trucks (~7%)	🔋	ⒽⒽⒽ	⛽⛽
Off-road (10%)	🔋🔋	Ⓗ	⛽
Rail (2%)	🔋🔋	ⒽⒽ	⛽⛽
Maritime (3%)	🔋	ⒽⒽ†	⛽⛽⛽
Aviation (11%)	🔋	Ⓗ	⛽⛽⛽
Pipelines (4%)	🔋🔋	TBD	TBD
Additional Opportunities	• Stationary battery use • Grid support (managed EV charging)	• Heavy industries • Grid support • Feedstock for chemicals and fuels	• Decarbonize plastics/chemicals • Bio-products
RD&D Priorities	• National battery strategy • Charging infrastructure • Grid integration • Battery recycling	• Electrolyzer costs • Fuel cell durability and cost • Clean hydrogen infrastructure	• Multiple cost-effective drop-in sustainable fuels • Reduce ethanol carbon intensity • Bioenergy scale-up

* All emissions shares are for 2019

† Includes hydrogen for ammonia and methanol

OEMs and Suppliers Supporting a Three-Pronged Strategy to Decarbonize HD Transportation

H_2-ICE

- Drop-in replacement
- Existing manufacturing base
- Known maintenance
- Lowest initial cost

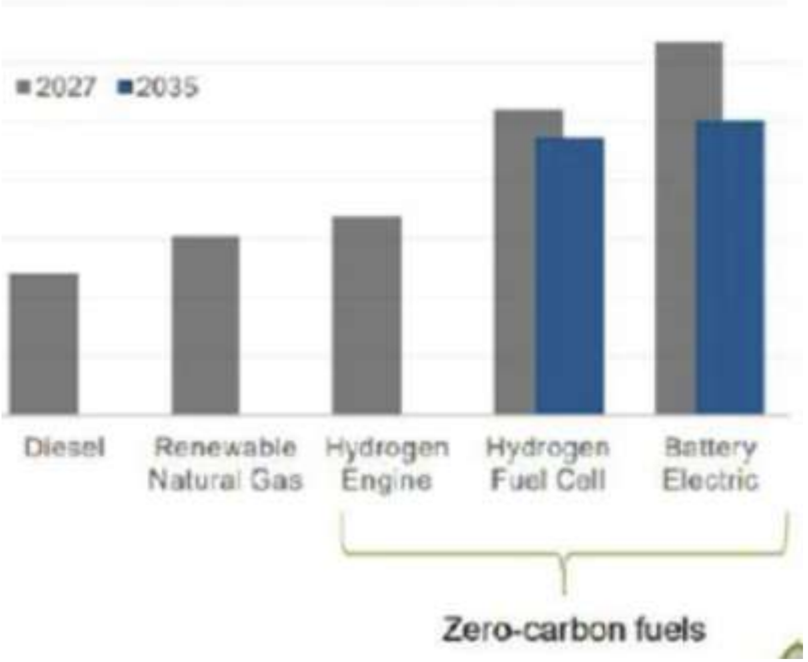
FCEV

- Zero Tailpipe emissions
- High *conversion* efficiency
- Smaller battery size

BEV

- Zero Tailpipe.
- Low maintenance costs
- Low operating cost

Vehicle Purchase Price Forecast



Source: Cummins

Multiple pathways may provide range of solutions to address infrastructure challenges

Broad Industry Support for H_2-ICE Engines

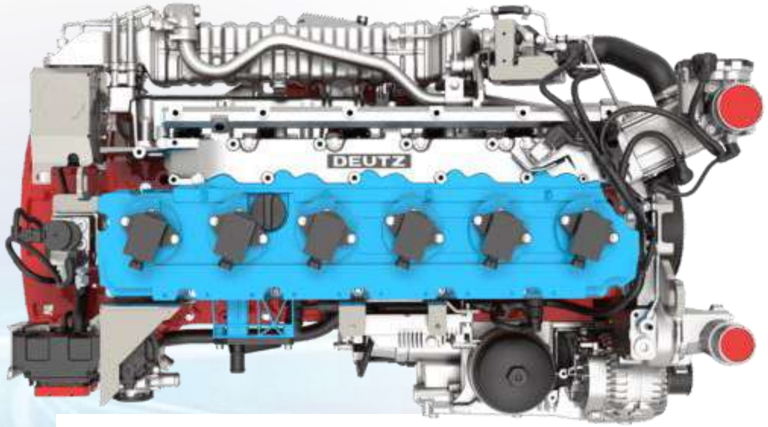
JCB Announces Hydrogen Fuel Combustion Engine Technology

Cummins Newsroom: Hydrogen Technologies

CUMMINS BEGINS TESTING OF HYDROGEN FUELED INTERNAL COMBUSTION ENGINE

Jul 13, 2021 ▪ Columbus, Ind.

MAHLE supports Liebherr in developing hydrogen-fueled heavy-duty engines



DEUTZ hydrogen engine ready for the market

Press Release: AVL and SuperTurbo™ Technologies Partner on Hydrogen Engine Application

Caterpillar to Expand Hydrogen-Powered Solutions to Customers

September 1, 2021

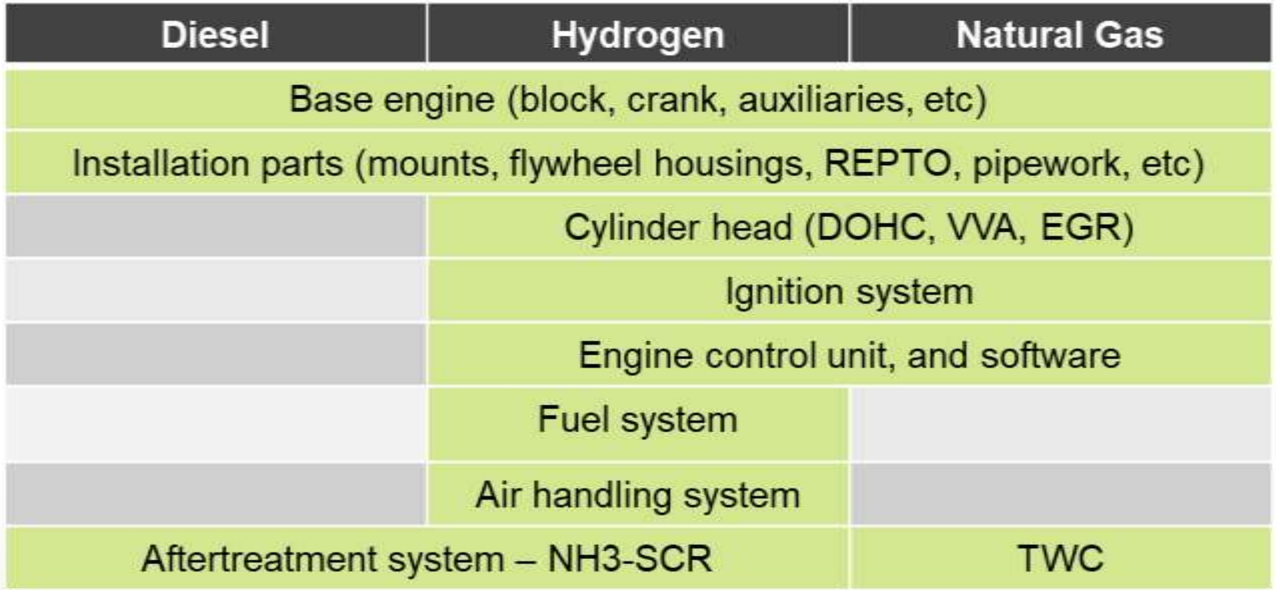
FOR IMMEDIATE RELEASE

FEV pushing hydrogen IC engine development

H2 – key player in the Maritime Energy Transition

MAN Energy Solutions
Future in the making

Technology Commonality Accelerates Cost Parity with FCEVs



<table>
<tr><th>Diesel</th><th>Hydrogen</th><th>Natural Gas</th></tr>
<tr><td colspan="3">Base engine (block, crank, auxiliaries, etc)</td></tr>
<tr><td colspan="3">Installation parts (mounts, flywheel housings, REPTO, pipework, etc)</td></tr>
<tr><td></td><td colspan="2">Cylinder head (DOHC, VVA, EGR)</td></tr>
<tr><td></td><td colspan="2">Ignition system</td></tr>
<tr><td></td><td colspan="2">Engine control unit, and software</td></tr>
<tr><td></td><td>Fuel system</td><td></td></tr>
<tr><td></td><td>Air handling system</td><td></td></tr>
<tr><td colspan="2">Aftertreatment system – NH3-SCR</td><td>TWC</td></tr>
</table>

<table>
<tr><th>H2 Fuel Cell</th><th>H2 ICE</th></tr>
<tr><td colspan="2">H_2 production</td></tr>
<tr><td colspan="2">H_2 distribution</td></tr>
<tr><td colspan="2">H_2 filling station availability</td></tr>
<tr><td colspan="2">On-board H_2 storage</td></tr>
<tr><td>Needs electrification of driveline & accessories</td><td>Uses existing drivelines & accessories</td></tr>
<tr><td>No aftertreatment</td><td>Requires aftertreatment</td></tr>
</table>

- H2-ICE can serve as alternate hydrogen technology by utilizing existing powertrain technologies to keep up front capital costs low. Facilitates training and transition of labor force to future technology.
- Offers near term advantages in total cost of ownership, existing maintenance practices
- Would create a market for green hydrogen to support build-out of infrastructure.

Creates Business Case for Hydrogen Fueling Technology

Allows fleets to seamlessly transition to fuel cell technology

Technology & product portfolio

Gaseous H2 supply – Compressor

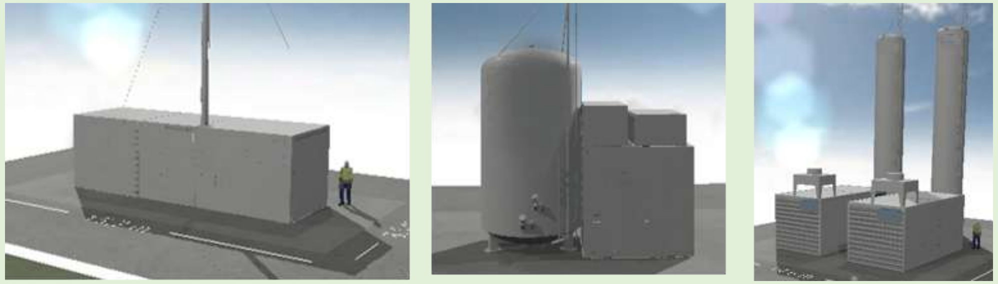
- Outlet pressures	500 or 900 bar
- Inlet pressure	5 – 200 bar
- Capacity	28 or 56 kg/hour
- Efficiency	1 – 3,3 kWh/kg

Compressor based hydrogen refueling stations

Liquid H2 supply – Cryogenic Pump

- Outlet pressures	500 or 900 bar
- Inlet pressure	2 – 2,5 bar
- Capacity	40 or 100 kg/hour
- Efficiency	1,3 – 1,5 kWh/kg

Cryogenic Pump based hydrogen refueling stations



Applications

Material handling

Light vehicles

Buses

Trucks

Trains

Source: Linde plc

Hydrogen Engine and Aftertreatment Technology

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Industry consortium demonstrating hydrogen pathway to decarbonizing on-road sector but applicable to nonroad

WOODWARD

Cummins

ExxonMobil

BOSCH

CATERPILLAR®

aramco

MECA
SUPPLYING CLEAN MOBILITY

H_2 ICE
ZERO CARBON FUEL
ULTRA-LOW EMISSIONS

DAIMLER TRUCK
North America

FORVIA
·faurecia

MAHLE

SUPERTURBO™
TECHNOLOGIES

Chevron

Oronite

Afton®
CHEMICAL

HD HYUNDAI
INFRACORE

SwRI®

PHINIA

JCB

Allison
Transmission

MECA
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Industry consortium demonstrating hydrogen pathway to decarbonizing hard-to-electrify sectors

Program Targets

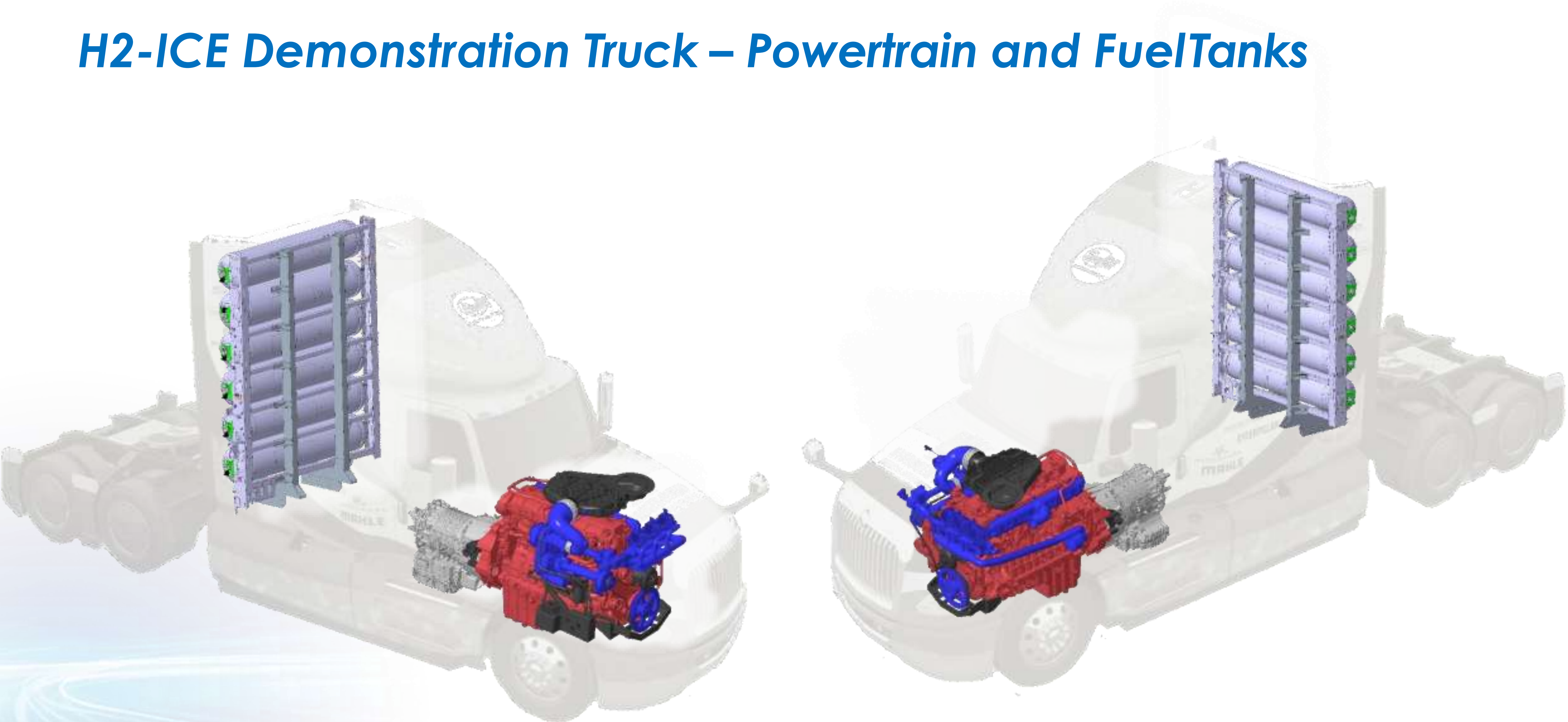
Efficiency:

- 40-45% Peak BTE

Emissions:

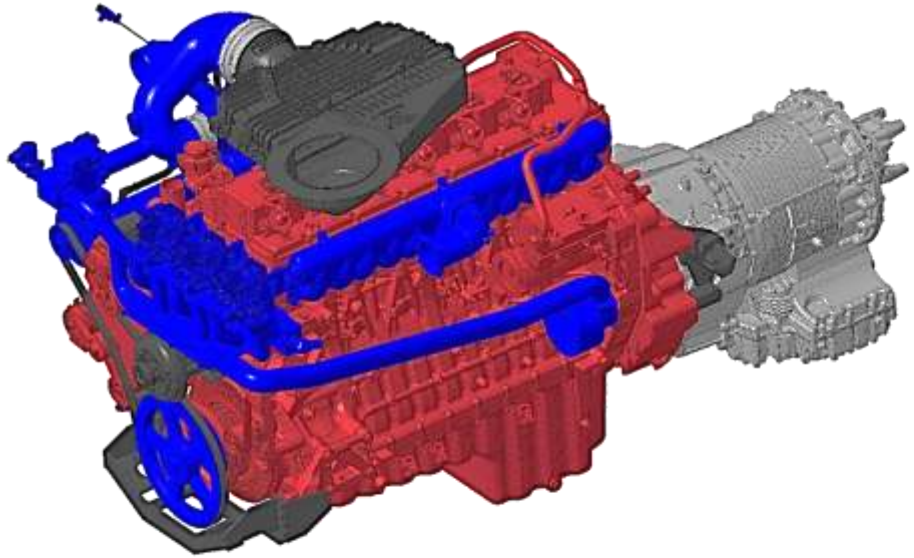
- < 0.02 g/hp-hr)
- < 1.0 g CO_2/hp-hr (99.9% reduction from diesel trucks)

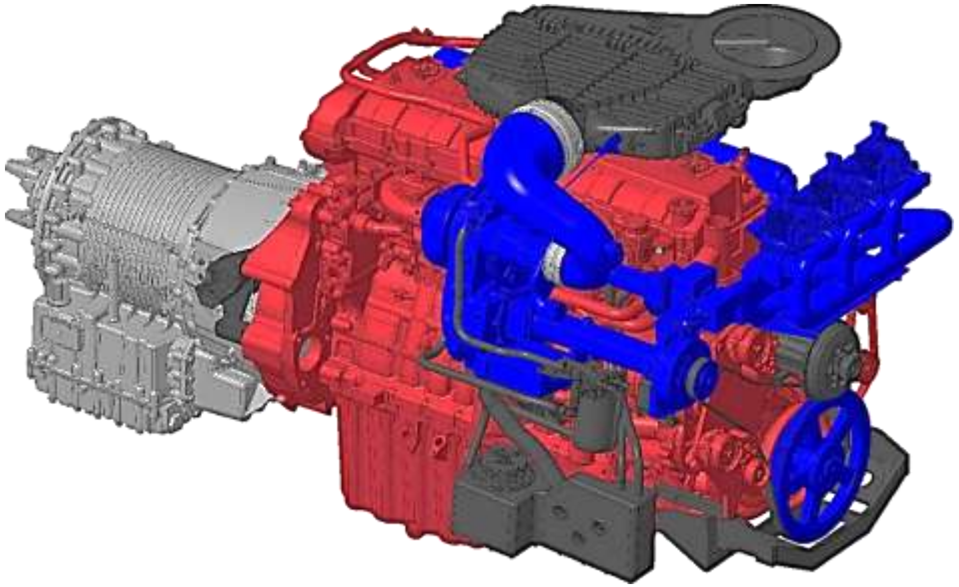
H2-ICE Demonstration Truck – Powertrain and FuelTanks



Engine Hardware Changes

- Removal of OEM Hardware from Cummins X15N
- **Addition of Hydrogen Hardware (Blue)**
  - **SuperTurbo**
  - **Port Fuel Injection System**
  - **Ignition System**
  - **Crankcase Ventilation System**

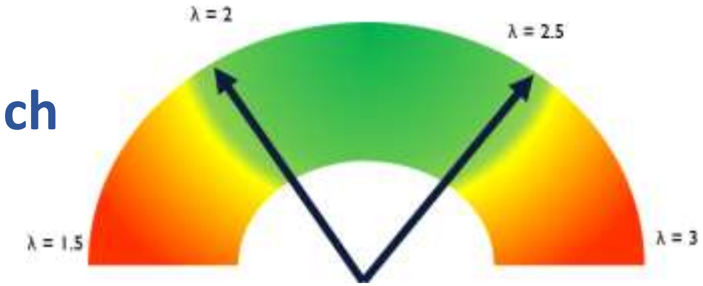




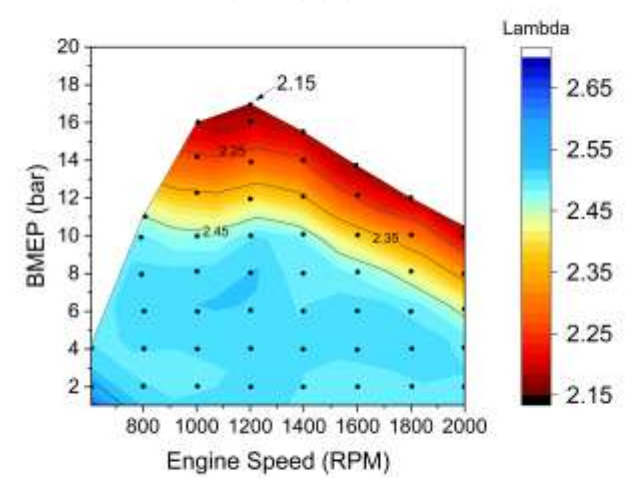
Red – Cummins X15N Engine
Gray – Allison 4000 HS Transmission
Blue – H_2 ICE Specific components
Black –Vehicle Specific Components

Calibration of the Engine and Exhaust Temperature Creates Optimal Conditions for near Zero NOx and CO_2

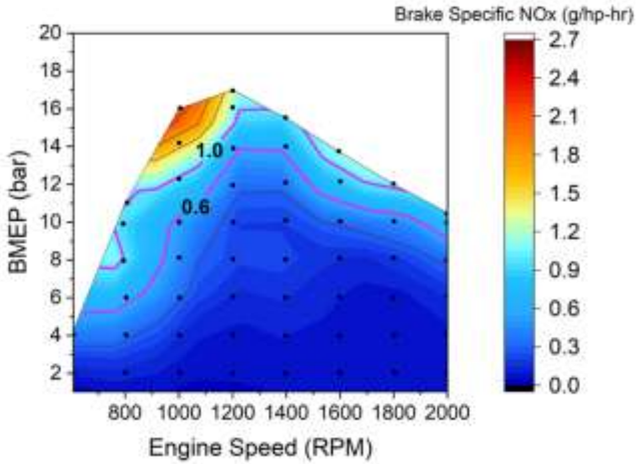
- Unique turbo design and engine integration allowed for air/fuel ratio tight lambda control around λ=2.1-2.5 over entire engine map
- Lambda of 2.1-2.5 maintained brake thermal efficiency (BTE%) around 40% with peak efficiency of 43%
- Turbine out temperature is maintained between 300°C – 350°C which is ideal for NO_X conversion
- Higher exhaust temperature and short heat-up time avoids N_2O formation at temperatures below 300°C



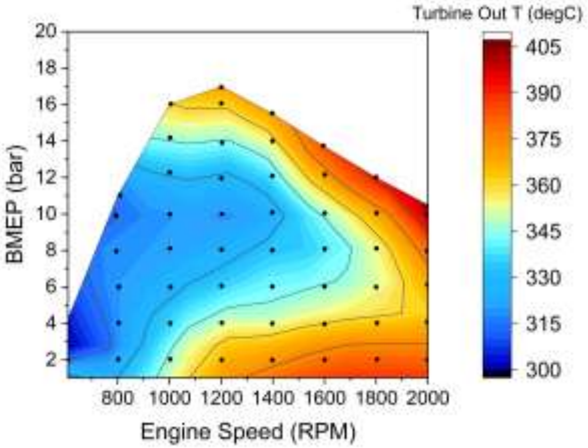
Lambda



NO_X (0.6 g/hph on cycles)

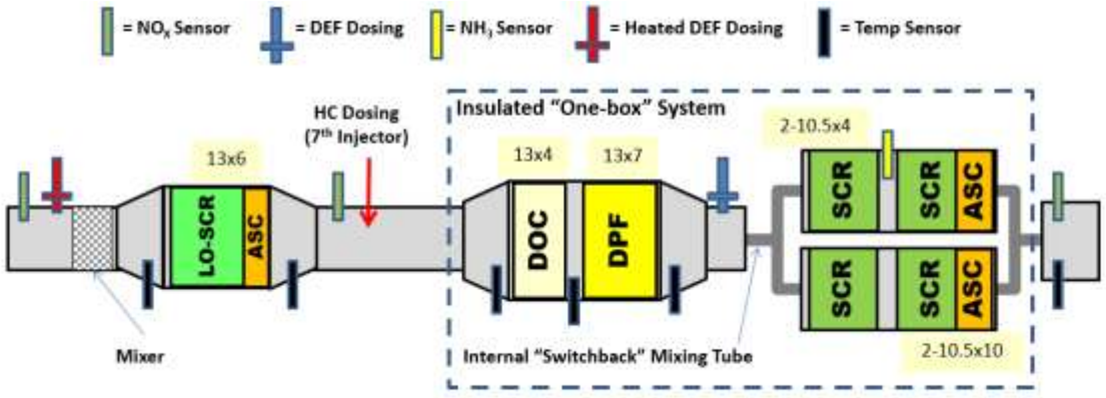


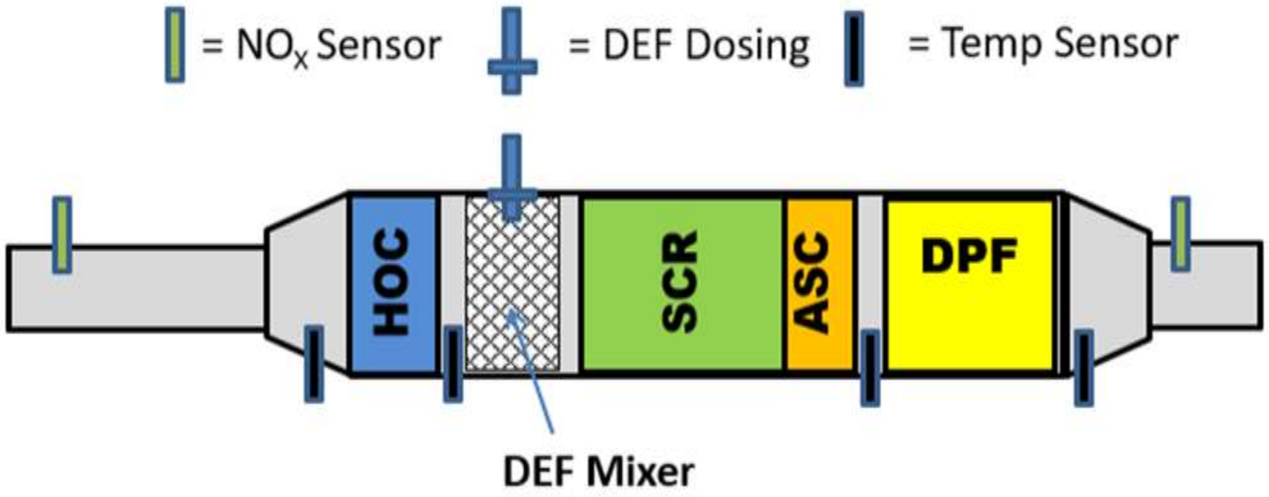
Temperature



Suppliers are Addressing NOx with Streamlined Aftertreatment

Diesel Low NO_X AT System





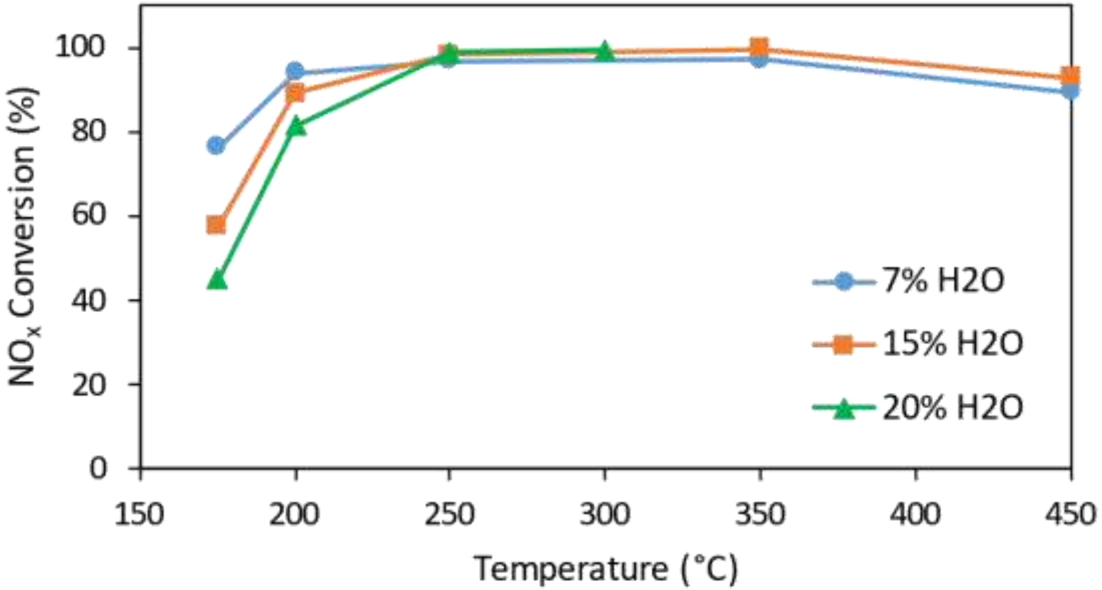
H2-ICE Low NO_X AT System

- Lean combustion and NOx emission control with existing aftertreatment solutions provides best performance with lowest emissions.
- Particulate emissions like CNG mainly from lubricating oil can be addressed with conventional particulate filter.
- Catalyst and temperature control to manage N_2O
- Catalyst solutions exist to tackle NOx
  - Close-coupled oxidation catalyst for thermal management and feed gas for SCR

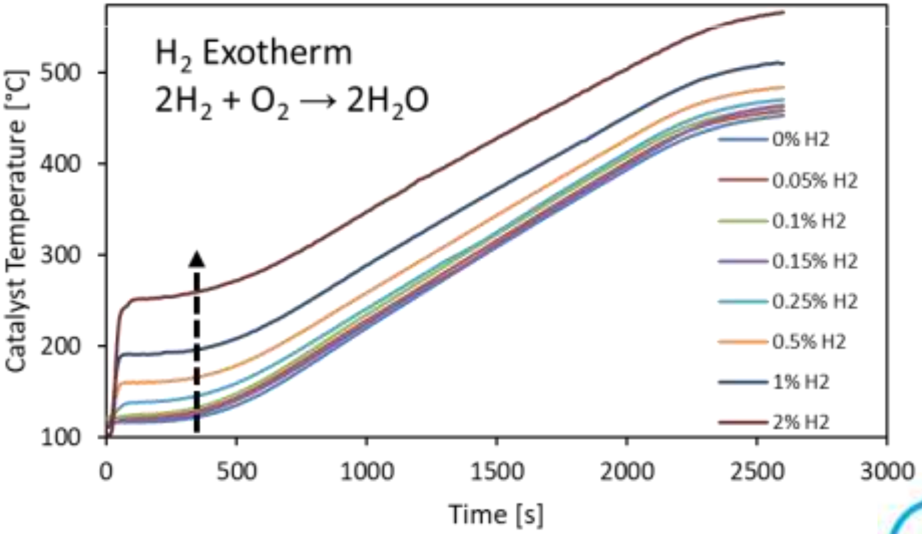
Aftertreatment Performance

Bench evaluation of catalysts showed no negative impact from water concentrations in H_2 exhaust above 250 °C

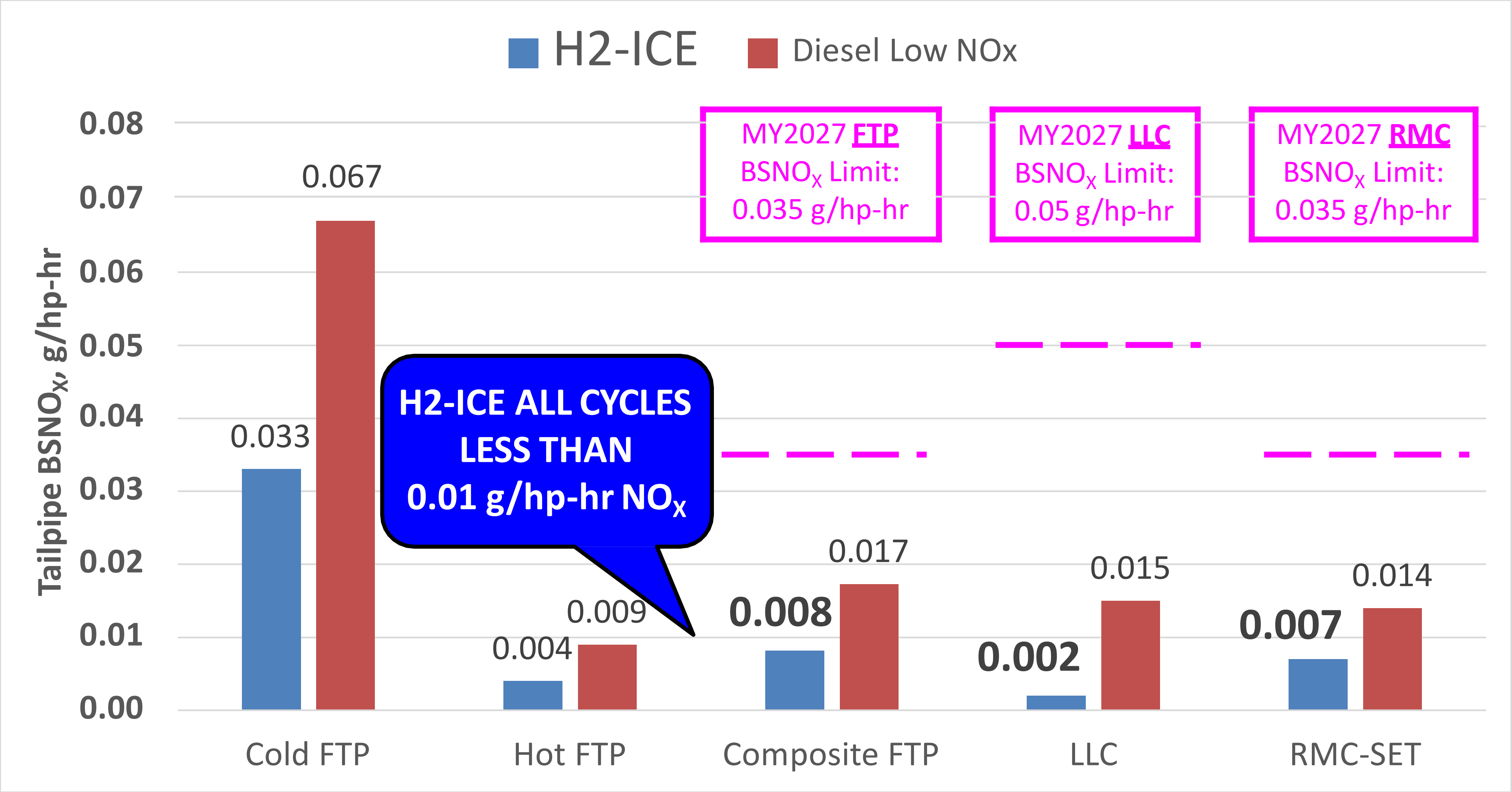
- Conversion at 300 °C is over 99%



Oxidation catalyst showed strong exotherm from hydrogen slip, minimizes low-temperature operating window for minimal N_2O formation



Tailpipe BSNO$_X$ Results – Better Than Low NO$_X$



MY2027 **FTP** BSNO$_X$ Limit: 0.035 g/hp-hr

MY2027 **LLC** BSNO$_X$ Limit: 0.05 g/hp-hr

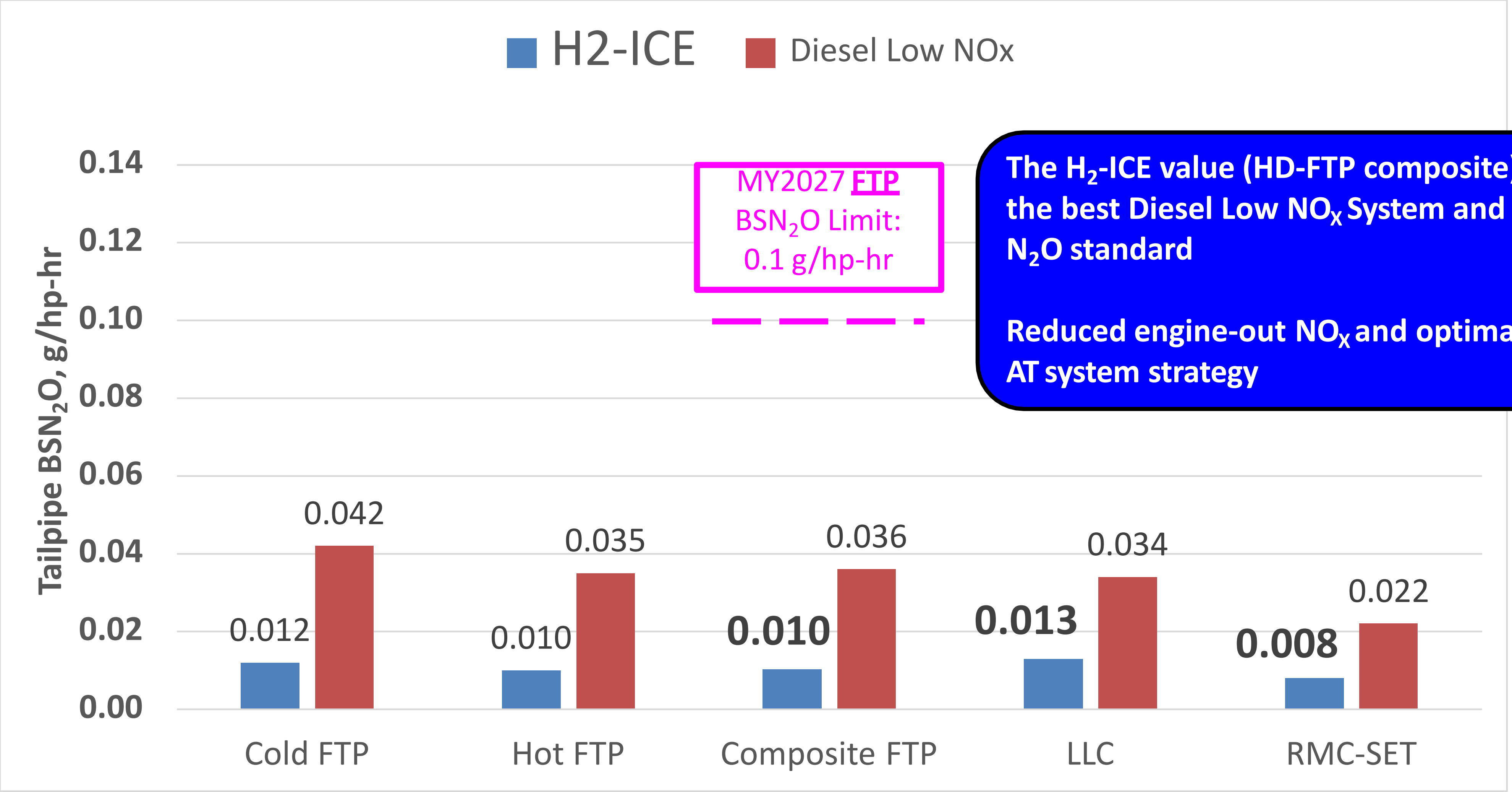
MY2027 **RMC** BSNO$_X$ Limit: 0.035 g/hp-hr

H2-ICE ALL CYCLES LESS THAN 0.01 g/hp-hr NO$_X$

Diesel +/- 0.002 g/hp-hr
H2-ICE +/- 0.001 g/hp-hr

H2-ICE is *significantly* better than best Diesel Low NO$_X$

Tailpipe BSN_2O Results – Much Better than Low NO_X



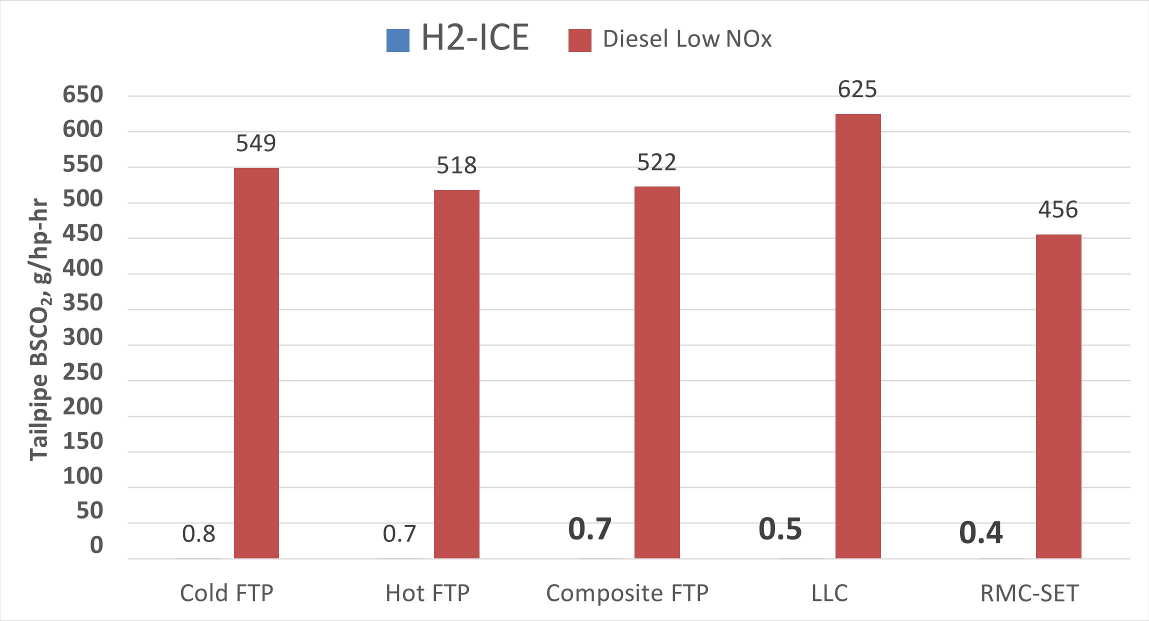
	H2-ICE	Diesel Low NOx
Cold FTP	0.012	0.042
Hot FTP	0.010	0.035
Composite FTP	0.010	0.036
LLC	0.013	0.034
RMC-SET	0.008	0.022

The H_2-ICE value (HD-FTP composite) is 1/3rd of the best Diesel Low NO_X System and 1/10th of N_2O standard

Reduced engine-out NO_X and optimal engine-AT system strategy

N_2O is not a concern for *properly designed* H2-ICE, and in fact is *significantly* better than best Diesel Low NO_X

Tailpipe Net CO_2 Emissions



- **99.9% CO_2 Reduction with H2-ICE**
  - Remaining CO_2 is mostly from DEF injection for NO_X control
- **H2-ICE < 1 g/hp-hr CO_2** on all cycles
  - Diesel ~ 450-625 g/hp-hr CO_2

CO_2 Concentrations

Location	Average CO_2 Concentration, ppm
Ambient Air	420
H2-ICE Exhaust Cold FTP	480
H2-ICE Exhaust Hot FTP	490
H2-ICE Exhaust LLC	430
H2-ICE Exhaust RMC	470

- H2-ICE exhaust CO_2 is only slightly above ambient, **~+60ppm from ambient**
- For comparison Diesel cycle average is **~+5% from ambient** (~800X higher than H2-ICE)

Summary of H2ICE Demonstration

Engine and vehicle successfully converted to operate on H2

- Including updated aftertreatment system and actual measured emissions data generated on all cycles

Measured tailpipe NOx levels are <10 mg/hp-hr on all U.S. regulatory cycles

Tailpipe CO2 levels show consistent 99.9% reduction from comparable diesel platform

N2O levels are well below diesel and 10% of current standard

HC, CO and PM are all zero

Tailpipe emission levels are near zero or zero for all measured pollutants and CO2

The Role of Government Policies

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Government Support Needed in Hydrogen Transition

- **Regulations should be designed to not be a barrier to clean H2-ICE technology**
  - EU HD CO_2 regulations propose to treat H2-ICE as zero carbon in VECTO
  - China's policy supports diverse technology paths and hydrogen infrastructure
  - EPA Phase 3 treat hydrogen as zero carbon in GEM
  - Regulations that require zero-emission technologies should consider H2-ICE as partial or full compliance, especially if BEVs or FCEVs are not viable
- **Incentives needed to promote technology through DERA and state agency programs**
- **Infrastructure availability must begin to be utilized to justify investment**
- **The U.S. Department of Energy has several hydrogen initiatives:**
  - H2@Scale,
  - Hydrogen Shot
  - Hydrogen Hubs
  - Research funding through national labs

Hydrogen Combustion Summary

- **Zero carbon option for early reductions in the 10-15 year time horizon**
  - Existing manufacturing would allow scale production by 2027
  - Zero-carbon with green hydrogen
- **Complementary with a hydrogen fuel cell future**
  - Drives buildout of hydrogen fueling infrastructure
  - Reduces hydrogen cost by creating business case
  - Builds scale for hydrogen storage tanks on vehicle
- **Fits with carbon neutral transportation goals**
  - Fills need where BEV or FCEV challenges exist
- **Benefits to fleets**
  - Competitive initial capital cost
  - Drop-in powertrain replacement for regional haul / long haul
  - Familiar technology, and existing maintenance, workforce and practices
  - Seamless fuel transition with FCEV cost parity
- **Regulations should not be a barrier to clean H2-ICE technology**
  - EU HD CO_2 regulations treat H2-ICE as zero carbon in VECTO when CO_2 is less than 3 g/tonne-km
  - EPA Phase 3 treat hydrogen ICE as zero carbon emitting vehicle in GEM
  - EPA Phase 3 engine CO_2 emissions default value for H2-ICE is 3 g/bhp-hr