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

Brad A. Boyer

Ford Motor Company

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 Dynomometer
- 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

2004 – H2ICE C-Max

2003 – Centennial H2RV

2005 – H2ICE Hybrid Bus (Designline)

6.8L Boosted V10

2006 – H2ICE Demo/Fleet

2004 – H2ICE Generator (Generac)

2004 – H2ICE Hybrid Bus (ISE)

2004 – H2ICE Rotary

(Mazda)

Benefits of Hydrogen Fuel

- **Air Quality**
  - Reduce or eliminate regulated tailpipe emissions (HC, CO, NOx)
- **Climate Change**
  - Eliminate CO_2 emissions *if H_2 derived from renewable resources*
- **Sustainability**
  - Potential sources of H_2 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

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

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 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 Corbiel'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

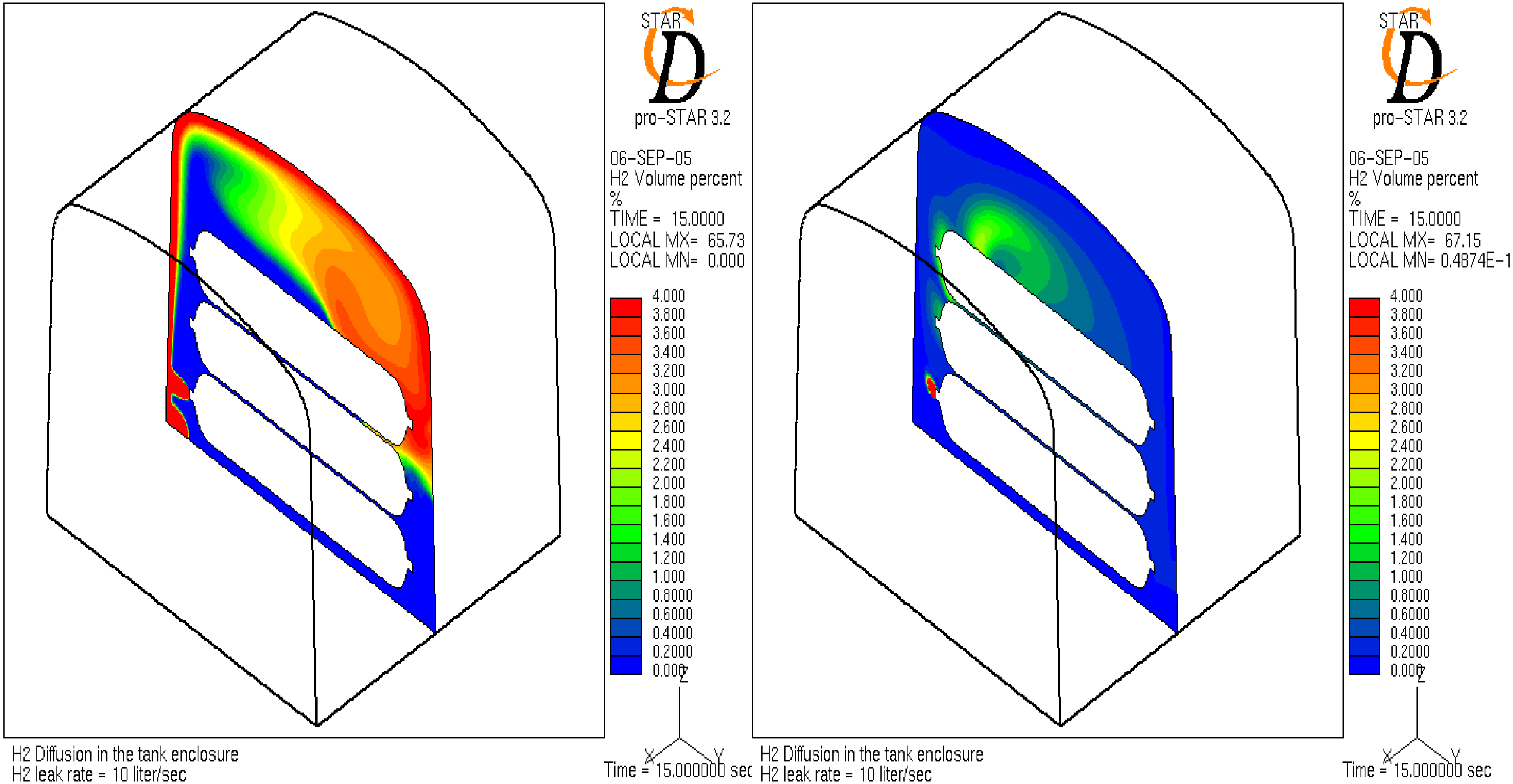
- **System design strategy**
  - **Utilized past experience with H2 sensing strategy**
  - **Used system FMEA and fault tree analysis to**
    - **Confirm and quantify functions**
    - **Determine prevention and detection actions**
    - **Define mitigation actions and control strategy requirements**

- **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

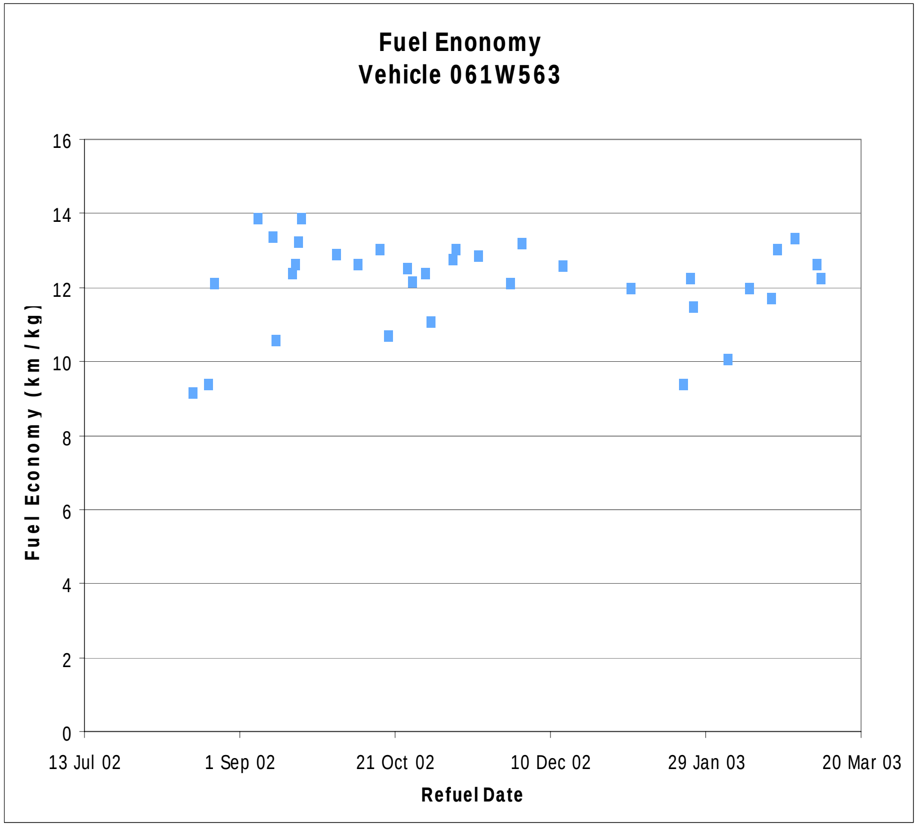


Telematics

- **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

Diagnostics/Prognostics for Customer Fleet Data

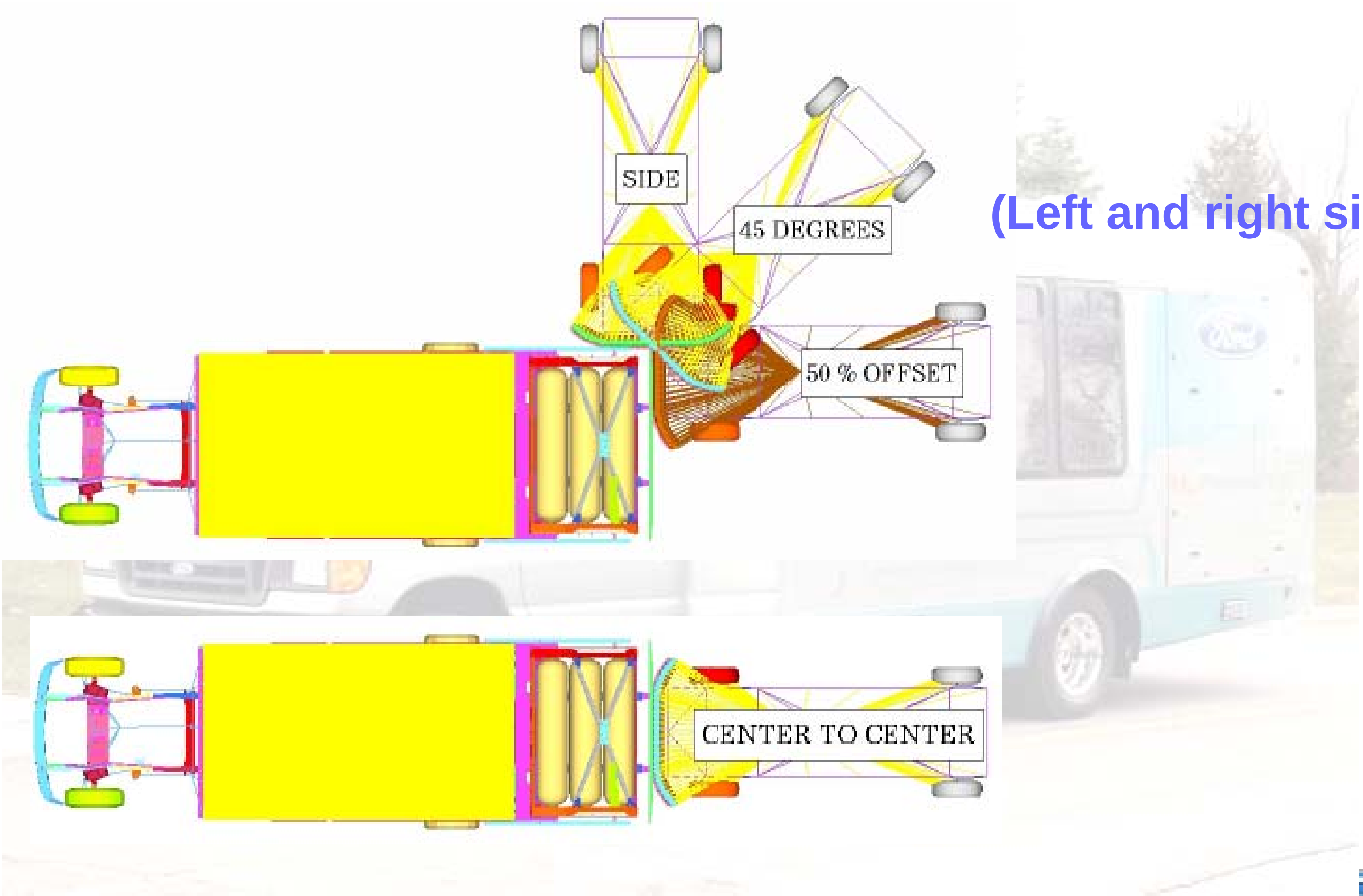
- Engine oil quality
- Fuel injector durability
- Fuel filter condition
- H_2 sensor performance
- Fuel economy under actual customer usage conditions
- Additional conditions being monitored



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

Intake Manifold
-Purpose Designed

Supercharger/Intercooler
-3300cc Twin Screw
-Water-to-air intercooler

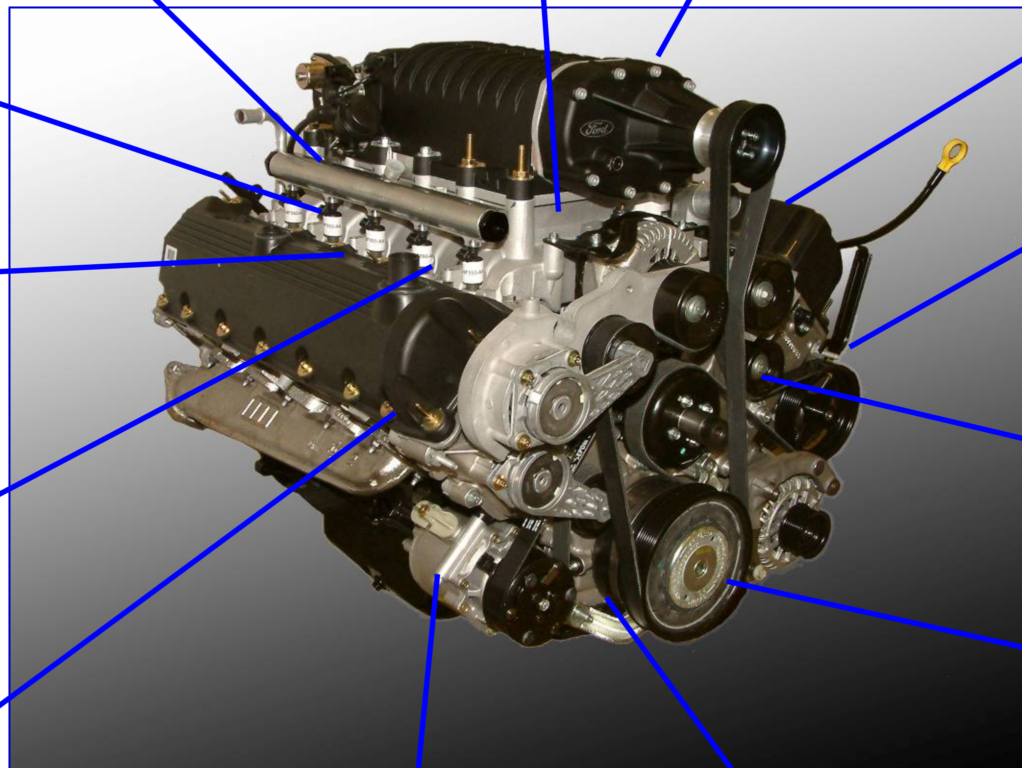
Fuel Rail Assemblies
-Greater Volume

Fuel Injectors
-Designed for H2

Spark Plug
-Iridium tipped

Ignition Coil
-High energy

Valves/Seats
-Premium material



PCV System
-External oil separator

FEAD
-Supercharger
-2nd alternator

Head Gasket
-Rated for 100 bar

Damper
-Tuned for H2 combustion

Piston/Rod/Rings
-Forged Eutectic piston
-Forged steel rods

New oil formulation
-Low ash content
-Extra corrosion inhibitors

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

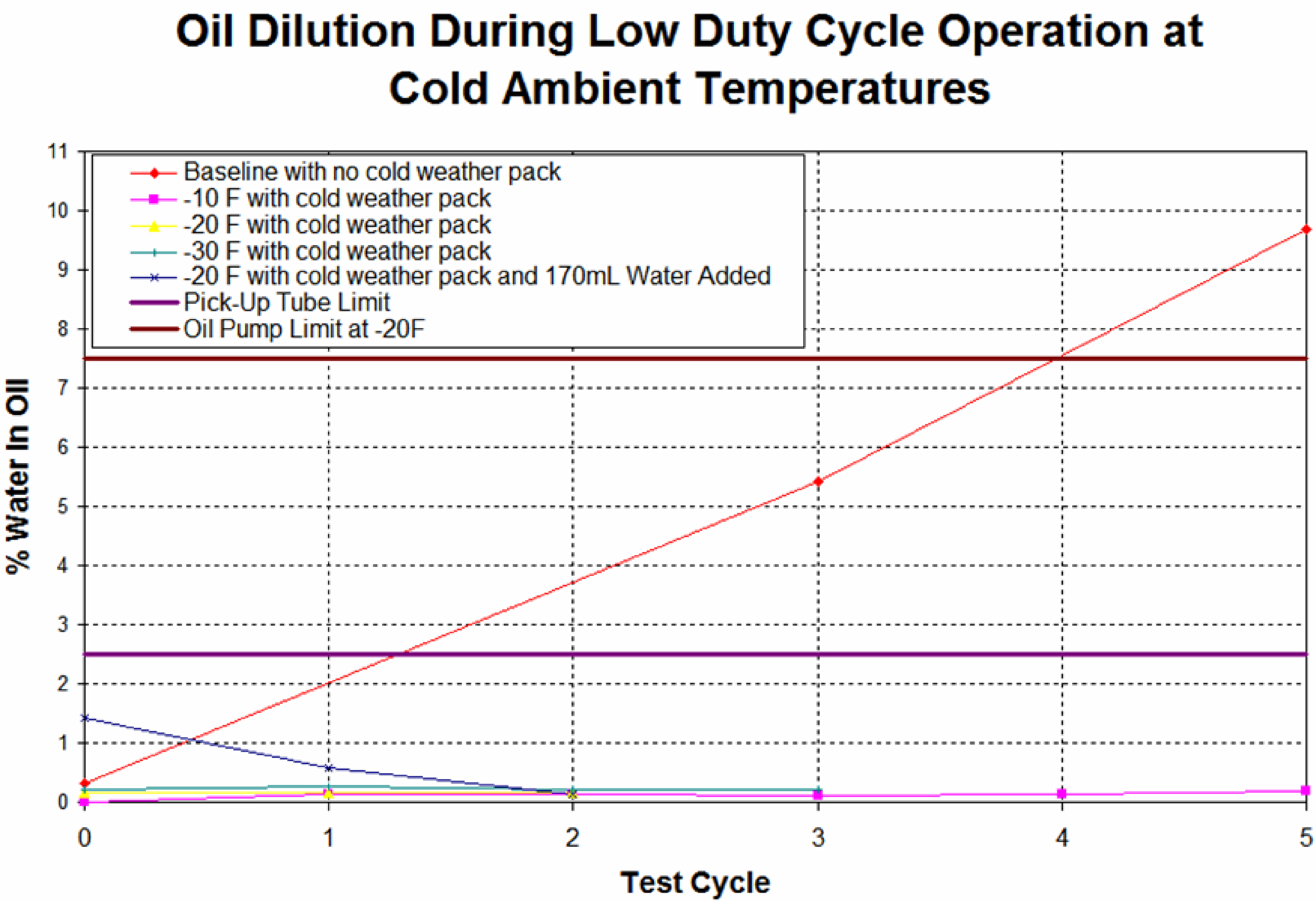
Durability Testing – Base Engine

- **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.

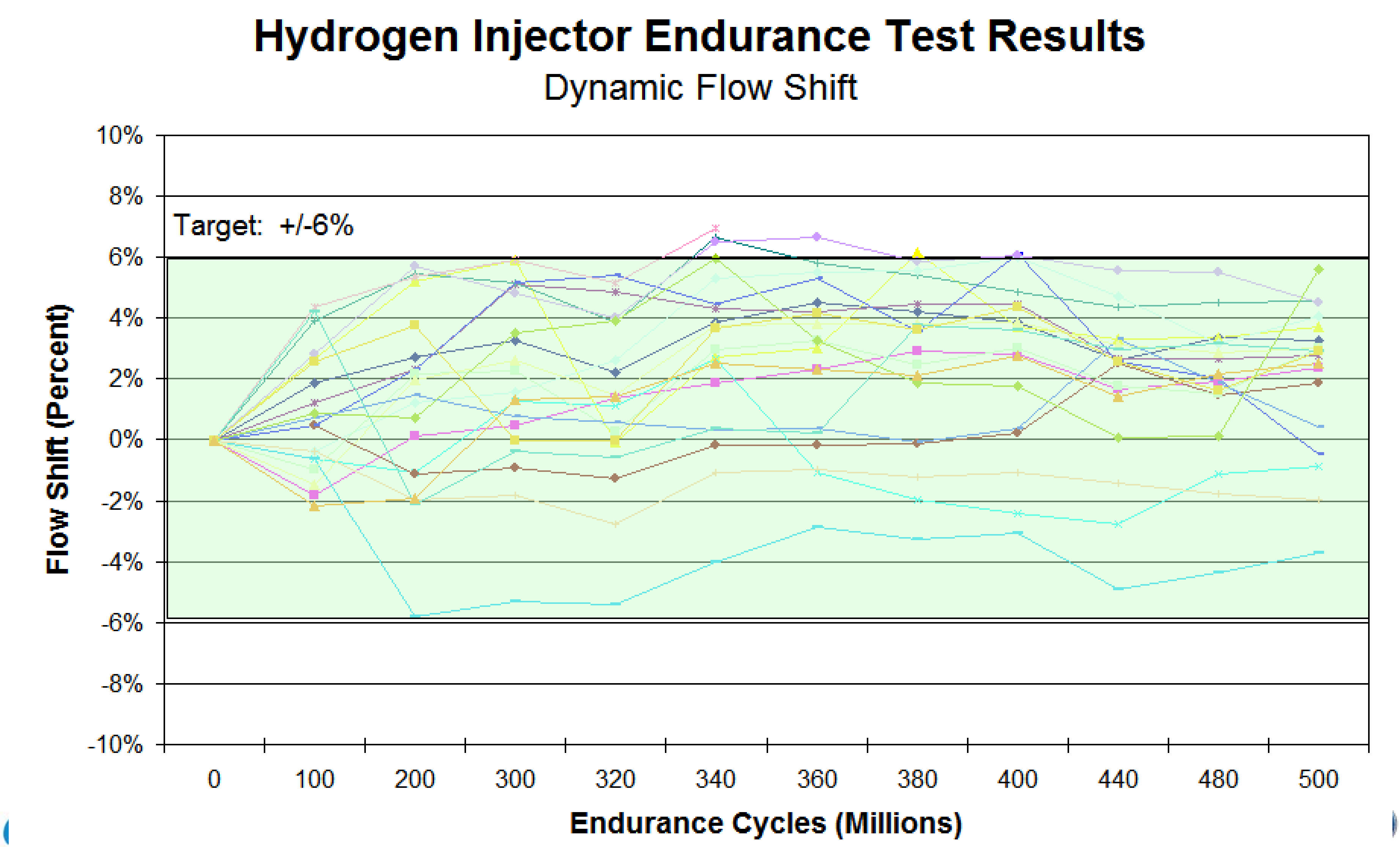
Durability Testing – Base Engine



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

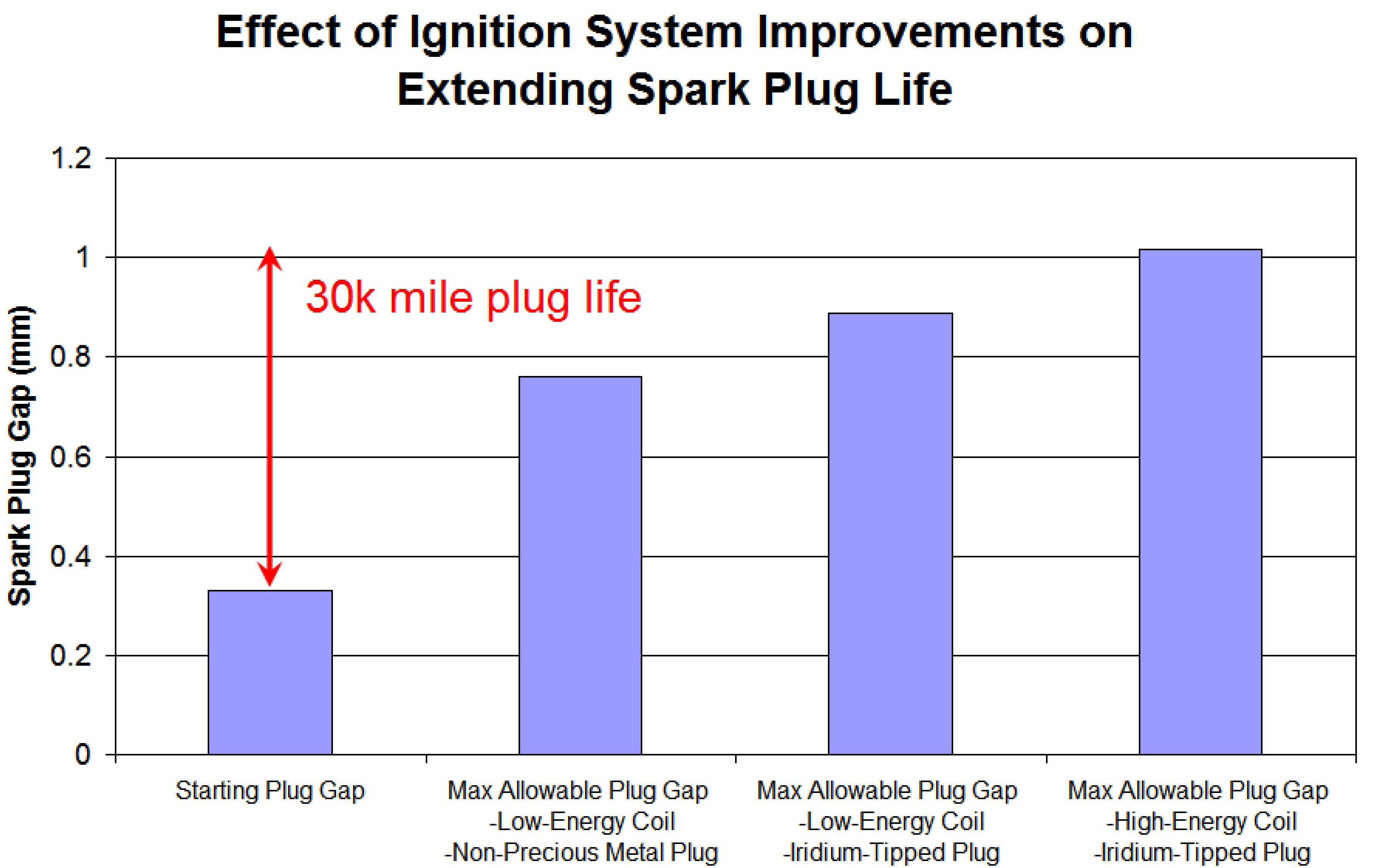
Durability Testing – Components



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

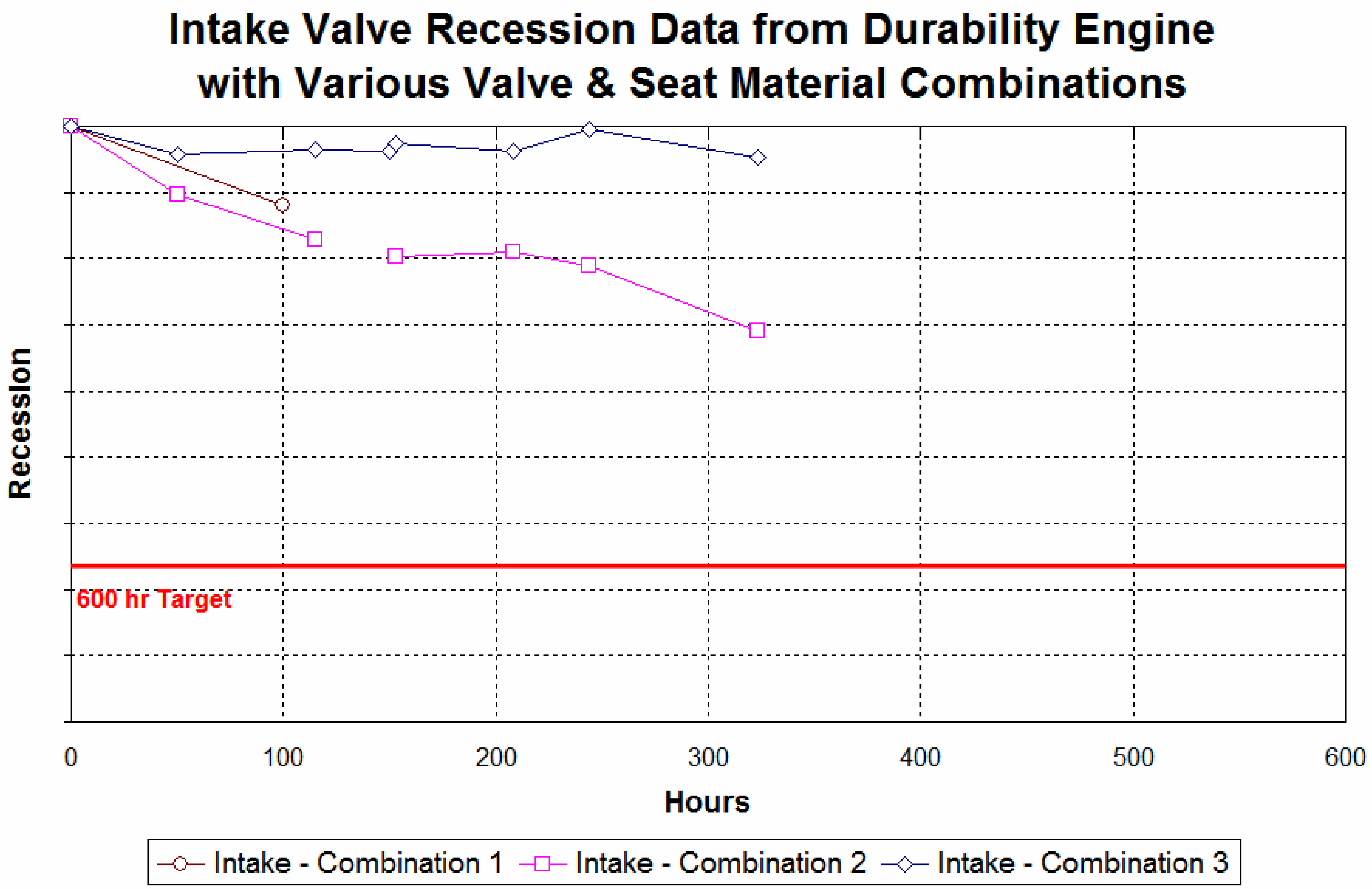
Durability Testing – Components



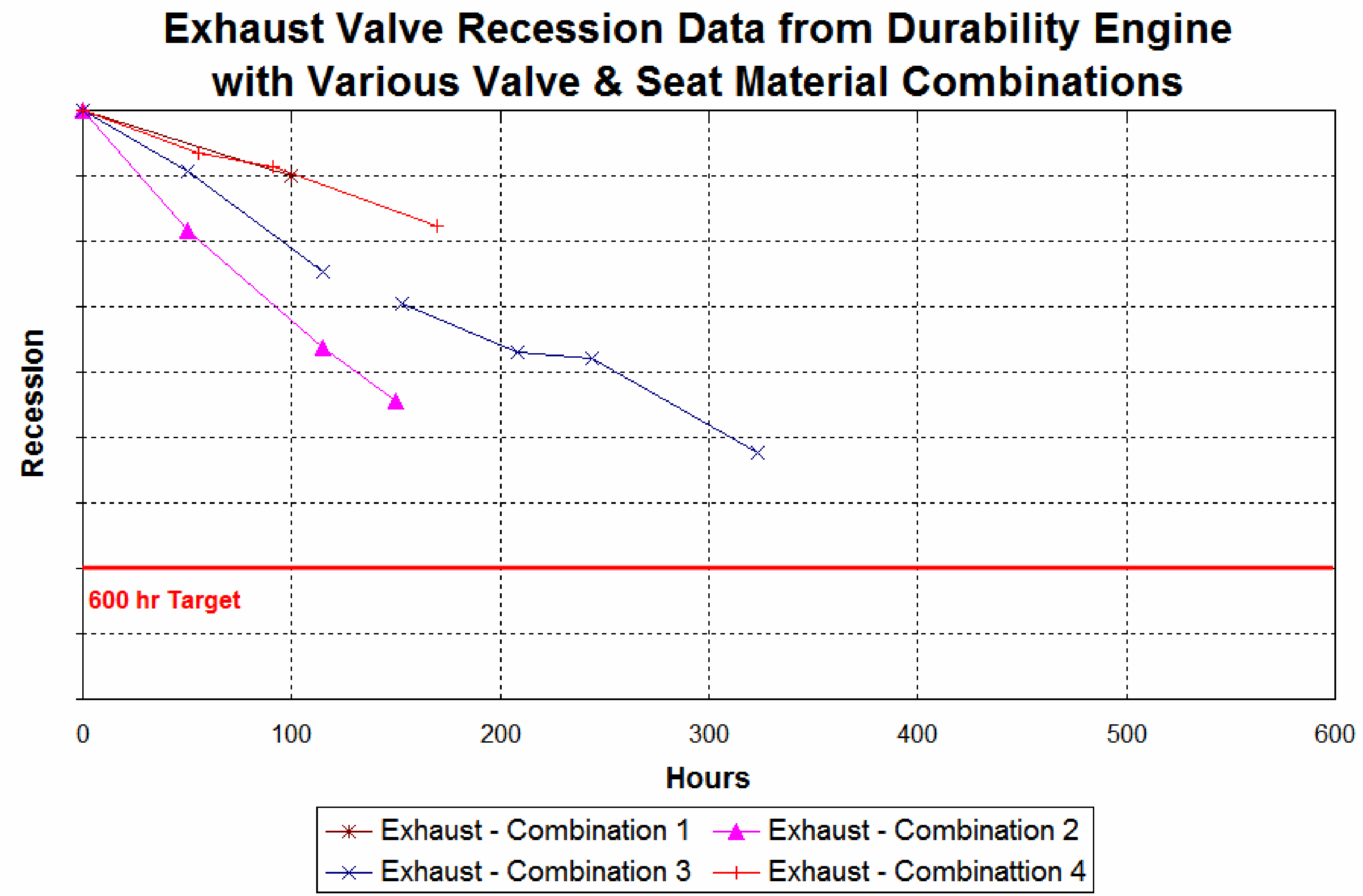
Durability Testing – Components

- **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



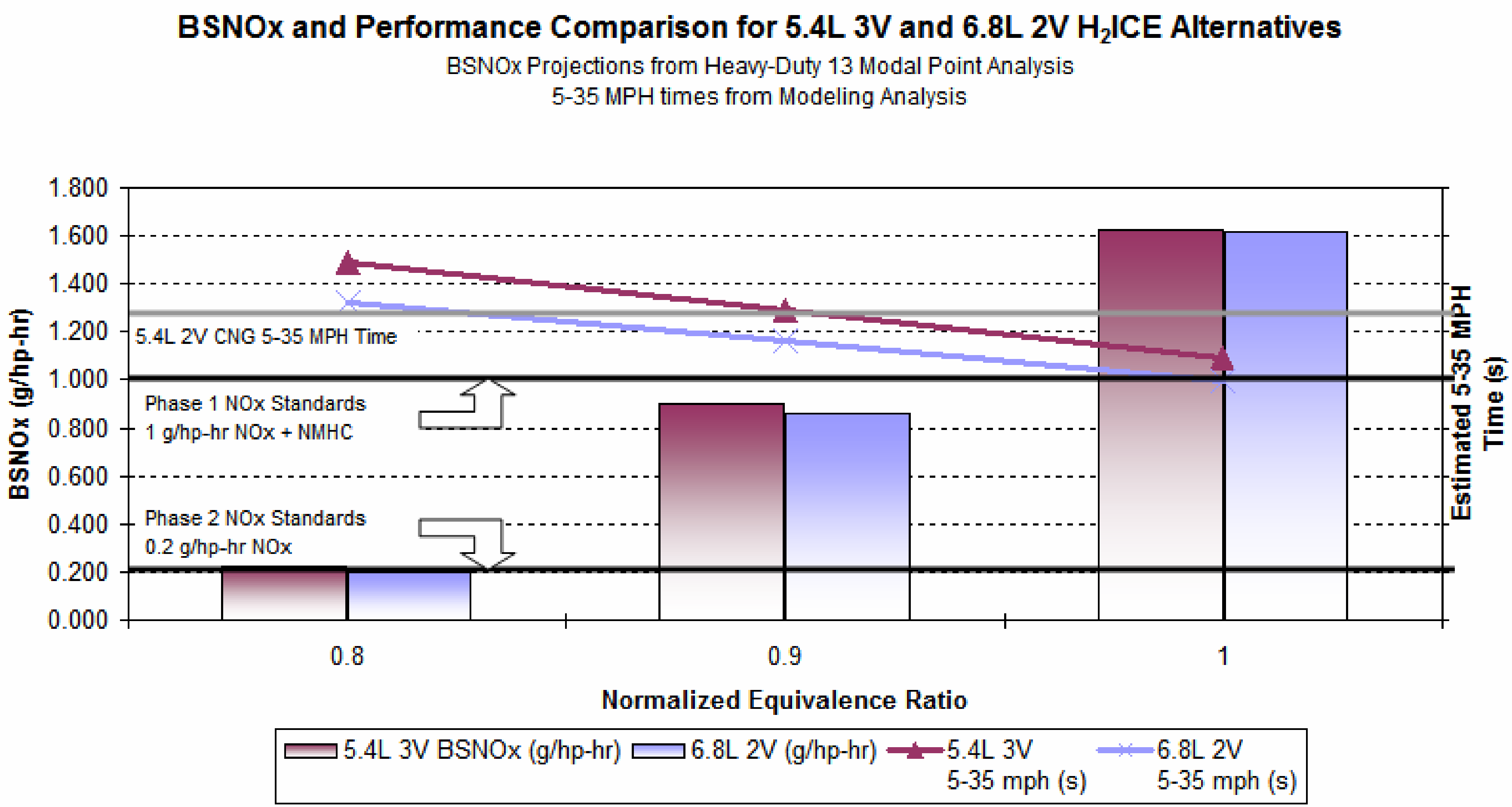
Durability Testing – Components



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



Engine Targets – Emissions

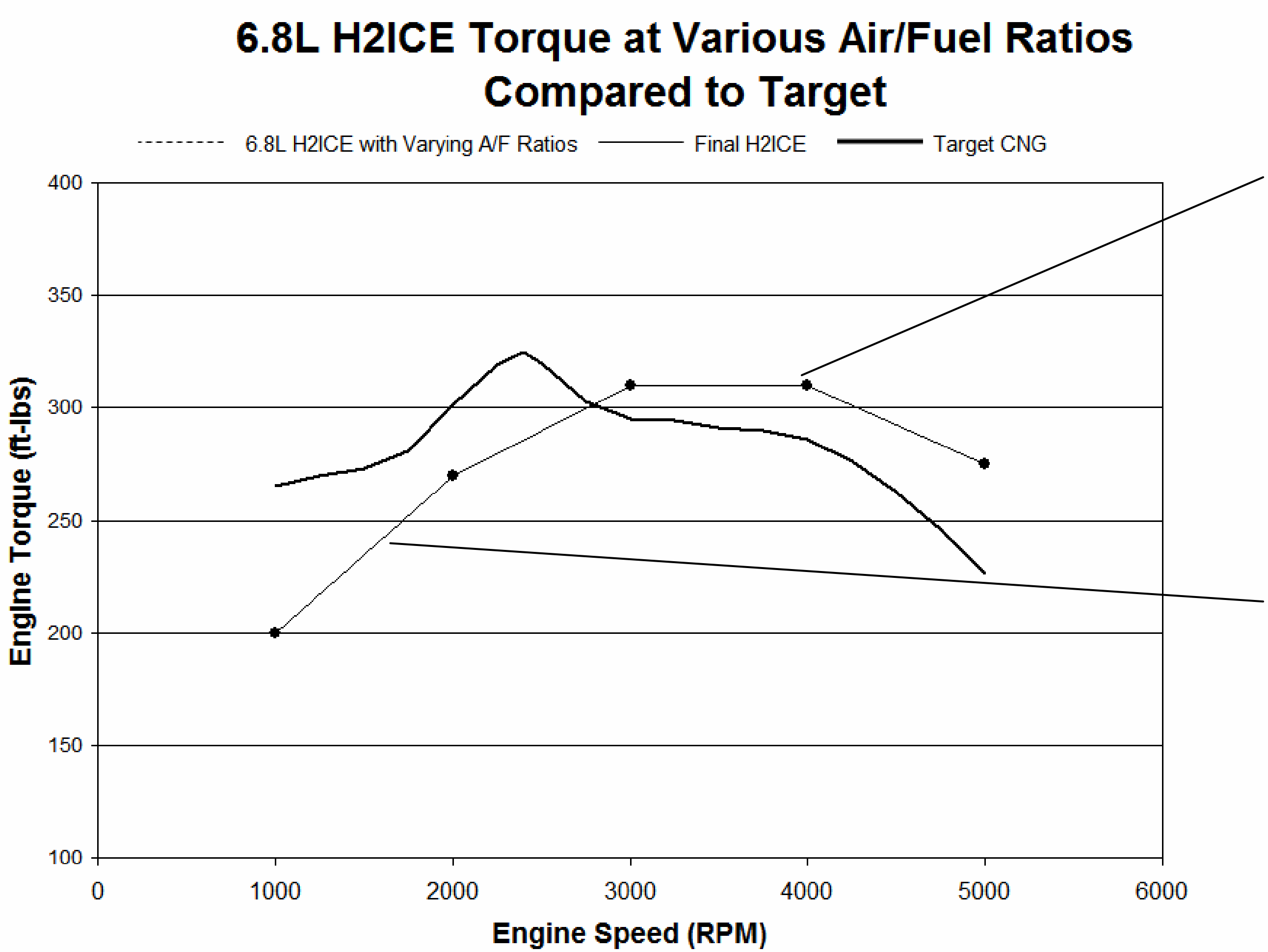
H2ICE Emissions Versus 2010 Phase II Heavy Duty Emission Standard

	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



Final Torque Curve

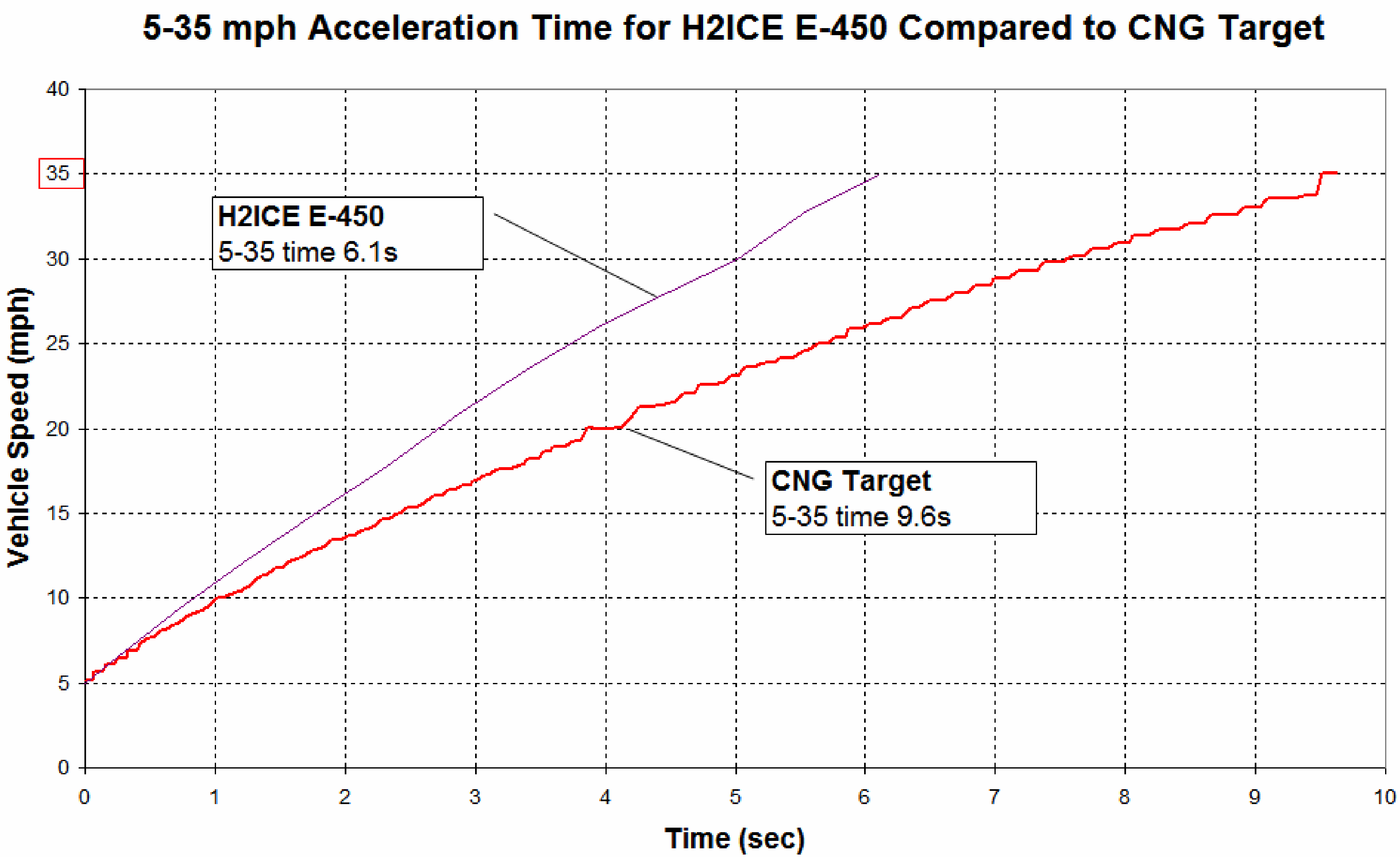
-Met NOx Target

-Met vehicle performance target

Vehicle Performance Recovery

-Electronic throttle map used to improve low-end performance

Engine Calibration – Vehicle Performance



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.