

Engineering the Ford Hydrogen Internal Combustion Engine E-450 Shuttle Bus Pilot Fleet

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E-450 H2ICE Shuttle Bus Fleet Team

- ▶ **Alan Richardson: Fuel System Engineer**
- ▶ **Adam Denlinger: Engine Program Management Team Leader**
- ▶ **Al Schamp: Electrical Engineer**
- ▶ **Brian Tillman: Engineer Vehicle Assembly**
- ▶ **James Herber: Vehicle Assembly Coordinator**
- ▶ **Mike Kozykoski: Engineer Vehicle Testing**
- ▶ **Matthew Fast: Vehicle Service Coordinator**
- ▶ **Colby Buckman: Calibration Engineer**
- ▶ **Tom Vaught: Engineer Supercharger**
- ▶ **Tejas Chayya: Hydrogen Management System Engineer**
- ▶ **Kevin Reed: NVH Engineer**
- ▶ **Matt Younkins: Engineer Dynamometer**
- ▶ **Allison Weimer: H2 Fuel Injector Engineer**
- ▶ **Yonglu Zhao: Quality Engineer**
- ▶ **Chris Buchan: Vehicle and Material Coordinator**
- ▶ **Sam Hashemi: Lead Calibrator**
- ▶ **Steve Szwabowski: Control Strategy Lead**
- ▶ **Rich Williams: Program Management Supervisor**
- ▶ **M.J. Throop: Telematics Technical Specialist**
- ▶ **Ravi Gopalakrishnan: E-450 H2 ICE Vehicle Engineering Team Supervisor**
- ▶ **Bob Natkin: H2 IC Engine Applications Technical Leader**
- ▶ **John Lapetz: Vehicle Program Manager, H2ICE E-450 Shuttle Bus**
- ▶ **Vance Zanardelli: Chief Engineer, H2 IC Engine Department**
- ▶ **Brad Boyer, H2 Research Team Leader**

Overview

- Background
- H2ICE specific vehicle modifications
- Vehicle testing
- Fleet customer service
- Unique H2 Engine Hardware
- Engine Durability Testing Overview
- Engine Targets & Calibration
- Conclusions

Background

2.0L I4



2001 - P2000

2.3L Supercharged I4



2003 - NAIAS Model U



2003 - H2ICE Focus

6.8L Boosted V10



2006 - H2ICE Demo/Fleet



2004 - H2ICE Generator (Generac)



2004 - H2ICE C-Max



2003 - Centennial H2RV



2004 - H2ICE Hybrid Bus (ISE)



2005 - H2ICE Hybrid Bus (Designline)



2004 - H2ICE Rotary (Mazda)



Benefits of Hydrogen Fuel

■ Air Quality

- ⌘ Reduce or eliminate regulated tailpipe emissions (HC, CO, NO_x)

■ Climate Change

- ⌘ Eliminate CO₂ emissions *if H₂ derived from renewable resources*

■ Sustainability

- ⌘ Potential sources of H₂ virtually unlimited (e.g. solar, wind, geothermal, hydroelectric, biomass)

■ Security

- ⌘ Eliminate dependence on imported oil

Strategic Rationale for H2ICE Vehicles

- Provide transition strategy from current petroleum economy to future hydrogen economy
- Advance H2ICE technology from research demonstration level to point of commercial launch
- Promote acceptance of hydrogen as a viable fuel alternative and provide insight into potential fuel concerns
- Provide business rationale to stimulate hydrogen infrastructure and supporting technologies

Benefits of H2 IC Engine Powered Vehicles

- Vehicles are all-weather capable
- H2 IC Engines can become cost competitive with current advanced ICE powertrains as volumes increase
- H2 IC Engines can achieve “Near Zero” regulated tailpipe emissions (SULEV or better) and CO2
- H2ICE Powertrains have been shown to be 10-25% more fuel efficient than gasoline counterparts
- With hybridization and direct injection, efficiency can be comparable with fuel cells

2006 E-450 H2ICE Shuttle Bus Fleet

- E-450 chassis with aftermarket Shuttle Bus body
- 6.8L Supercharged Hydrogen Internal Combustion Engine (H2 ICE)
- 350 Bar/5000 PSI Hydrogen Fuel Storage System
- Hydrogen Management System
- Compliant (not certified) to Canadian and Federal standards
- Vehicle Range: 150 - 200 miles
- Emissions: 2010 Phase II Compliant
- Engine Performance:
 - 310 ft-lb @3000 rpm
 - 235 hp @4000 rpm
- Performance & Reliability equivalent to 2004 Ford CNG Shuttle Bus
- Fleet volume: 30 vehicles
- Vehicle Variable Cost (Pilot Volumes): \$250K
- Customer 2-3 year leases begin: 4Q2006



Vehicle System Modifications

H2 Management System (H2MS)

- H2 Detection Sensors
- H2 Sensing Warning and Controls
- H2 Ventilation System (fans, vents & louvers)
- H2MS Control Module

IP Cluster

- Fuel gauge
- H2 warning

Telematics

- Pentium CPU
- Cellular / Satellite modem
- GPS

Air Intake

- Intake Manifold
- Supercharger (3.3L/ 1.3 – 1.5 Bar Boost)
- Bypass
- New Induction Plumbing

Shuttle Bus Body

- Seat layout
- Tank enclosure
- Removable side panels
- Rear floor modifications
- AC/Heater System modifications

Refueling

- Fuel Fill Connection
- Fuel/Defuel Actuation Switch

Fuel Storage Assembly

- Six H2 Fuel Tanks and Solenoid Valves
- Fill Receptacle
- One High Pressure Regulator (400 PSI)
- Two Trim Regulators (80 PSI)
- Pressure and Temperature Sensors
- Fuel Lines and Valves
- Pressure Relief Outlets

Chassis

- H2 tank mounting brackets
- ½" LP Fuel Lines & clips
- Rear frame extension
- Frame reinforcements

Electrical

- Additional Alternator
- Additional Battery
- Wiring Harnesses

Cooling System

- Radiator
- Mechanical Engine Fan
- Upper & Lower Radiator Hoses
- Intercooler (Charge Air Cooling)
- Degas Bottle
- Radiator (Charge Air Cooling)

H2 ICE Engine

- Fuel Rail/Injectors/ Solenoids FEAD (3 belt)
- New PCV Oil Separator
- Ignition Coil
- Modified Oil Filter Adapter
- Modified Alum. Intake & Oil Pan
- Modified Front Cover

Engine control system

- PCM
- AFCM



H2 Fuel System Initial Design Requirements

- Maximize fuel capacity
 - ≡ **150 mile vehicle range target**
- Minimize total weight of fuel storage and delivery system
 - ≡ **Comply with vehicle weight requirements**
- Package all tanks, valves, regulators and high pressure fuel piping together
 - ≡ **Contain most potential leak sources in one location for easier detection and mitigation actions**

H2 Fuel System Functions

- **Store compressed hydrogen gas**
 - ≡ 29.6 kilograms at 350 bar (5075 psi) and 15 degrees C (full capacity)
 - ≡ 0.6 kilograms at 4.8 bar (70 psi) / 15 C (nominal empty)
 - ≡ 29.0 kilograms nominal useable capacity
- **Deliver hydrogen to engine**
 - ≡ At any flow from 0 to 7 grams/second (25 kg/hr)
 - ≡ At pressure of 4.8 (+/- 0.3) bar gauge (70 psi)
- **Refuel**
 - ≡ Fast fill with data connection to fill station
- **Facilitate maintenance and troubleshooting**
 - ≡ Indicate pressure mechanically for each of 4 sub-systems
 - ≡ De-fuel via unique fitting and manual isolation valve
 - ≡ Isolate all tanks with single manual shutoff valve

H2 Fuel Storage System – Packaging

- **High pressure cylinders do not conform to liquid fuel storage space in chassis**
- **Not enough clearance below chassis**
- **Roof mount not an option due to safety reasons**
- **Rear portion of passenger cabin selected**
 - ≡ Separate compartment with dedicated hydrogen sensors and ventilation is beneficial for safety
 - ≡ Consolidated fuel storage assembly allows full system verification at vendor
 - ≡ Modular installation during vehicle assembly

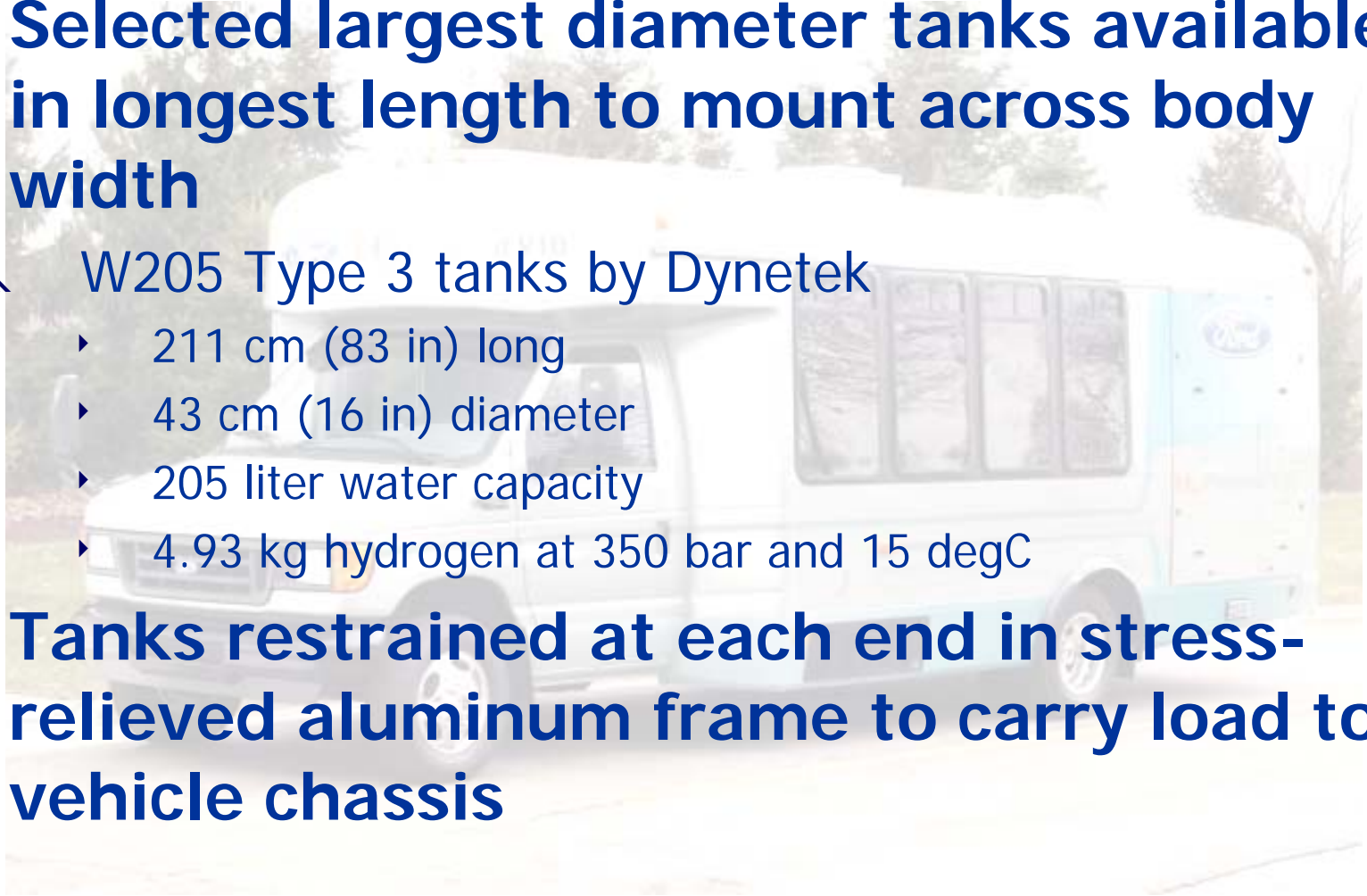
Maximize fuel storage capacity and minimize weight

- **Selected largest diameter tanks available in longest length to mount across body width**

- ▮ W205 Type 3 tanks by Dynetek

- ▶ 211 cm (83 in) long
- ▶ 43 cm (16 in) diameter
- ▶ 205 liter water capacity
- ▶ 4.93 kg hydrogen at 350 bar and 15 degC

- **Tanks restrained at each end in stress-relieved aluminum frame to carry load to vehicle chassis**



Hydrogen Fuel Storage System



- Six H2 tanks
- Aluminum tank frame
- Two regulator stages (5000 psi to 70 psi)
- Control panel for fuel fill and de-fuel
- Pressure relief piping that connects to roof mounted vents

H2 fuel system – External challenges

- **Lack of definitive standards for hydrogen vehicle fuel systems**
 - ≡ Used CNG standards when appropriate
- **Limited supplier base for hydrogen fuel system components**
- **H2ICE vehicle operating temperature range is significantly lower than contemporary fuel cell vehicles (FCVs)**
- **Fuel quality across North America is unknown**

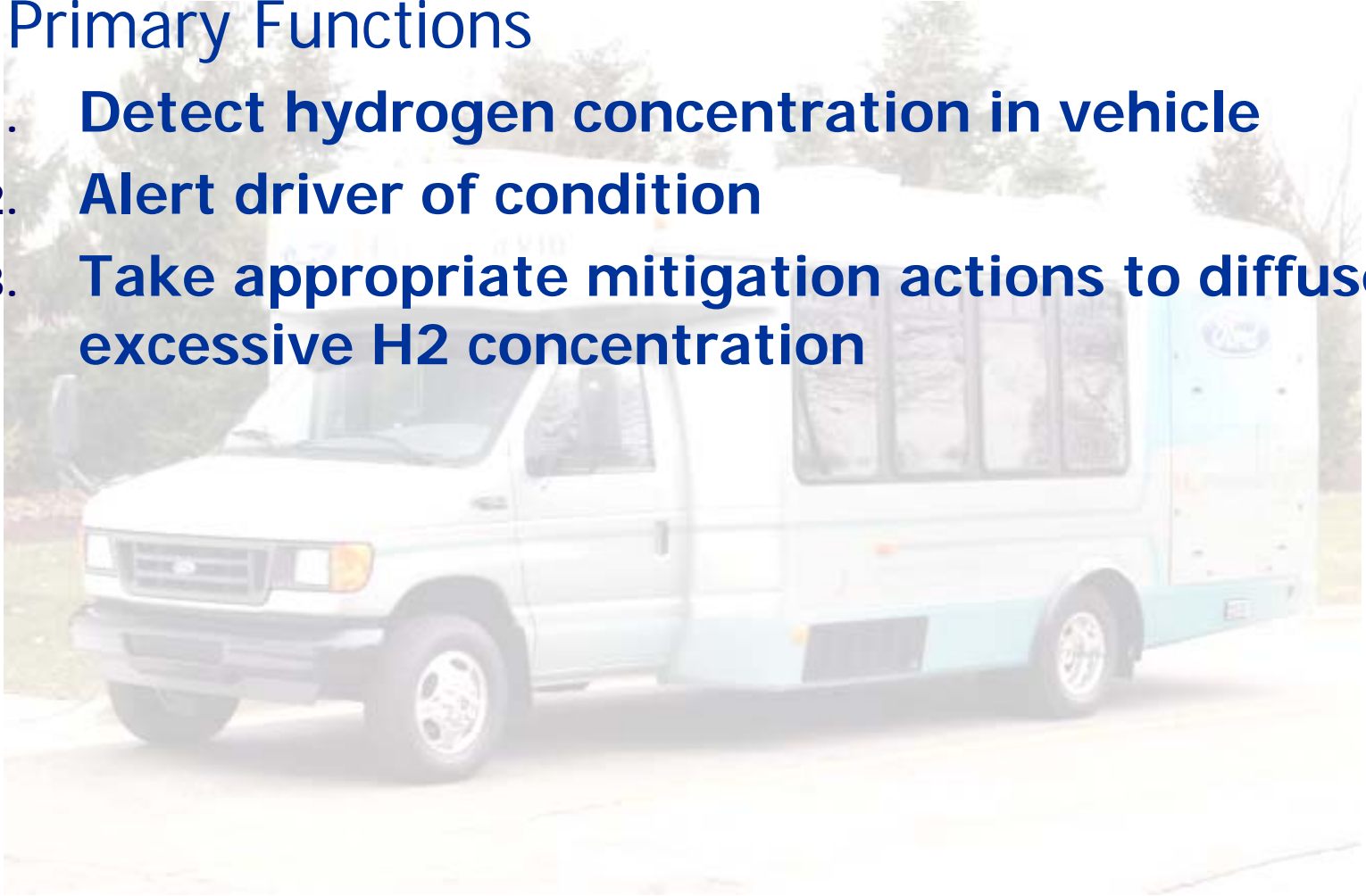
Shuttle Bus Body

- **Shuttle bus body was installed by Corbeil (Montreal, Canada)**
- **Utilized Corbeil's current production shuttle bus design with several improvements and modifications to suit H2ICE application.**
 - ≡ H2 tank enclosure at the rear of the vehicle
 - ≡ Electrical systems
 - ≡ HVAC systems
 - ≡ Body NVH improvements
- **Fleet vehicles have different floor plans with seating capacity ranging from 8 to 12**

Hydrogen Management System (H2MS)

■ Primary Functions

1. **Detect hydrogen concentration in vehicle**
2. **Alert driver of condition**
3. **Take appropriate mitigation actions to diffuse excessive H₂ concentration**



Hydrogen Management System (H2MS) Design

■ System design strategy

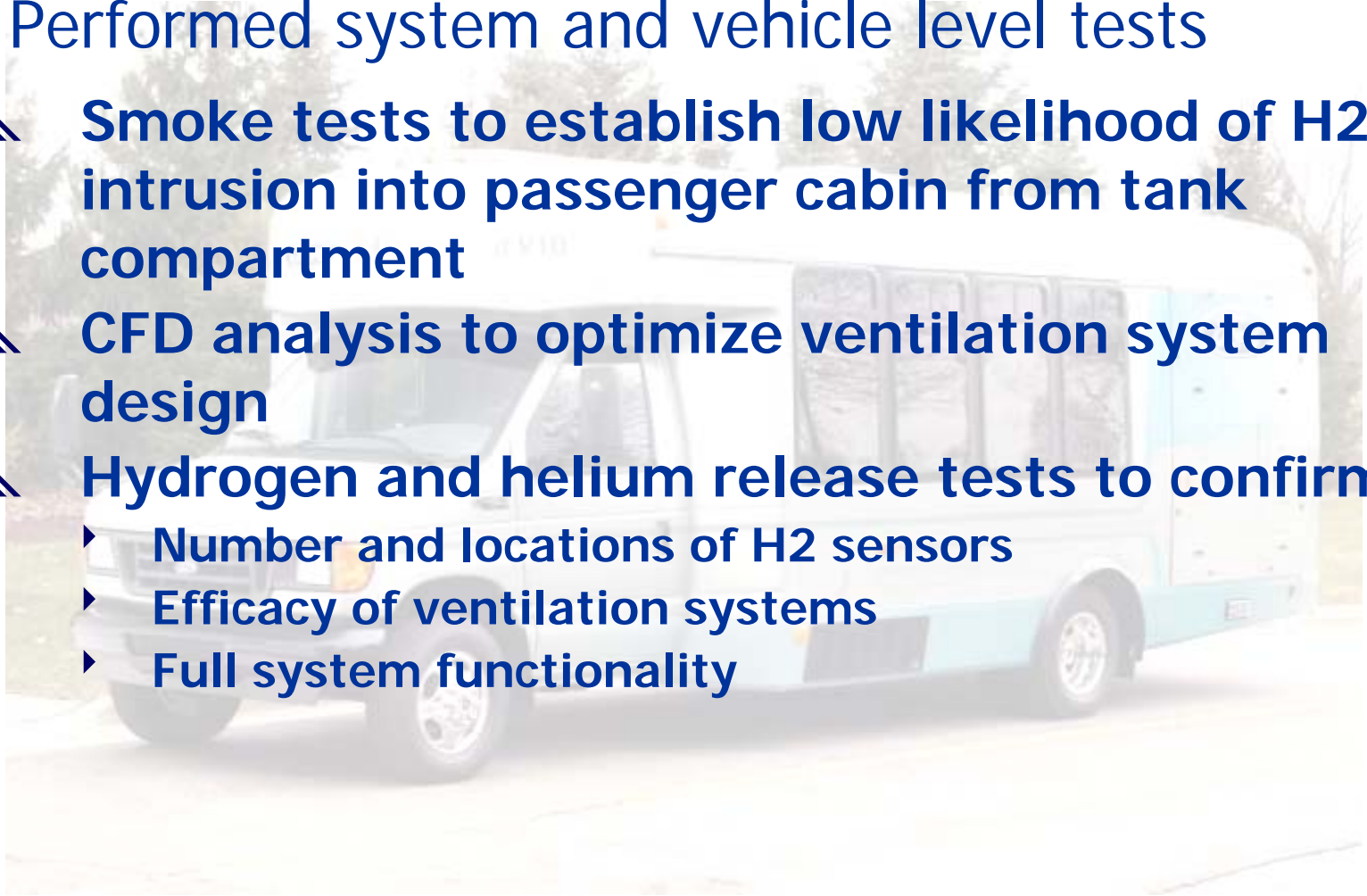
- ≡ Utilized past experience with H2 sensing strategy
- ≡ Used system FMEA and fault tree analysis to
 - ▶ Confirm and quantify functions
 - ▶ Determine prevention and detection actions
 - ▶ Define mitigation actions and control strategy requirements

■ System components

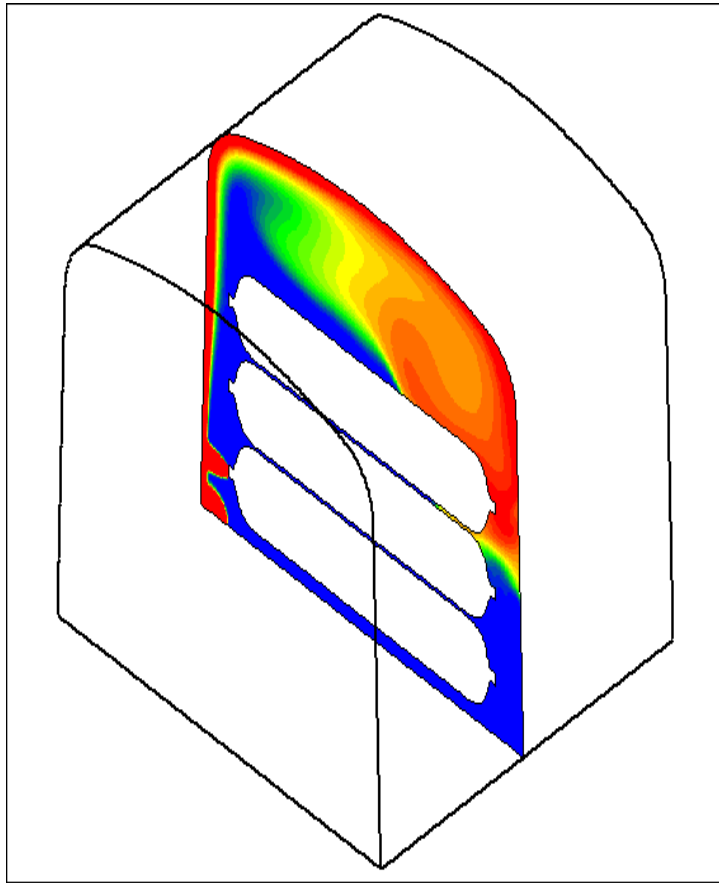
- ≡ (4) H2 concentration sensors
 - ▶ (2) in the tank compartment
 - ▶ (1) in the passenger cabin
 - ▶ (1) under hood
- ≡ (2) Ventilation fans in the tank compartment
- ≡ H2MS system control module

Hydrogen Management System Design Verification

- Performed system and vehicle level tests
 - ≡ Smoke tests to establish low likelihood of H₂ intrusion into passenger cabin from tank compartment
 - ≡ CFD analysis to optimize ventilation system design
 - ≡ Hydrogen and helium release tests to confirm
 - ▶ Number and locations of H₂ sensors
 - ▶ Efficacy of ventilation systems
 - ▶ Full system functionality



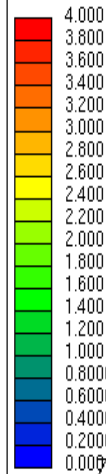
Hydrogen Management System CFD analysis



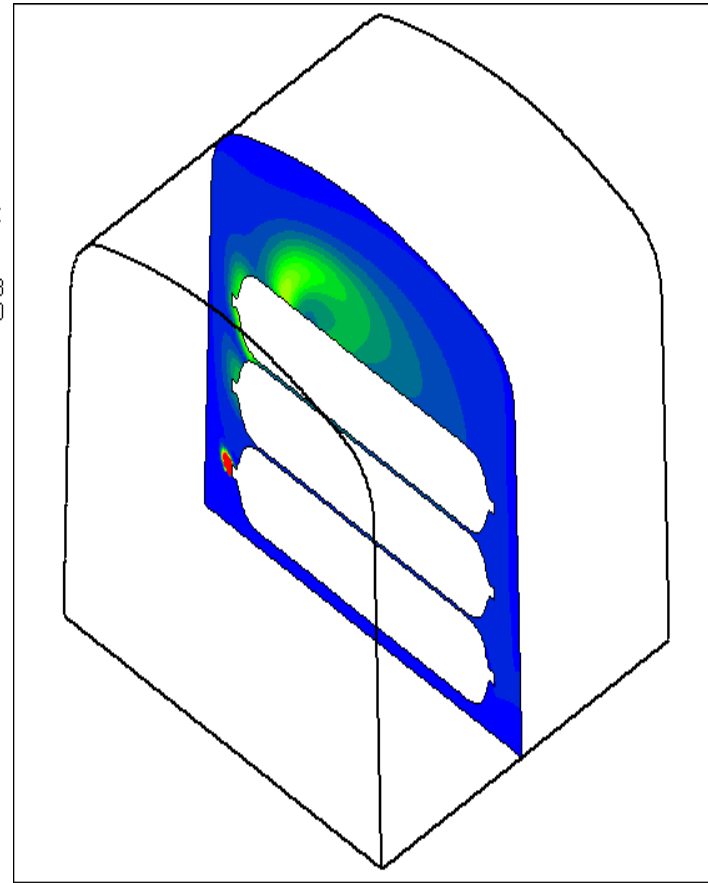
H2 Diffusion in the tank enclosure
H2 leak rate = 10 liter/sec

STAR
D
pro-STAR 3.2

06-SEP-05
H2 Volume percent
%
TIME = 15.0000
LOCAL MX= 65.73
LOCAL MN= 0.000



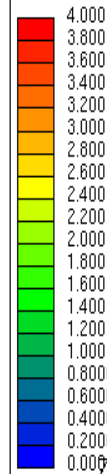
Time = 15.000000 sec



H2 Diffusion in the tank enclosure
H2 leak rate = 10 liter/sec

STAR
D
pro-STAR 3.2

06-SEP-05
H2 Volume percent
%
TIME = 15.0000
LOCAL MX= 67.15
LOCAL MN= 0.4874E-11



Time = 15.000000 sec

Telematics

■ Purpose – to provide a timely report of fleet vehicle performance

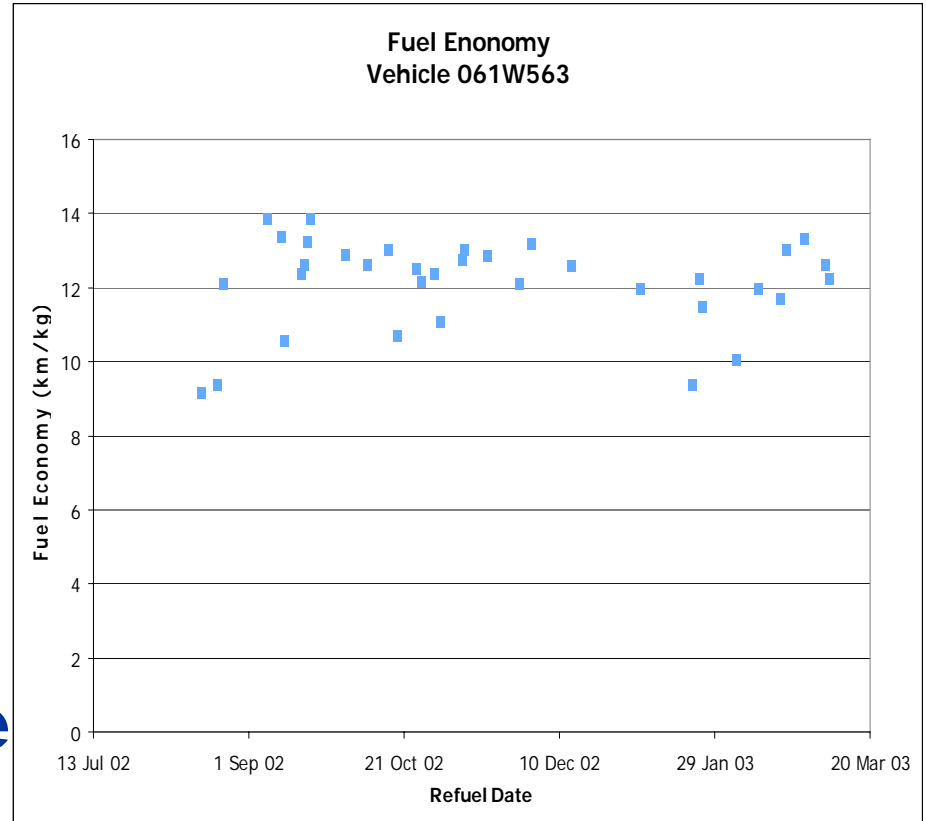
- ⌘ Transmits data in real time
- ⌘ Enables direct engineer access to data
- ⌘ No driver interaction required
- ⌘ Remotely configurable
- ⌘ Transmits ~ 50 variables/sec, primarily hydrogen related
- ⌘ 19.2 kb/s wireless link to primary Internet based server via iDEN network
 - Alternate link by satellite if cellular service is not available
- ⌘ Secondary Internet based server is closely synchronized to primary server but remote from it
 - Performs primarily hydrogen related diagnostics/prognostics
 - Provides near-real time notices and alerts based on vehicle events



behind
driver's
seat

Diagnostics/Prognostics for Customer Fleet Data

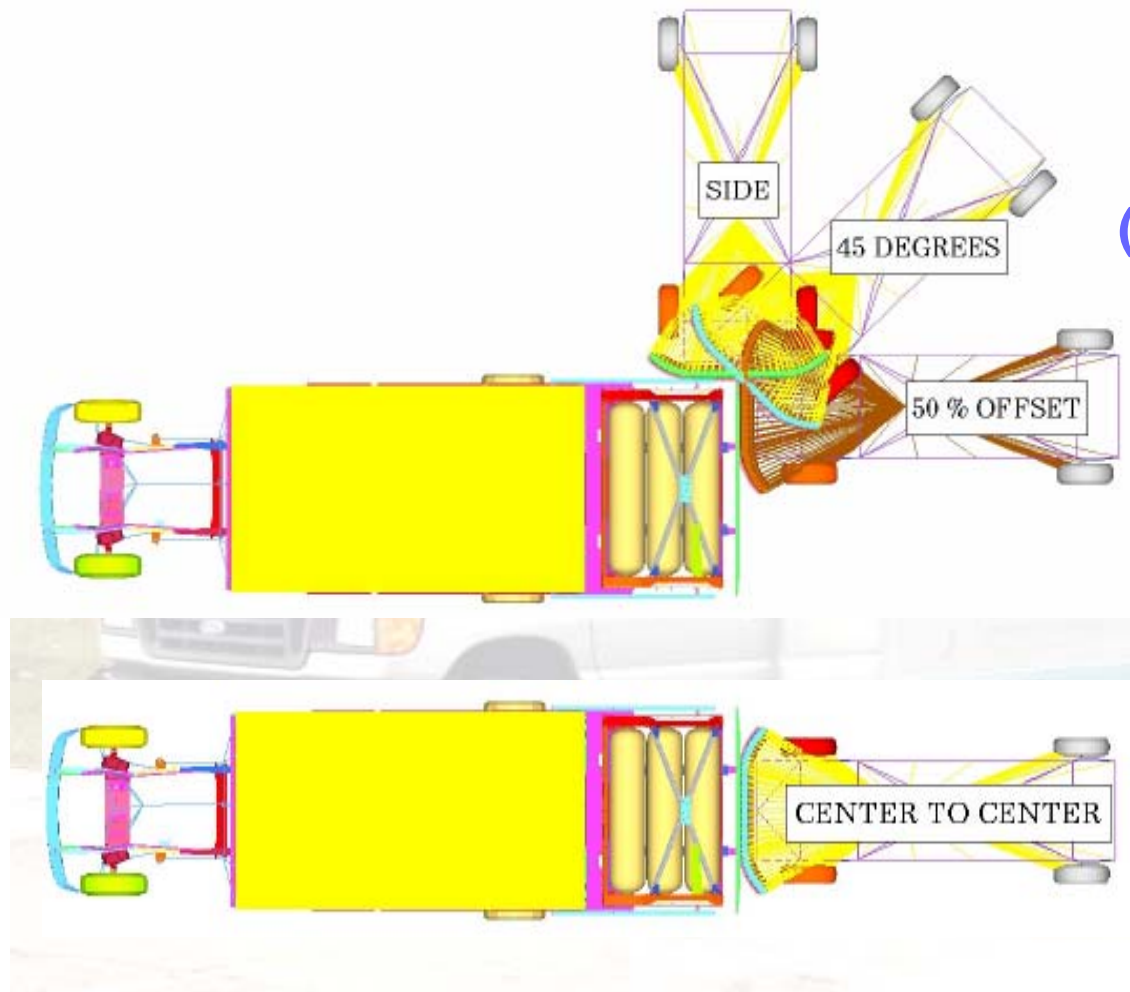
- Engine oil quality
- Fuel injector durability
- Fuel filter condition
- H₂ sensor performance
- Fuel economy under actual customer usage conditions
- Additional conditions being monitored



Vehicle Testing

- **Applied standard Ford analytical and product testing/verification to E450 H2ICE vehicles**
 - ≡ Design verification of all affected vehicle systems
 - ≡ Tested under extreme environmental conditions, altitude and duty cycle
- **Ensured compliance to all applicable F/CMVSS regulations**

CMVSS 301.2 crash modes simulated



(Left and right side)



Customer Service Support

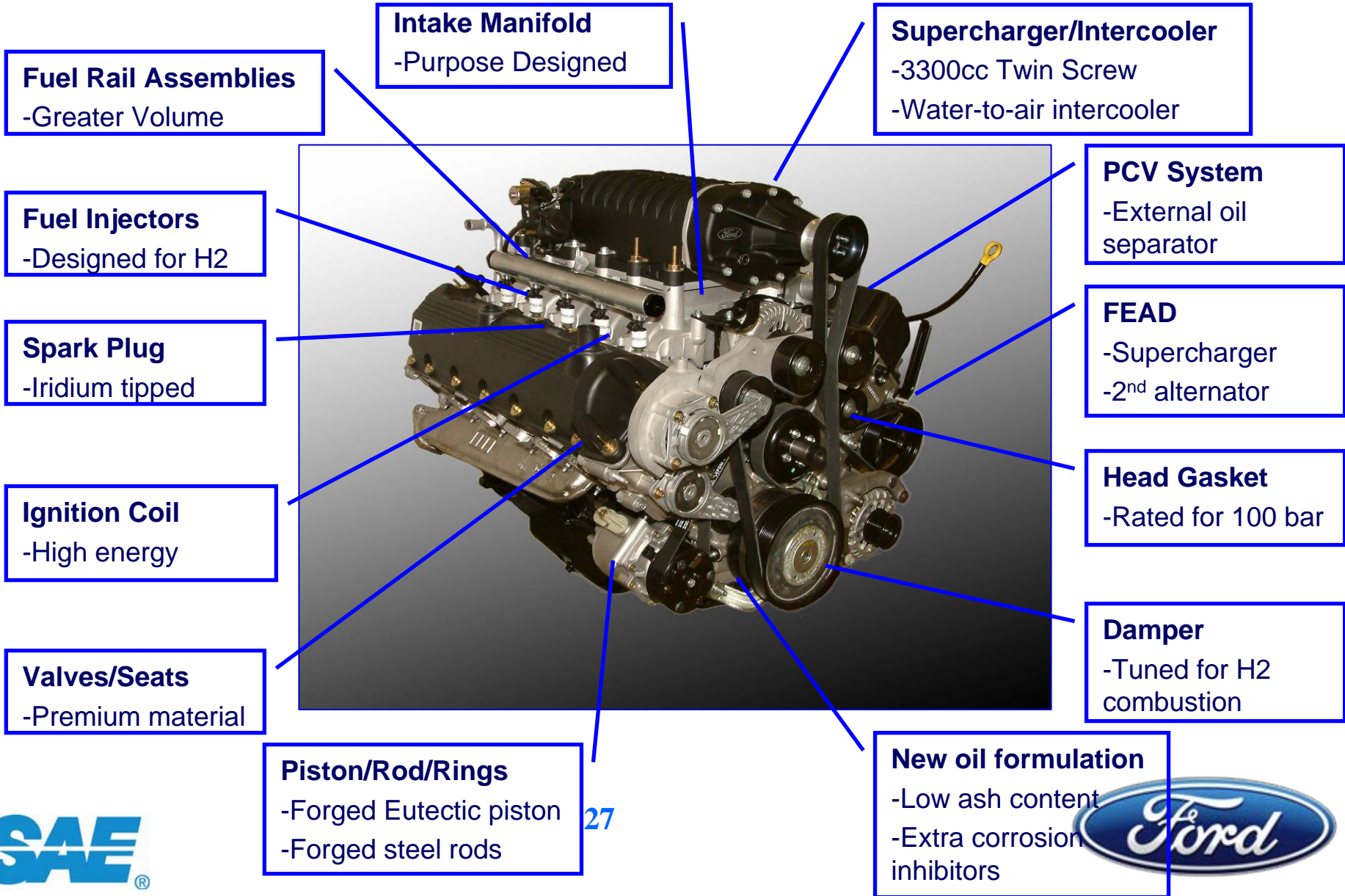
- ≡ **Supplemental owners manual**
- ≡ **Emergency responders training**
- ≡ **Technical training and material**
- ≡ **Special service tools and publications**
- ≡ **Toll free customer support hotline**



H2ICE Hardware - Geometry

•Engine Platform	•6.8L SOHC Triton® V-10
•Engine Configuration	•90-degree V-10
•Displacement / CR	•6751 cc / 9:1
•Bore x Stroke	•90.2 x 105.8 mm
•Supercharger / Boost	•3.3L/rev twin screw / 1.3 bar
•Power	•175 kW (235 hp)
•Torque	•420 N-m (310 lb-ft)

Unique H2ICE Hardware



Durability Testing Overview

- Emphasis of previous demonstration vehicles was function
- Fleet was an enabler to ensure technology was robust in real-world customer usage
- Applied standard Ford product testing and verification methods

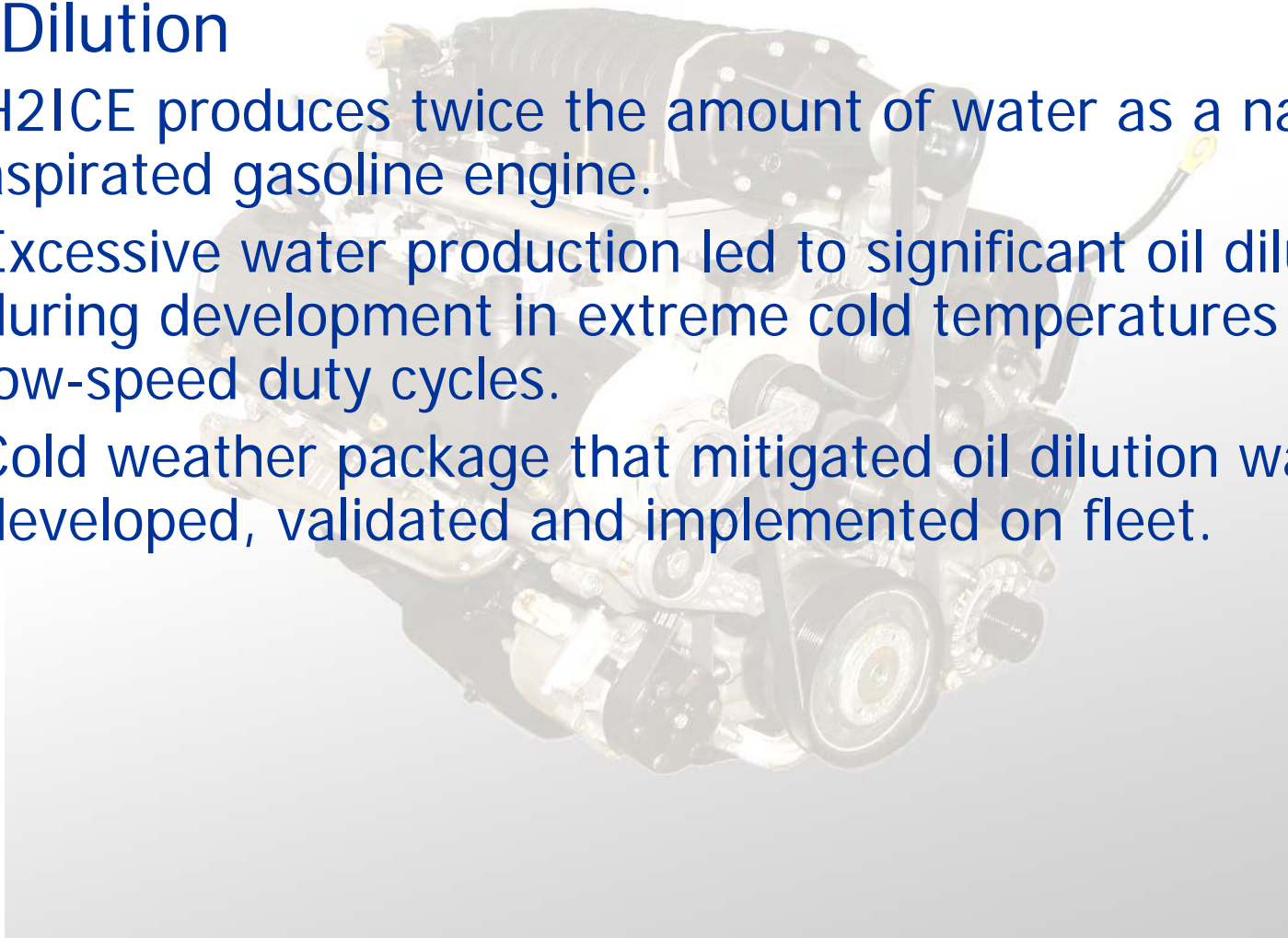
Durability Testing – Base Engine

- **600 hr passenger car durability test**
 - Base engine structural fatigue test
- **Piston scuffing test**
 - Assess piston ring and piston skirt fit
 - Assess ability to resist scuff at cold operating conditions
- **400 hr PCV sludge test**
 - PCV system sludging characteristics
- **100 hr Crankshaft durability test**
 - Structural Fatigue: Piston, rods, crankshaft, cam drive
- **480 hr Head Gasket Key Life Test**
 - Thermal Fatigue (-30C to 115C): cylinder head surface, cylinder head gasket, cylinder block deck surface

Durability Testing – Base Engine

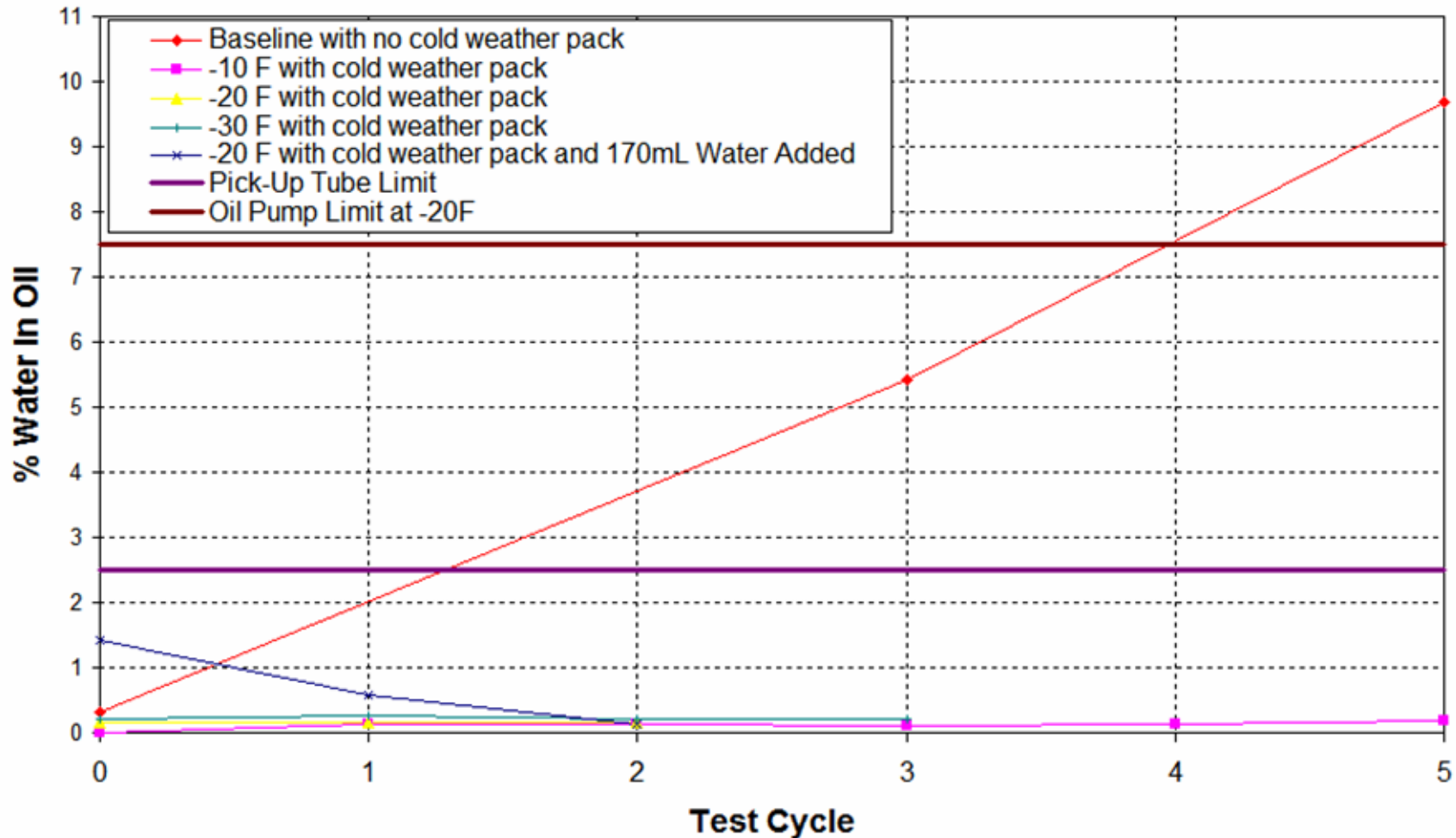
■ Oil Dilution

- ⌘ H2ICE produces twice the amount of water as a naturally-aspirated gasoline engine.
- ⌘ Excessive water production led to significant oil dilution during development in extreme cold temperatures and low-speed duty cycles.
- ⌘ Cold weather package that mitigated oil dilution was developed, validated and implemented on fleet.



Durability Testing – Base Engine

Oil Dilution During Low Duty Cycle Operation at Cold Ambient Temperatures



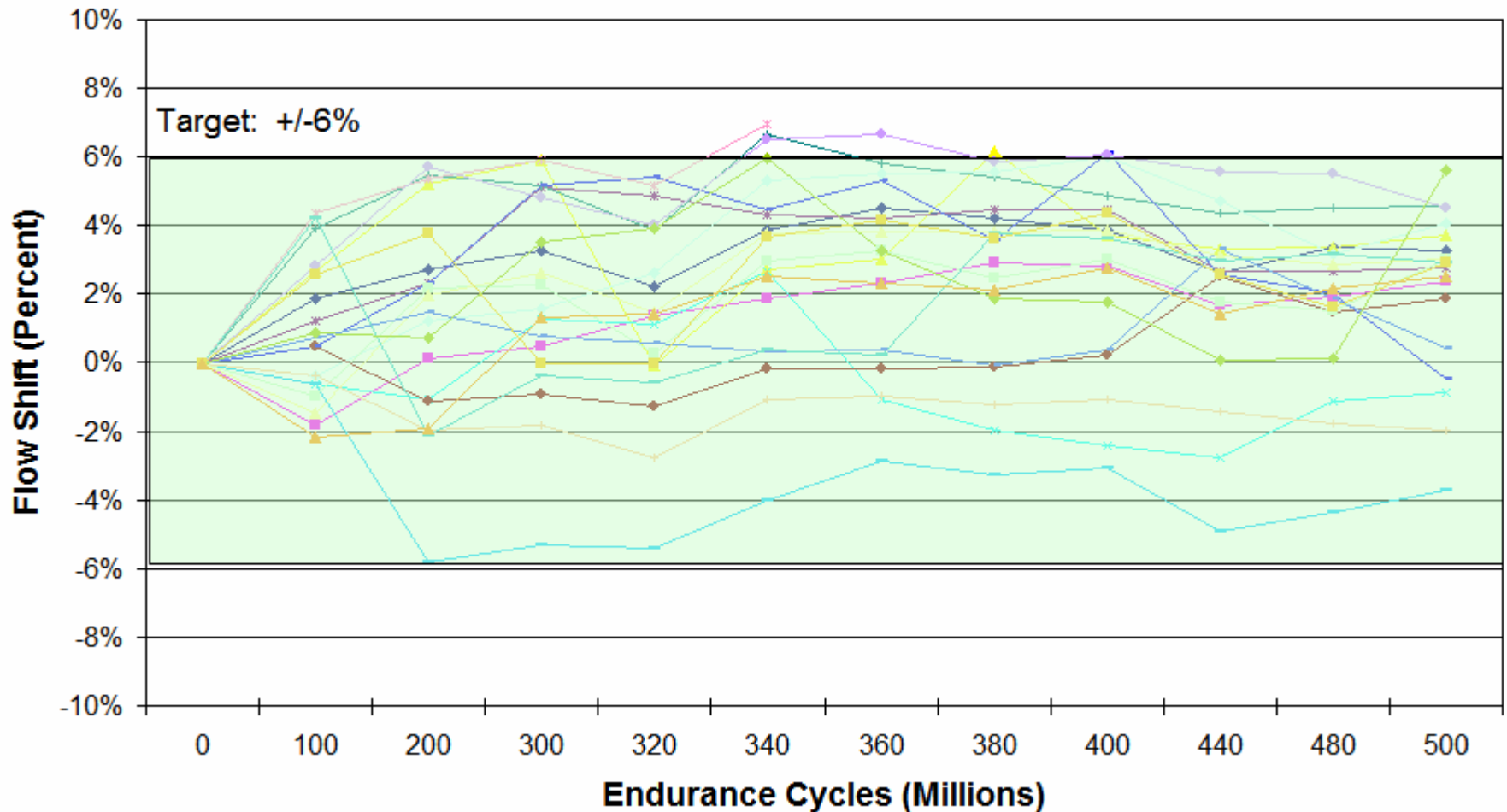
Durability Testing – Components

■ Hydrogen Fuel Injector

- ⌘ Hydrogen injector life at start of program was 11k-15k miles based on endurance test (Jan-04)
- ⌘ Hydrogen injector life at end of program was 150k miles based on endurance test (Aug-06)
 - Injector internal component material changes
 - Fuel system cleanliness

Durability Testing – Components

Hydrogen Injector Endurance Test Results Dynamic Flow Shift



Durability Testing – Components

■ Ignition System

≡ Goals

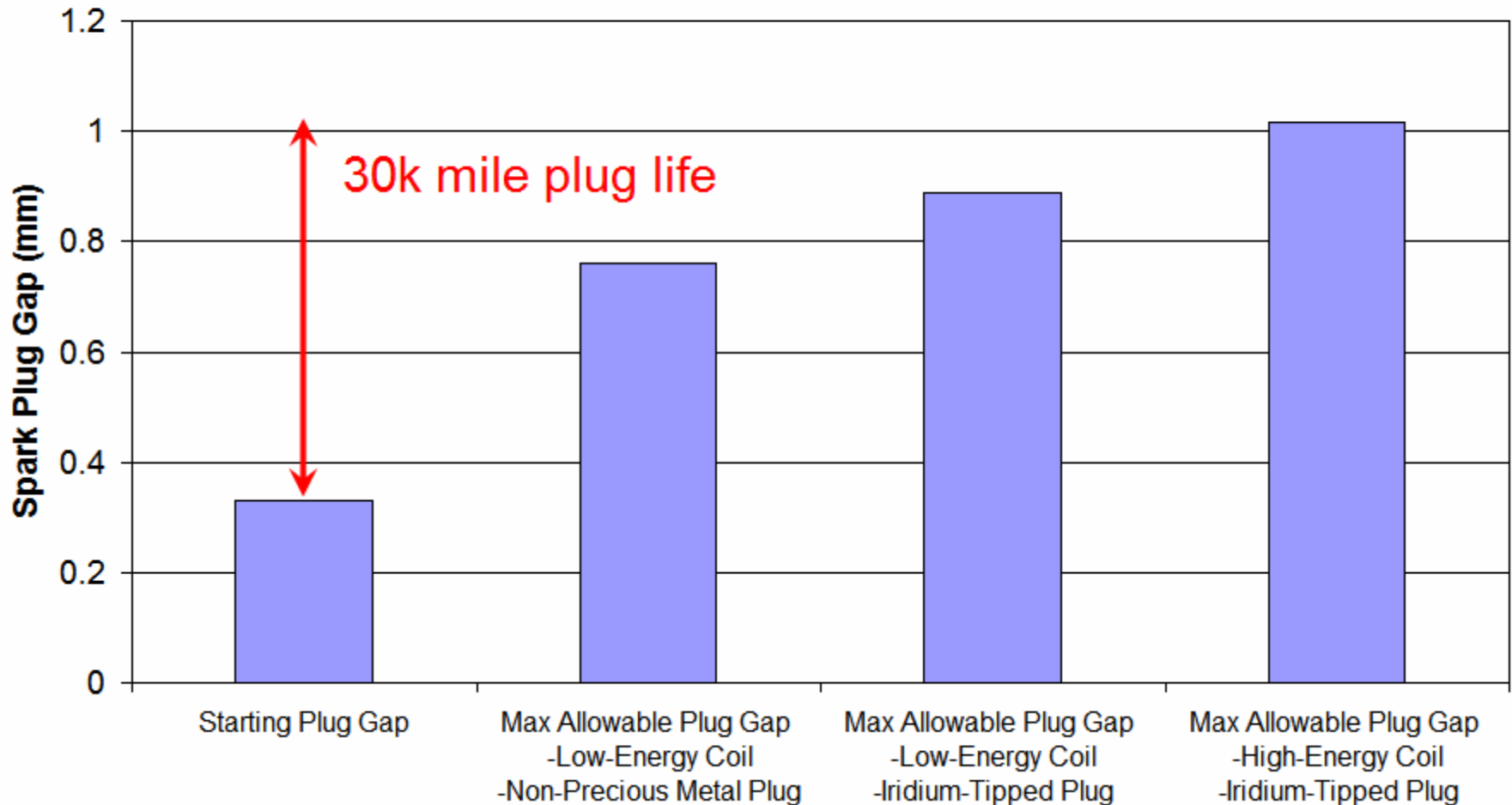
- Improve combustion stability
- Extend spark plug life (Target: 30k mile life)

≡ Enablers

- High-Energy Ignition Coils
- Iridium-Tipped Spark Plugs

Durability Testing – Components

Effect of Ignition System Improvements on Extending Spark Plug Life



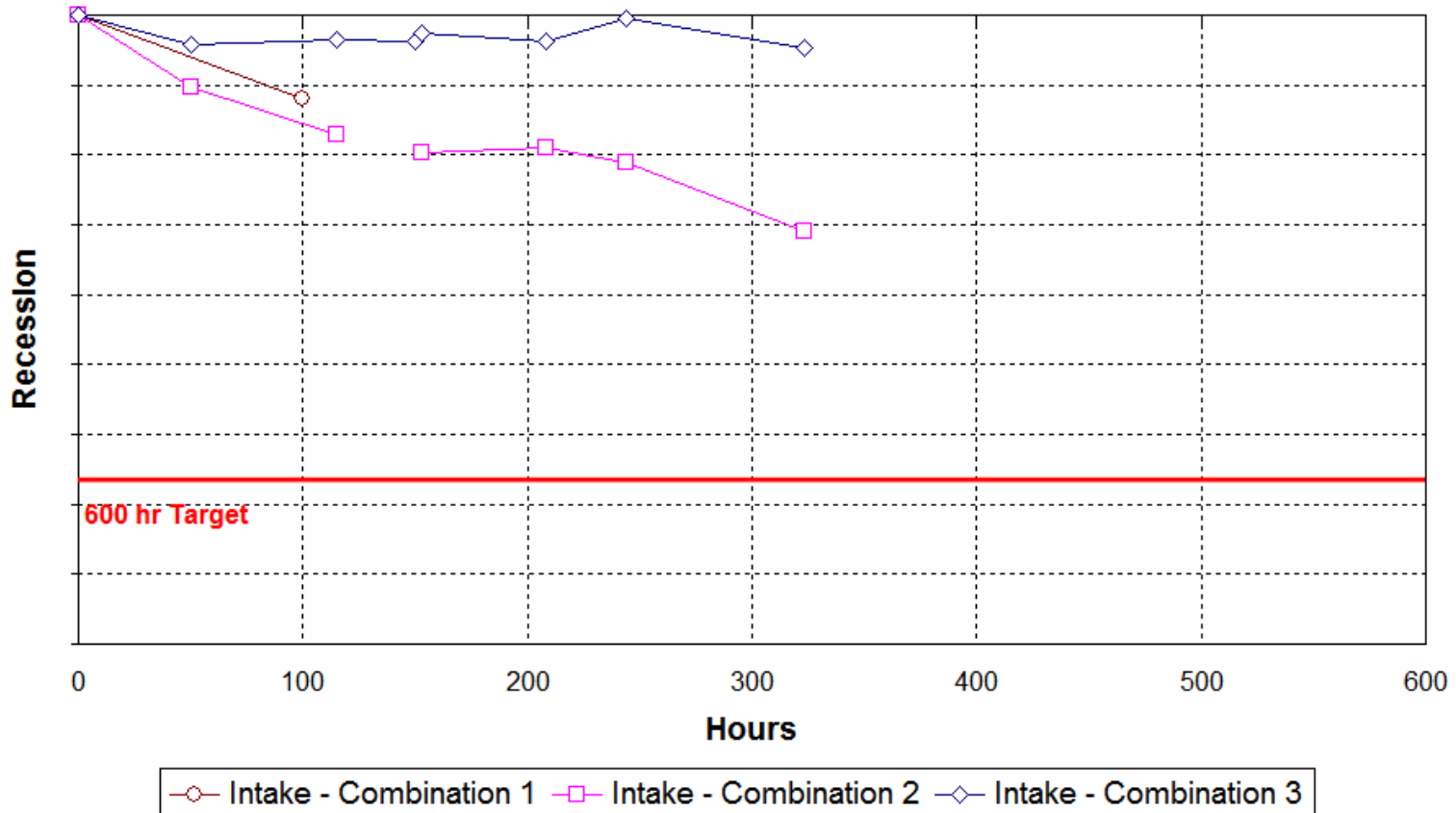
Durability Testing – Components

■ Valve & Seat Material

- ⌘ Excessive recession results from lack of lubricity in fuel
- ⌘ Several material combinations were tested on durability engine
- ⌘ Results
 - Intake – Robust valve and seat material combination
 - Exhaust – Acceptable valve and seat material combination for current 6.8L application

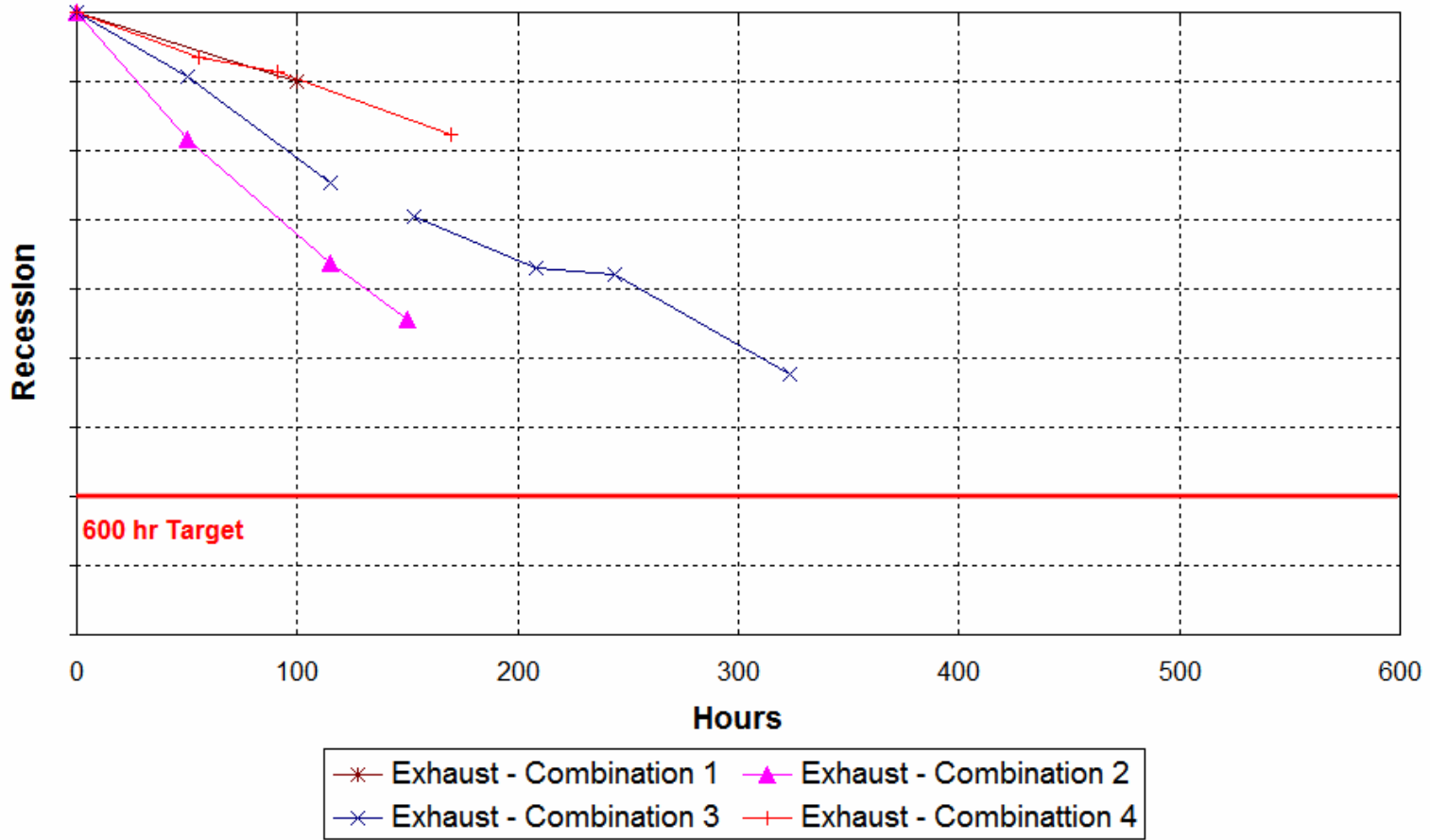
Durability Testing – Components

Intake Valve Recession Data from Durability Engine with Various Valve & Seat Material Combinations



Durability Testing – Components

Exhaust Valve Recession Data from Durability Engine with Various Valve & Seat Material Combinations



Engine Targets

■ Emissions

- ⌘ Demonstrate 2010 Phase II Heavy Duty Emission Standard Capability
- ⌘ No Exhaust Aftertreatment

■ Performance

- ⌘ Vehicle performance equal to 2005 CNG E-450

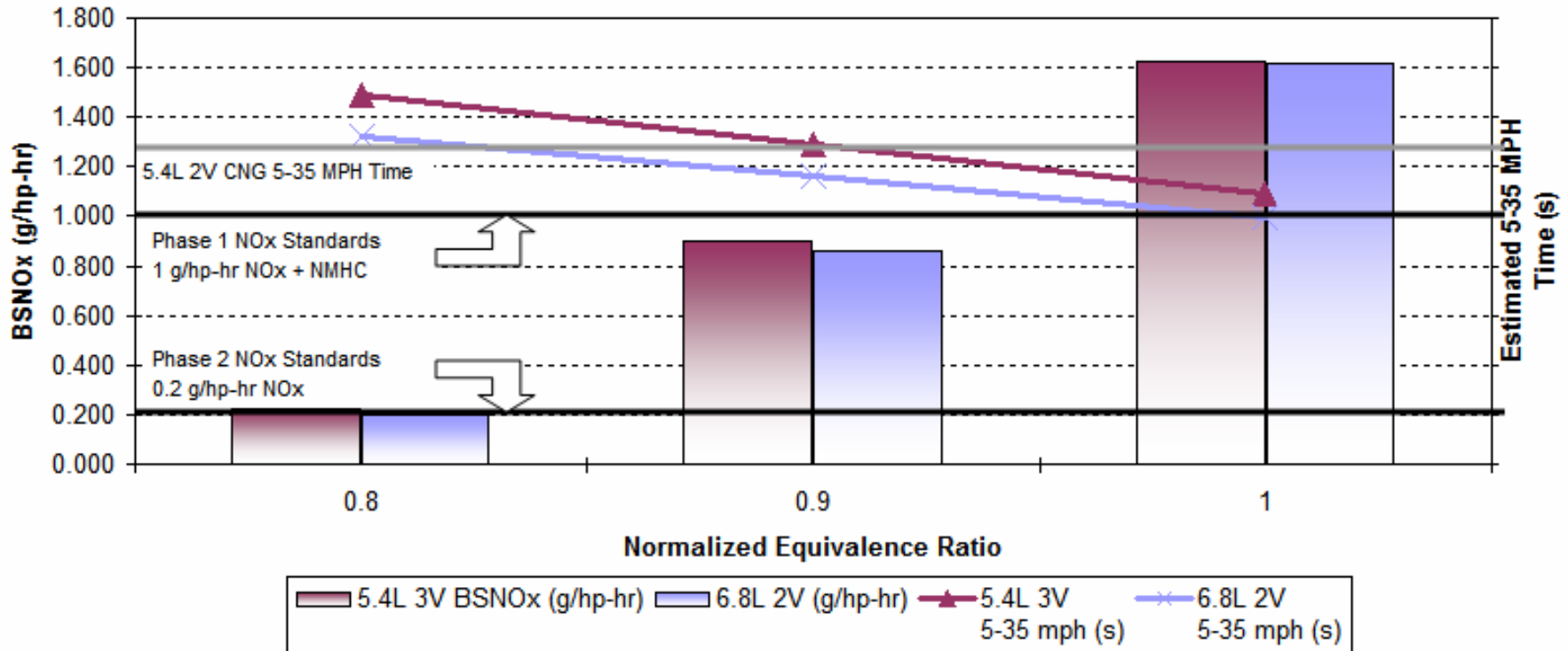
■ Fuel Economy

- ⌘ Fuel economy equal to or better than Gasoline 6.8L E-450

Engine Targets – Engine Selection

BSNOx and Performance Comparison for 5.4L 3V and 6.8L 2V H₂ICE Alternatives

BSNOx Projections from Heavy-Duty 13 Modal Point Analysis
5-35 MPH times from Modeling Analysis



Engine Targets – Emissions

H2ICE Emissions Versus 2010 Phase II Heavy Duty Emission Standard

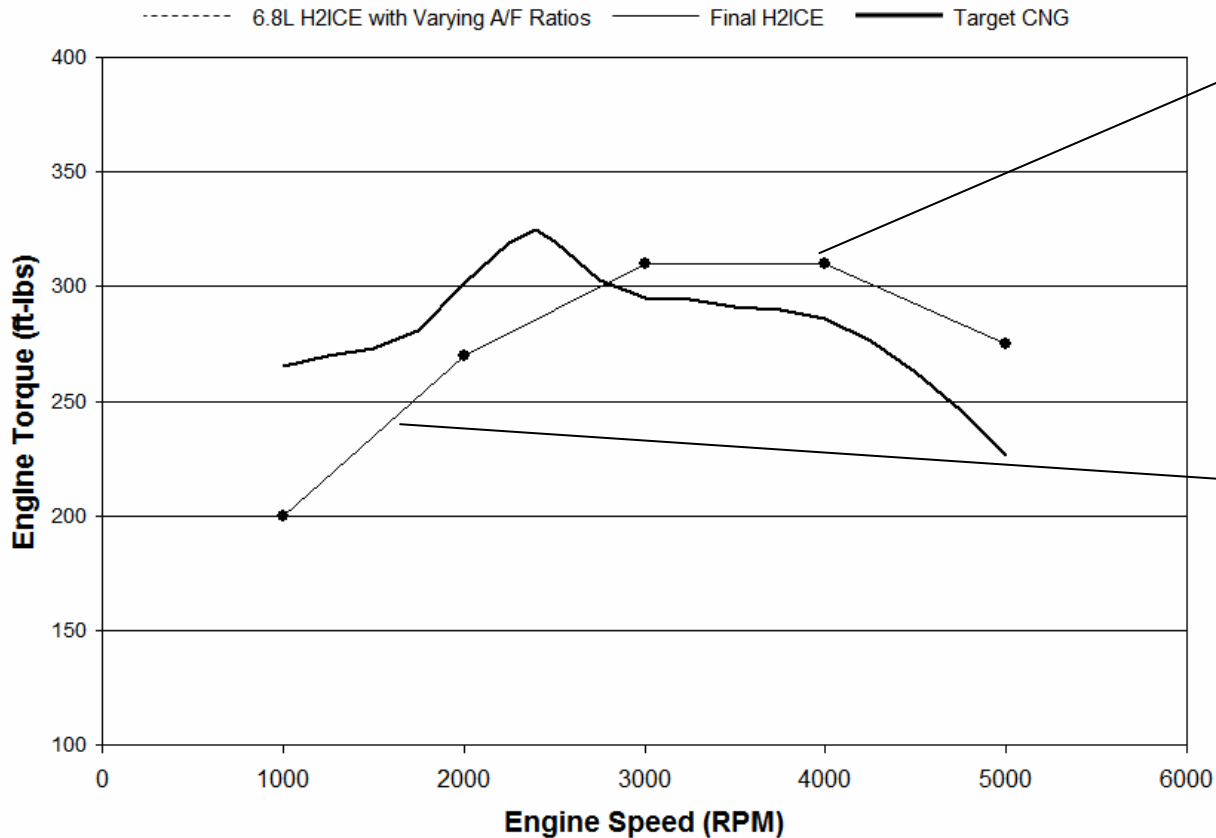
	Standard (g/hp-hr)	Status
NOx	0.2	Pass
CO	14.4	More than 99.7% below standard
NMHC	0.14	
CO2	(Gasoline Ref) 641	

Engine Targets – Emissions

- **Clearly demonstrated ability to meet dynamometer-based emission standard**
- **In-vehicle emissions were further improved with aggressive use of deceleration fuel shutoff feature**
 - ⌘ Not accounted for in dyno certification
 - ⌘ Enabled by lack of three-way catalyst

Engine Targets – Performance

6.8L H2ICE Torque at Various Air/Fuel Ratios Compared to Target



Final Torque Curve

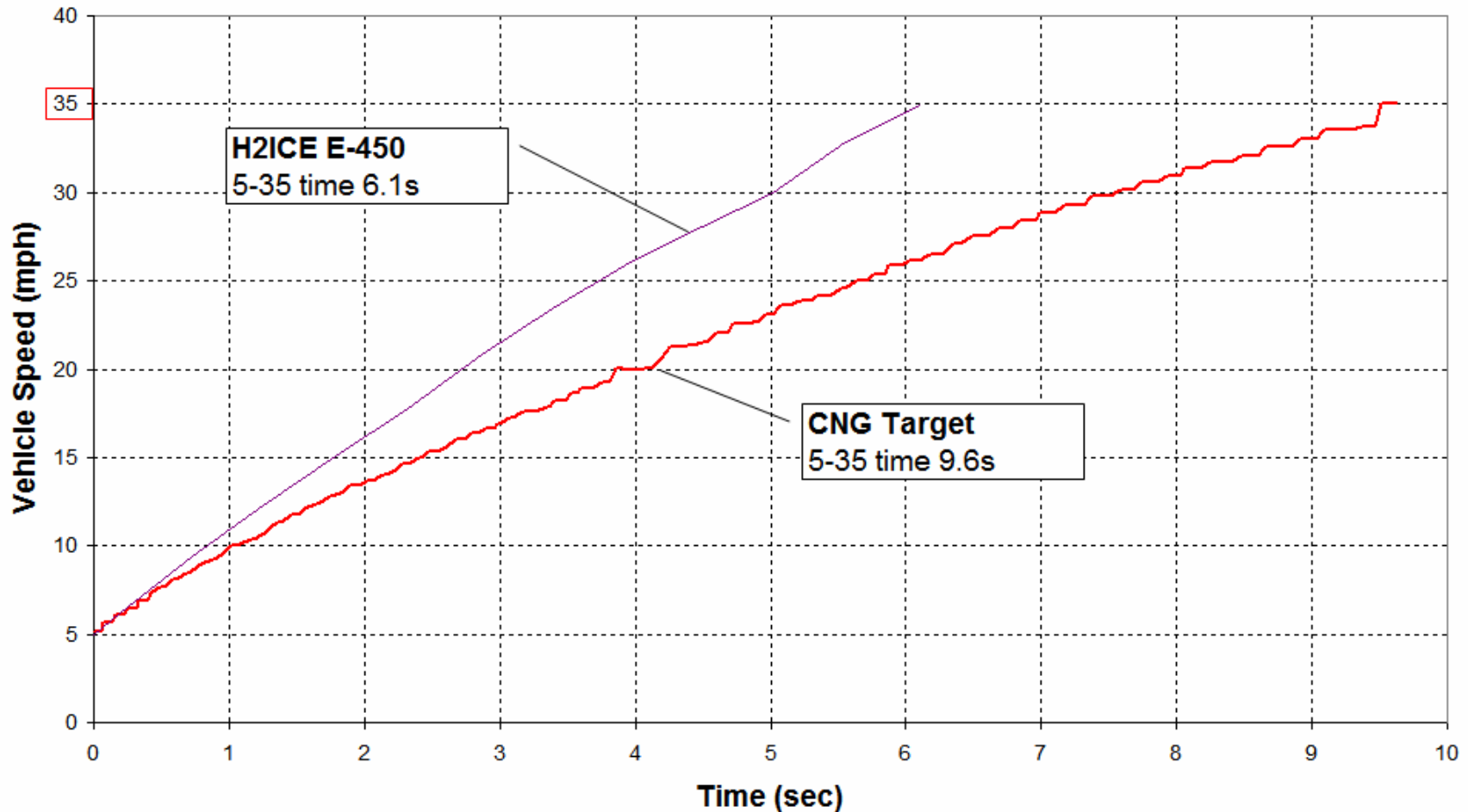
- Met NOx Target
- Met vehicle performance target

Vehicle Performance Recovery

- Electronic throttle map used to improve low-end performance

Engine Calibration – Vehicle Performance

5-35 mph Acceleration Time for H2ICE E-450 Compared to CNG Target



H2ICE E-450
5-35 time 6.1s

CNG Target
5-35 time 9.6s

Engine Targets – Fuel Economy

- **Brake Thermal Efficiency at 1500 RPM & 2.62 bar BMEP**
 - ≡ Target Gasoline: 26%
 - ≡ H2ICE: 29.25%
 - ≡ Improvement: 12.5%

Engine Calibration – Fuel Economy

■ Fuel Economy Improvements

≡ Deceleration fuel shutoff

- Aggressive DFS greatly increased fuel economy which was enabled by lack of three-way catalyst

≡ Minimize Idle Fuel Consumption

- Wide flammability limits of H₂ allowed for very lean operation during idle

Engine Calibration – Process

■ Calibration Validation Testing

- ≡ Cold ambient (-30F)
- ≡ Hot ambient (120F)
- ≡ High altitude (8500 ft)
- ≡ Performance feel
- ≡ Maximum vehicle load condition

■ Unique Development Challenges

- ≡ Test facilities not equipped for H2ICE testing
- ≡ Limited fuel availability at test sites

Engine Control Strategy

- **Strategy modified to accommodate:**
 - ≡ Supercharger
 - ≡ Hydrogen Properties
 - ≡ PFI Fuel Control
 - Equivalence Ratio Control
 - Fuel Rail Pressure and Temperature Compensation
 - ≡ Fleet Vehicle Service
 - Telemetry System Support
 - Diagnostic codes for unique features

Conclusions

■ Ford is among the leaders in H2ICE technology.

- ⌘ Demonstrated H2ICE technology previously in research vehicles.
- ⌘ Suitability of H2ICE technology in real-world application was not well understood.
 - Customer acceptance
 - Long-term durability
 - Infrastructure readiness

■ Ford planned a pilot fleet of H2ICE E-450 shuttle buses to acquire real-world experience

■ Ford leased a fleet of H2ICE E-450 shuttle buses

- ⌘ Ford production principles were applied to meet functional and durability requirements.
- ⌘ Performance and powertrain attributes are transparent relative to gasoline and CNG vehicles.
- ⌘ Regulated and GHG tailpipe emissions are near-zero with no aftertreatment.