Fuel Efficiency Potential of Hydrogen Vehicles*

Project ID: vssp_16_wallner

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Overview

Timeline

- Project start: 2007
- Project end: 2008
- Percent complete: 100%

Barriers

- No fuel economy information available for advanced hydrogen vehicles with hybrid powertrains

Budget

- Funding in FY08: 100k$

Partners

- Collaborative effort of Engines and Emissions and Vehicle Systems Group at Argonne National Laboratory

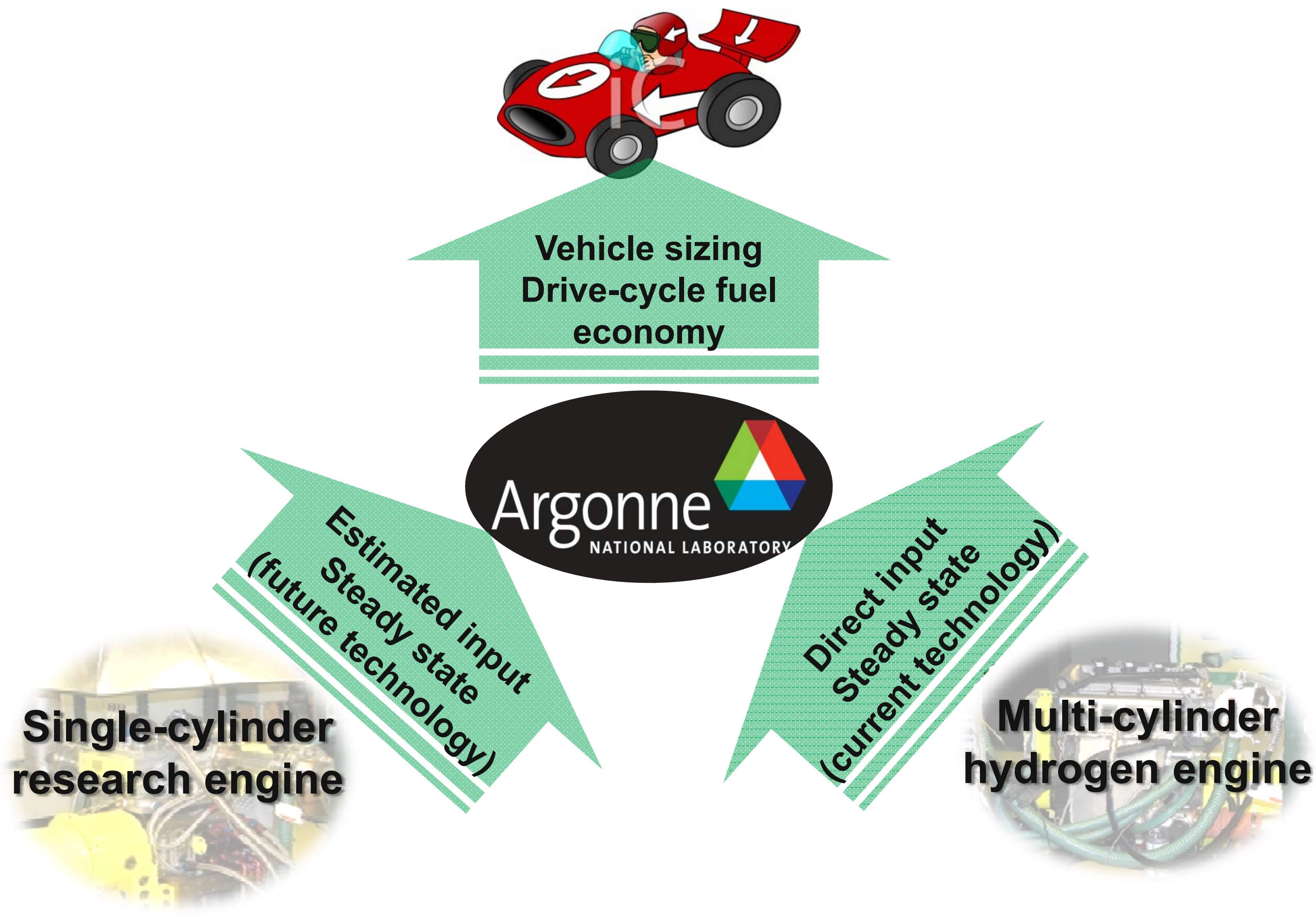
Objectives

- Real-world evaluation of hydrogen powertrain systems compared to a conventional gasoline baseline
- Estimate fuel economy improvement potential of advanced hydrogen combustion engines concepts with direct injection

Milestones

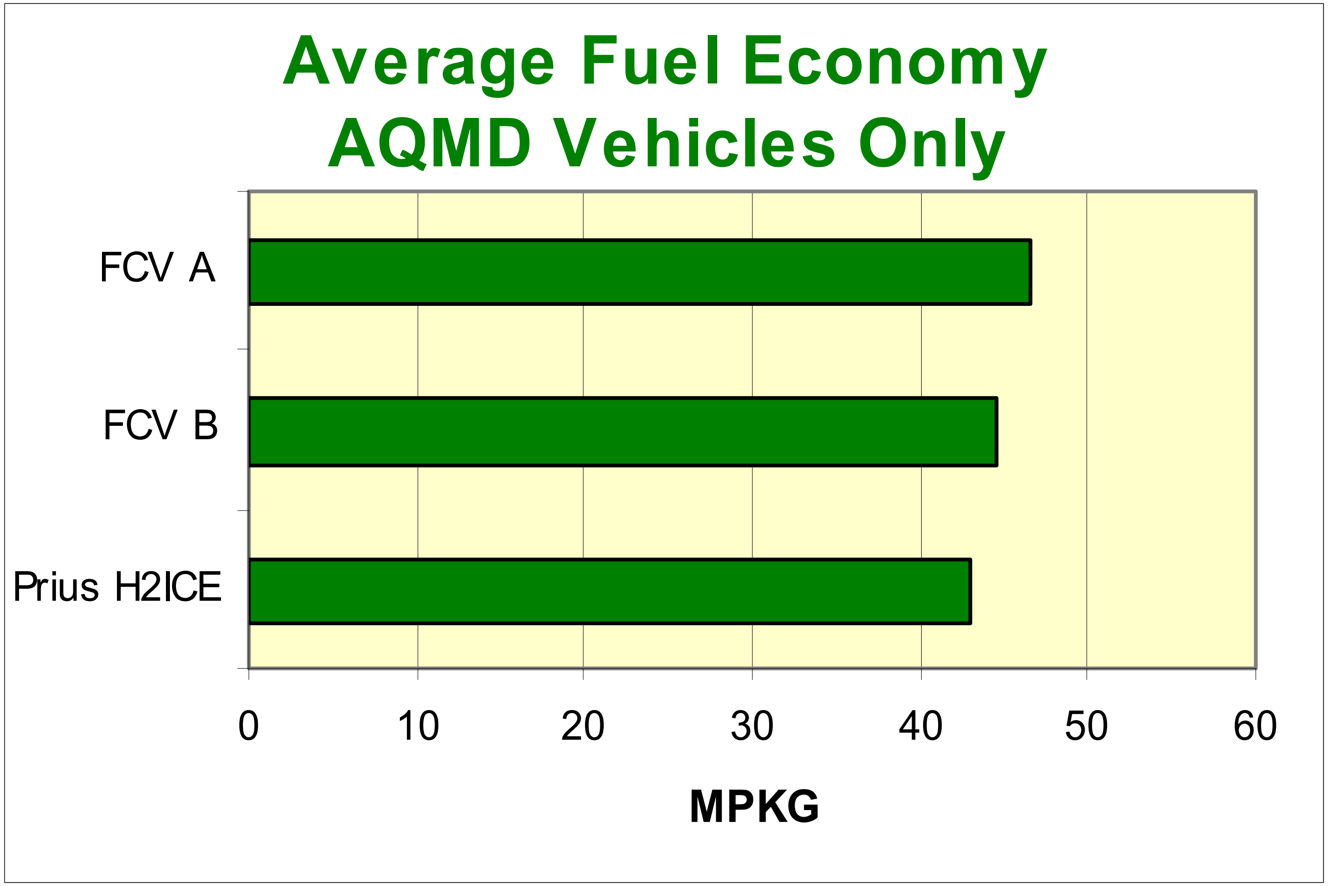
- Fuel economy estimates for advanced hydrogen combustion engine concepts established (**08/2007**)
- Realistic sizing of vehicle powertrains completed (**11/2007**)
- Completion of vehicle-level simulation using PSAT (**03/2008**)
- Present results to DOE (**05/2008**)
- Release results to engineering community (**10/2008**)

Approach



Vehicle sizing
Drive-cycle fuel economy
Estimated input
Steady state
(future technology)
Direct input
Steady state
(current technology)
Single-cylinder research engine
Multi-cylinder hydrogen engine

Background
On-road testing shows close results between ICE and FC



FCV A – 2 Vehicles

FCV B – 2 Vehicles

Prius H2ICE – 5 Vehicles

(Data - 12 Months)

Source: Berry, N. 'SCAQMD – Hydrogen ICE Projects' Weststart-Calstar Conference 'Hydrogen Internal Combustion Engines 2007 - Where do we go from here?' Los Angeles. 2007.

Vehicle Assumptions

- Midsize car platform
- Both non-hybrid and hybrid configurations considered
- All vehicles achieve similar performances (0-60mph, grade)
- All vehicles have same amount of onboard H2 (5kg) and use the same amount of H2 from the tank
- Component uncertainties taken into account
- UDDS and HWFET drive cycles considered
- Ratios based on fuel economy gasoline equivalent using 2008 EPA corrections

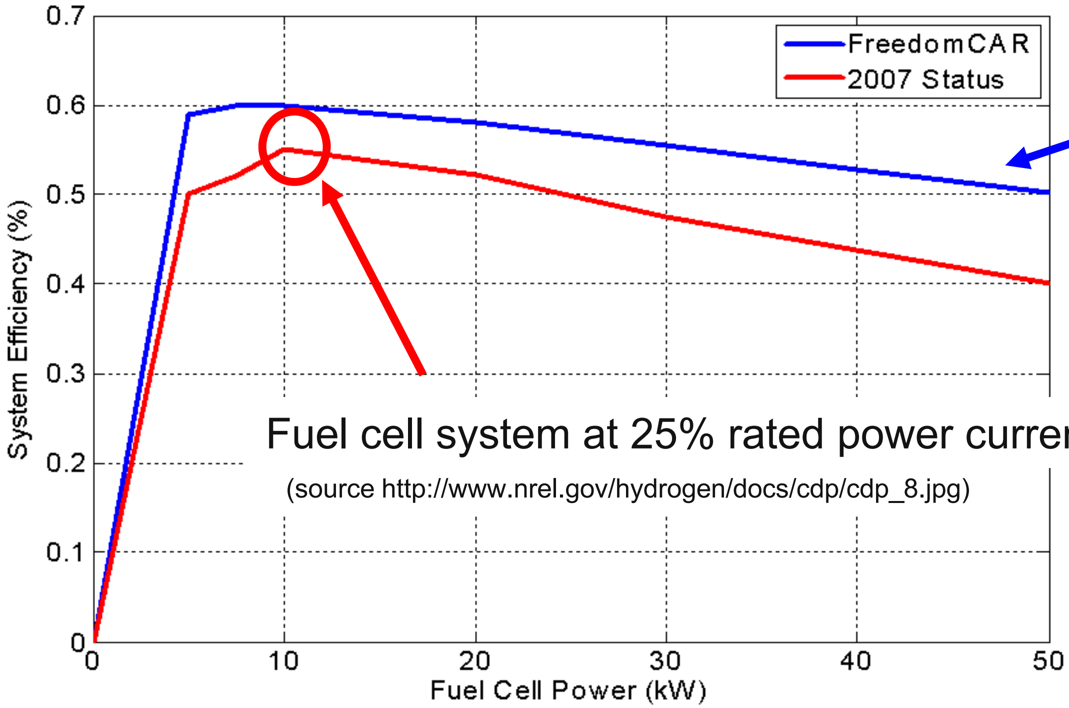
Parameter	Unit	Midsize Car
Glider Mass	kg	990
Frontal Area	m^2	2.1
Drag Coefficient		0.29
Wheel Radius	m	0.317
Rolling Resistance		0.008

Parameter	Unit	Value
0–60mph	s	9 +/- 0.1
0–30mph	s	3
Grade at 60 mph	%	6
Maximum Speed	mph	> 100 (1)

(1) Two gear transmission used for series

Fuel Cell System Assumptions

Parameter	Unit	Current Status	FreedomCAR Goal
Specific Power	W/kg	500	650
Peak Efficiency	%	55	60

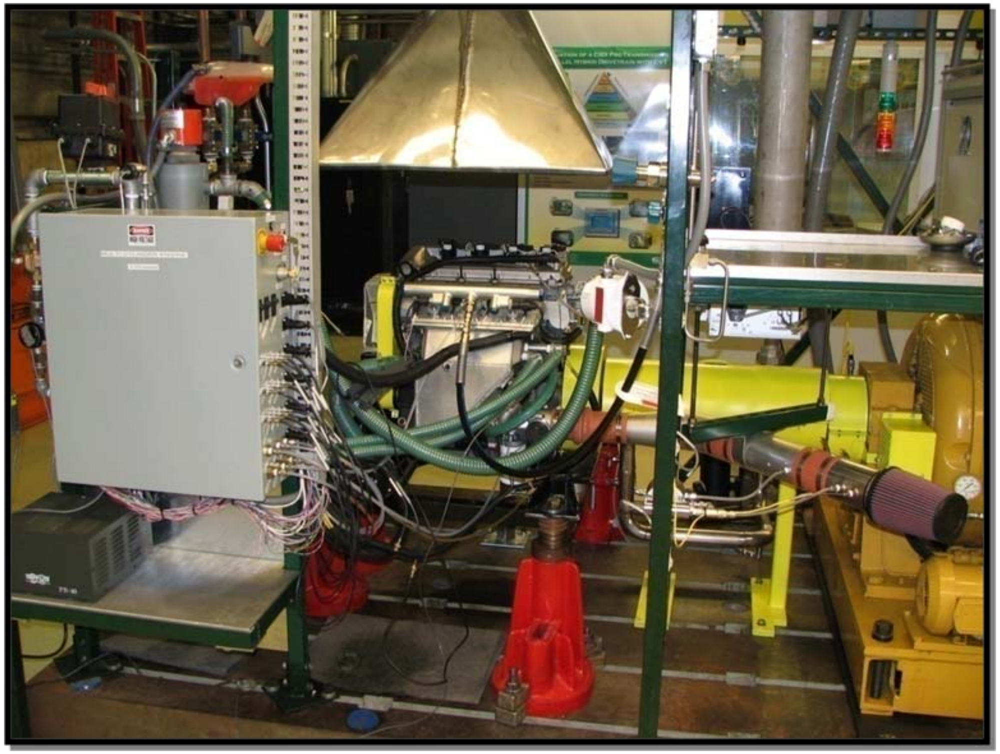


Source: Fuel Cell Tech Team

Fuel cell system at 25% rated power currently range from 52.5 to 58.1%

(source http://www.nrel.gov/hydrogen/docs/cdp/cdp_8.jpg)

Hydrogen Engine Characteristics for Current Technology Generated from Experimental Data

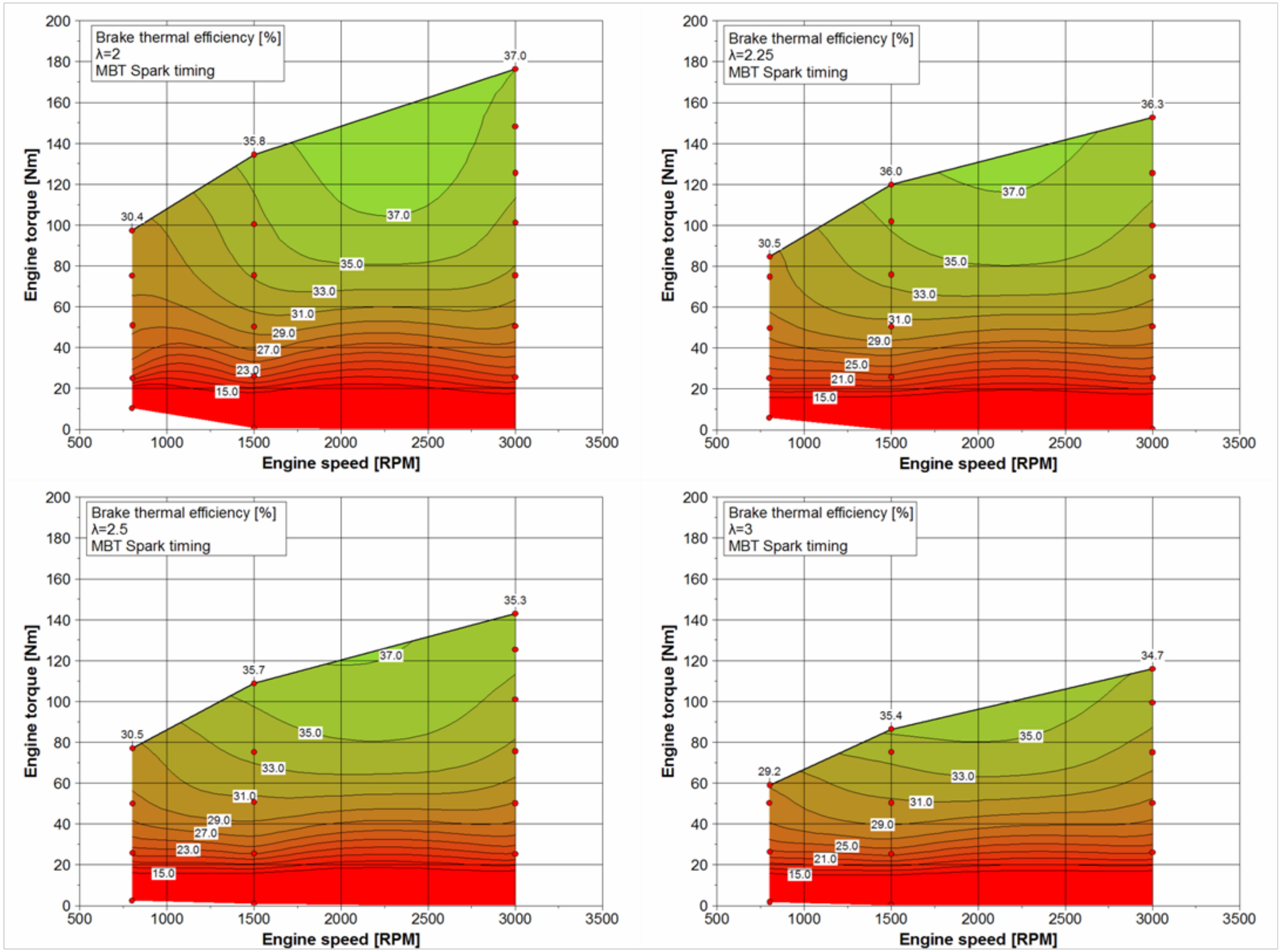


4-cylinder hydrogen engine setup

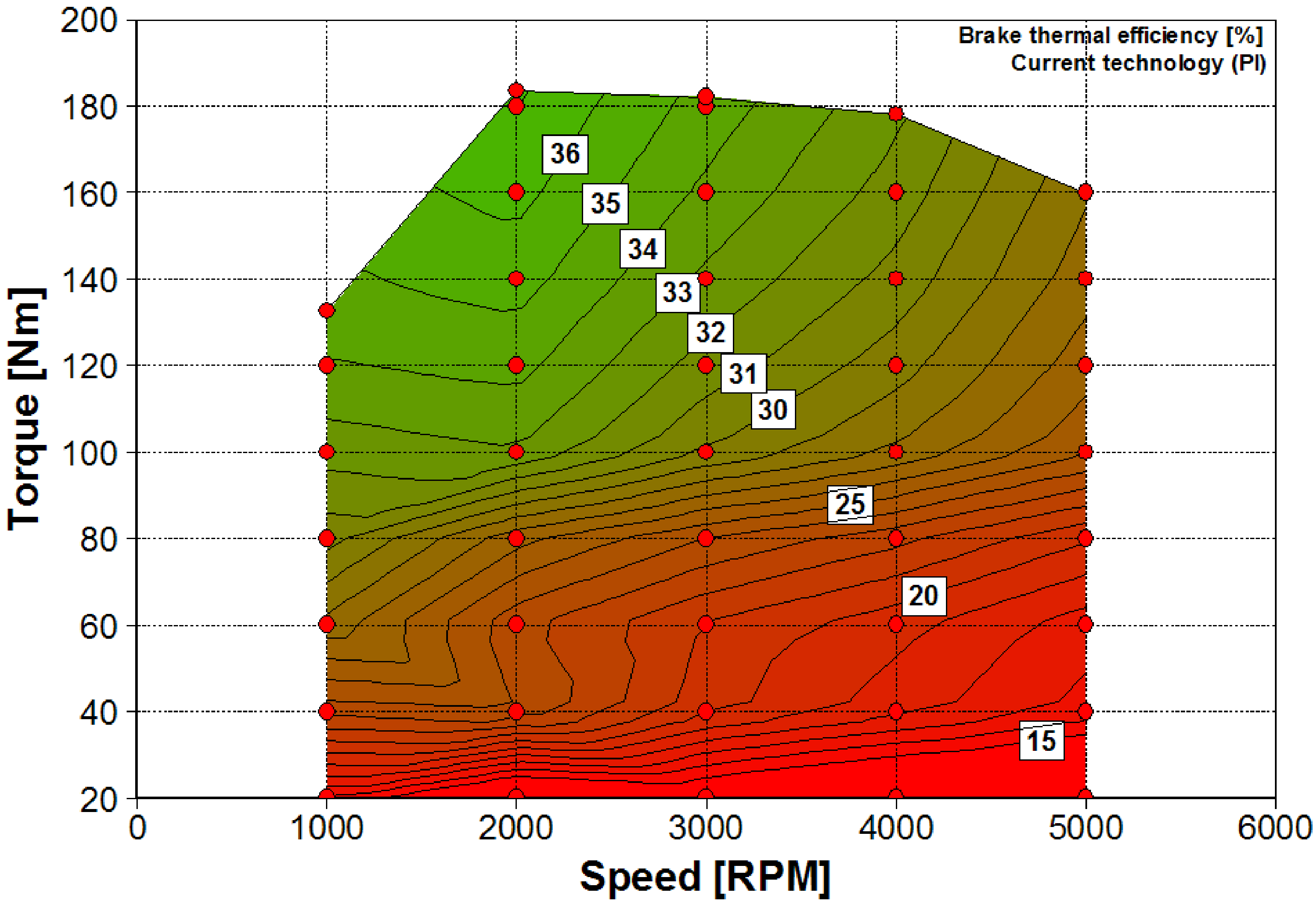
Manufacturer	Ford Motor Co.
Model	2.3L Duratec
Cylinders	4
Bore	87.5 mm
Stroke	94 mm
Compression ratio	12
Valve train	4V DOHC
Speed range	6000 RPM

- Modifications
  - Supercharger and intercooler
  - Hydrogen port fuel injection
  - After-market ECU

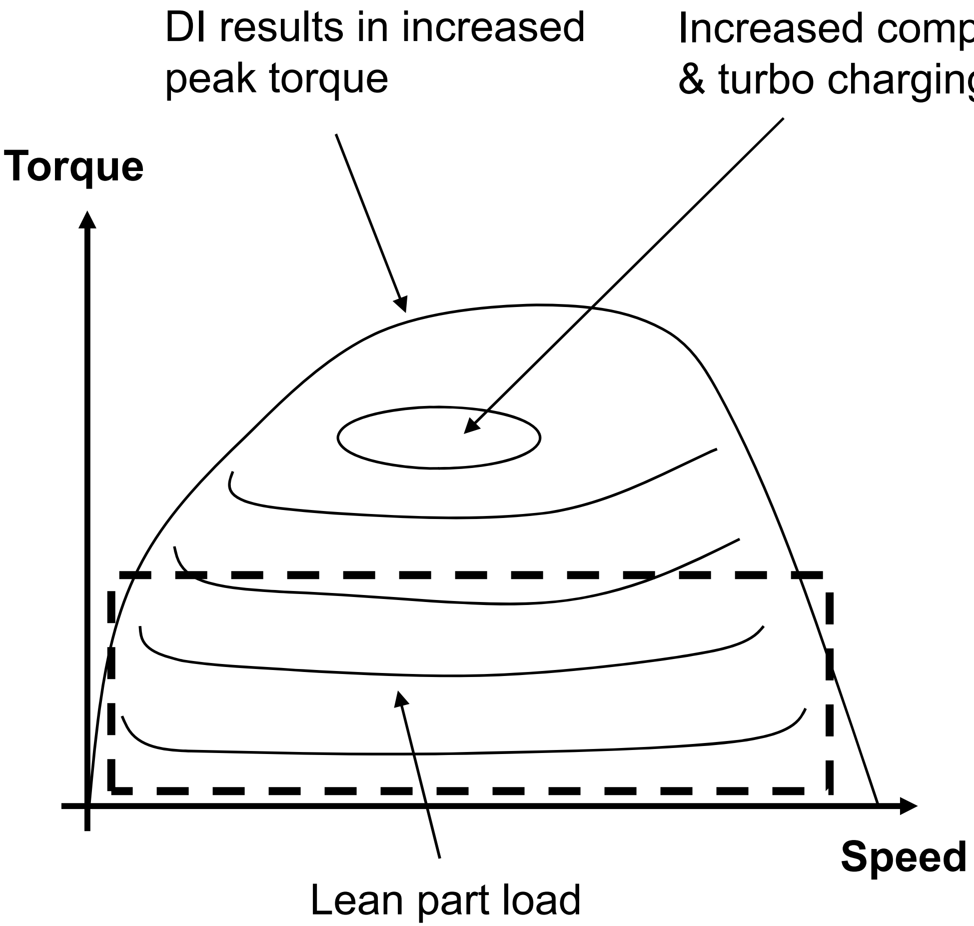
Port Injected Maps
Test data for Different Air/Fuel Ratios



Efficiency Map - Current Technology



Direct Injection Hydrogen Engine Operation
Estimated from Single Cylinder Test Data



- Hydrogen Direct Injection will increase the peak torque curve
- Increased compression ratio will result in an increase in engine efficiency
- Turbo-charging will increase the engine efficiency compared to supercharging
- Lean part load operation will result in a further part load efficiency increase compared to throttled operation

Peak efficiency of 45% assumed

H2 Engine Capable of Achieving*

*** Test performed at Ford Motor Company***

Brake Thermal Efficiency (LHV)

<u>Test Conditions:</u>

Date:	**17-Jan-2008**
Injection:	**Multiple DI**
Engine Speed:	**3000 RPM**

(Conservative PMEP compared to Turbo multi-cylinder)

Coolant temp:	**93°C**

Injection Pressure: 98 atm
(Consistent with FreedomCar Specification)

(Boost Assumptions Based on H_2 Multi-cylinder Correlation)

<u>Results:</u>

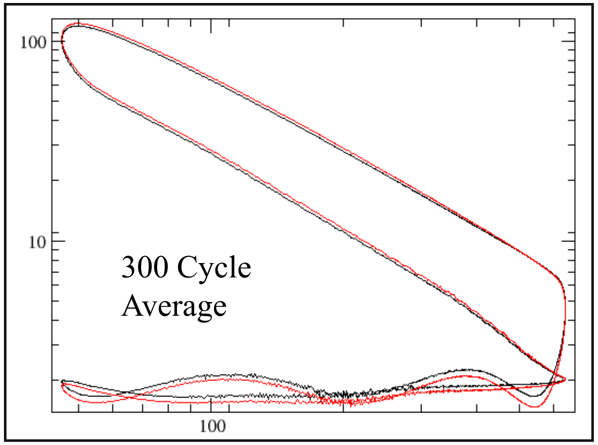
Net IMEP (720):	**14.56 bar**

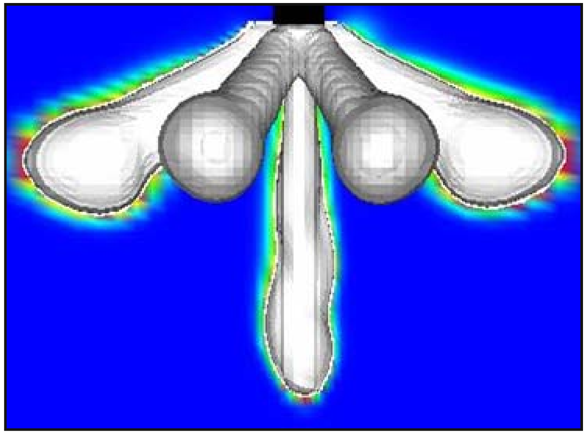
(300 Cycle Average of AVL GU21C and Kistler 6125B)

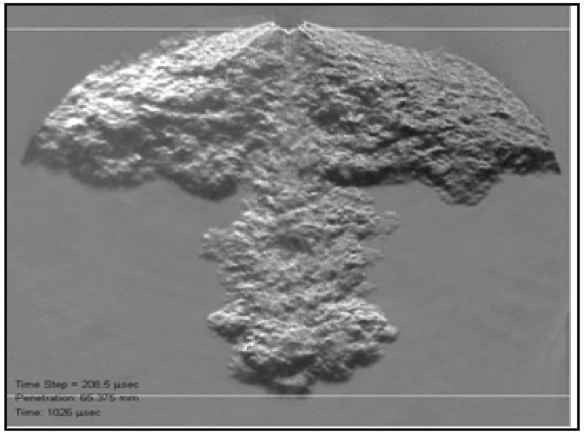
Applying Friction:	**0.70 bar**

(Published FEV/Porsche 4.8L Data)

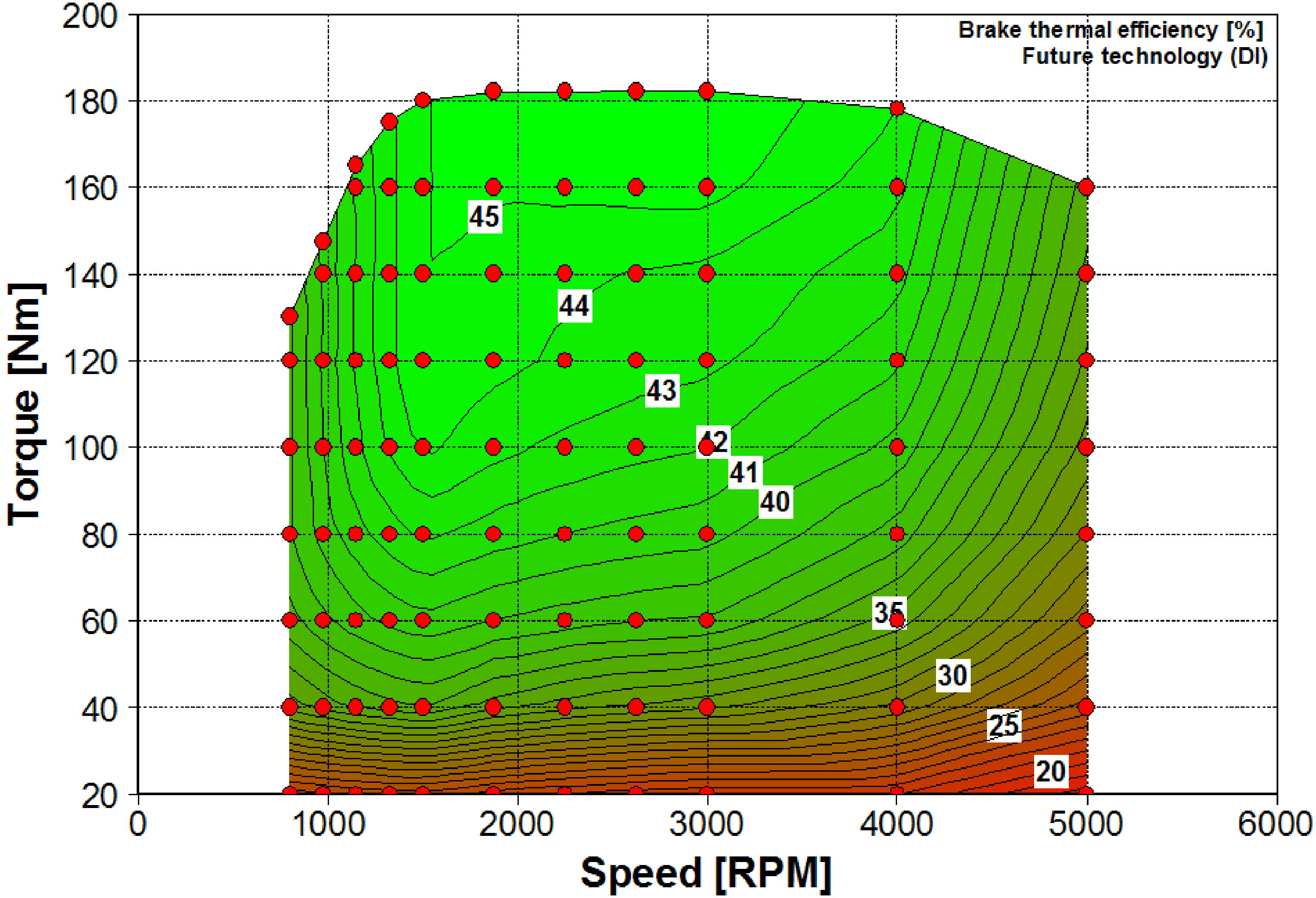
Resulting BMEP:	**13.86 bar**



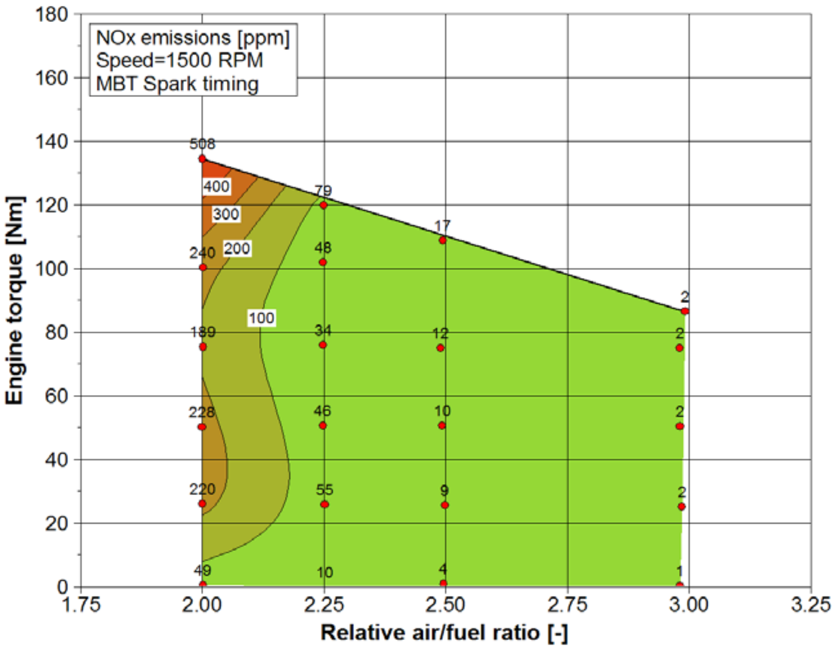




Efficiency Map - Future Technology

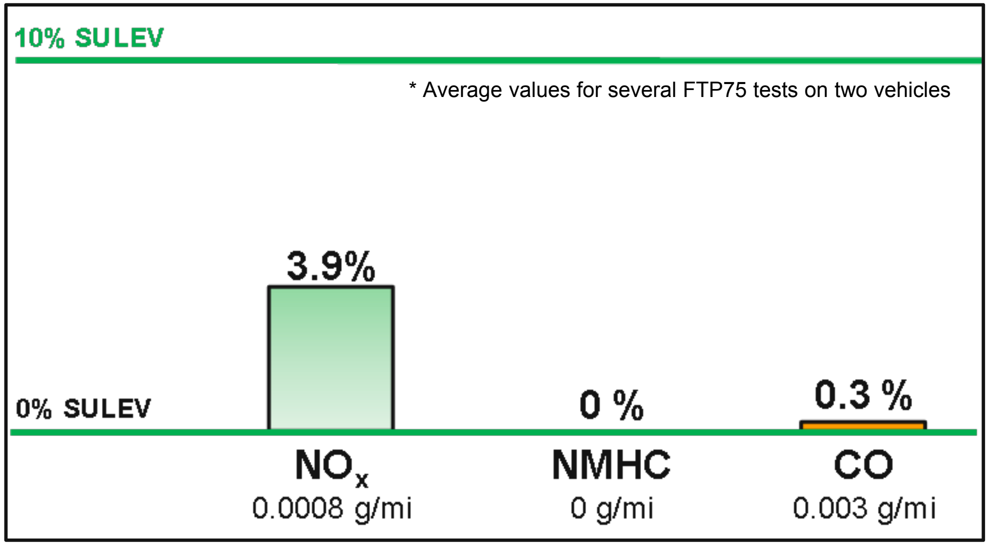


NOx emissions



- **Engine level results**
  - NOx emissions decrease with increased air/fuel ratio
  - At λ=2.25 NOx emissions are below 100 ppm in the entire load range
  - At λ=3 NOx emissions approach the detectability limit of the analyzer

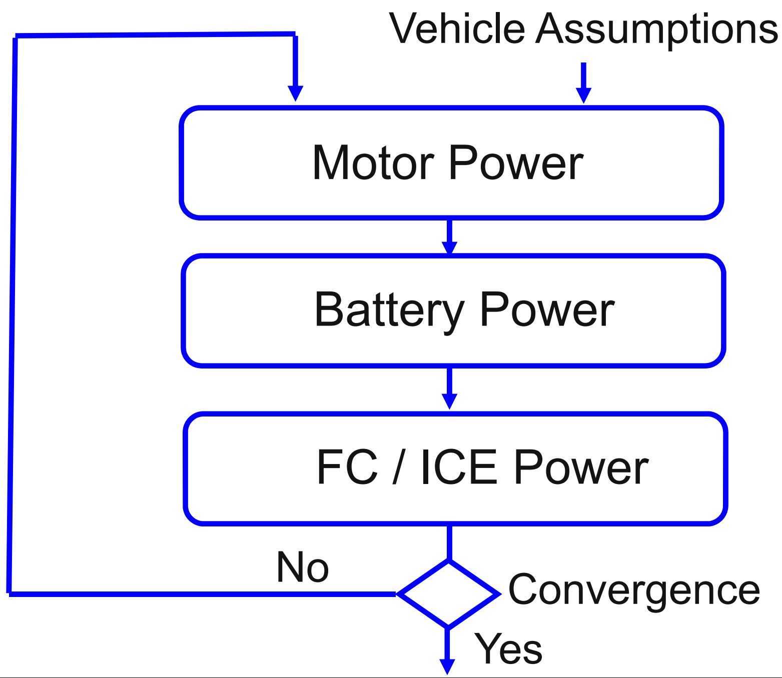
- **Vehicle level results**
  - Properly designed and calibrated hydrogen combustion engine vehicle can operate at emissions levels that are only a fraction of SULEV (Results from BMW Hydrogen 7)



Additional Component Assumptions

- Electric Machines
  - Power split -> based on 2004 Prius (from ORNL)
  - Series -> Ballard IPT (from Ballard)
- Energy Storage System
  - Current Technology -> NiMH Panasonic 6.5 Ah (from INL)
  - Future Technology -> Li-ion Saft 6 Ah (from ANL)

Vehicle Sizing Algorithm

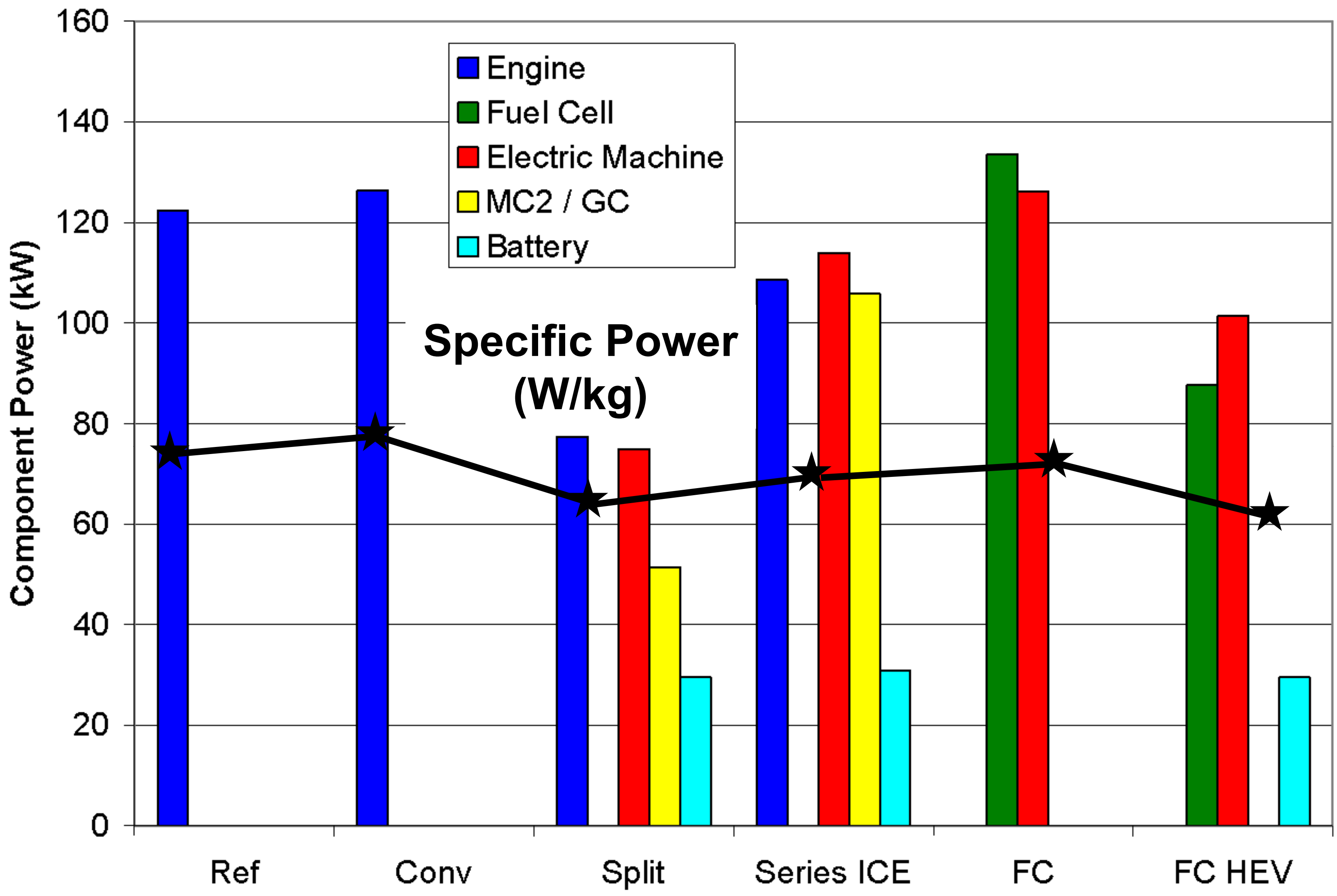


<u>Associated Requirements</u>

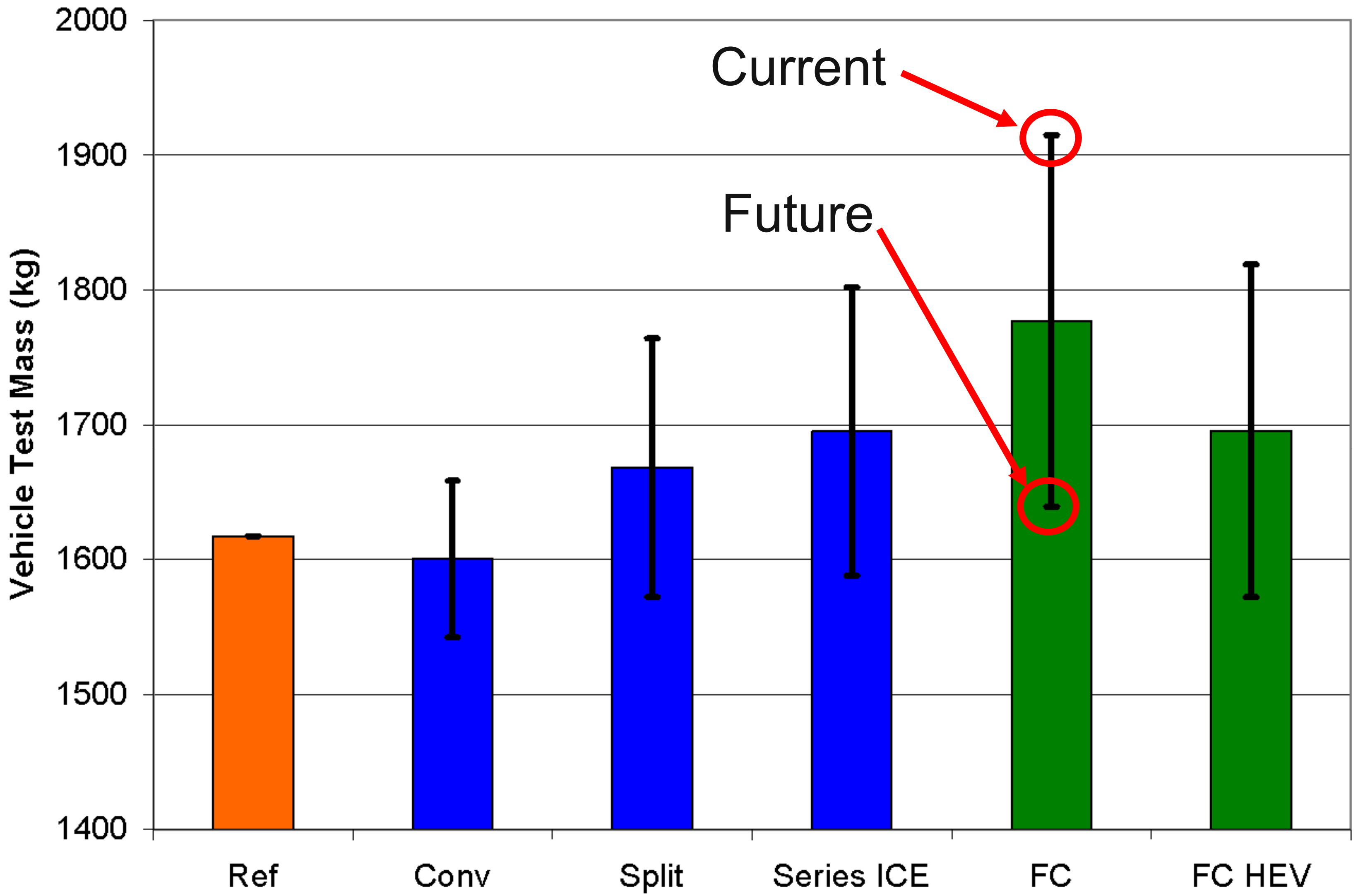
Capture all Regen on UDDS
<u>Performance:</u>
IVM-60 mph
<u>Grade:</u>
60 mph 6% grade

Note: Approach consistent with all current production HEVs based on APRF test data

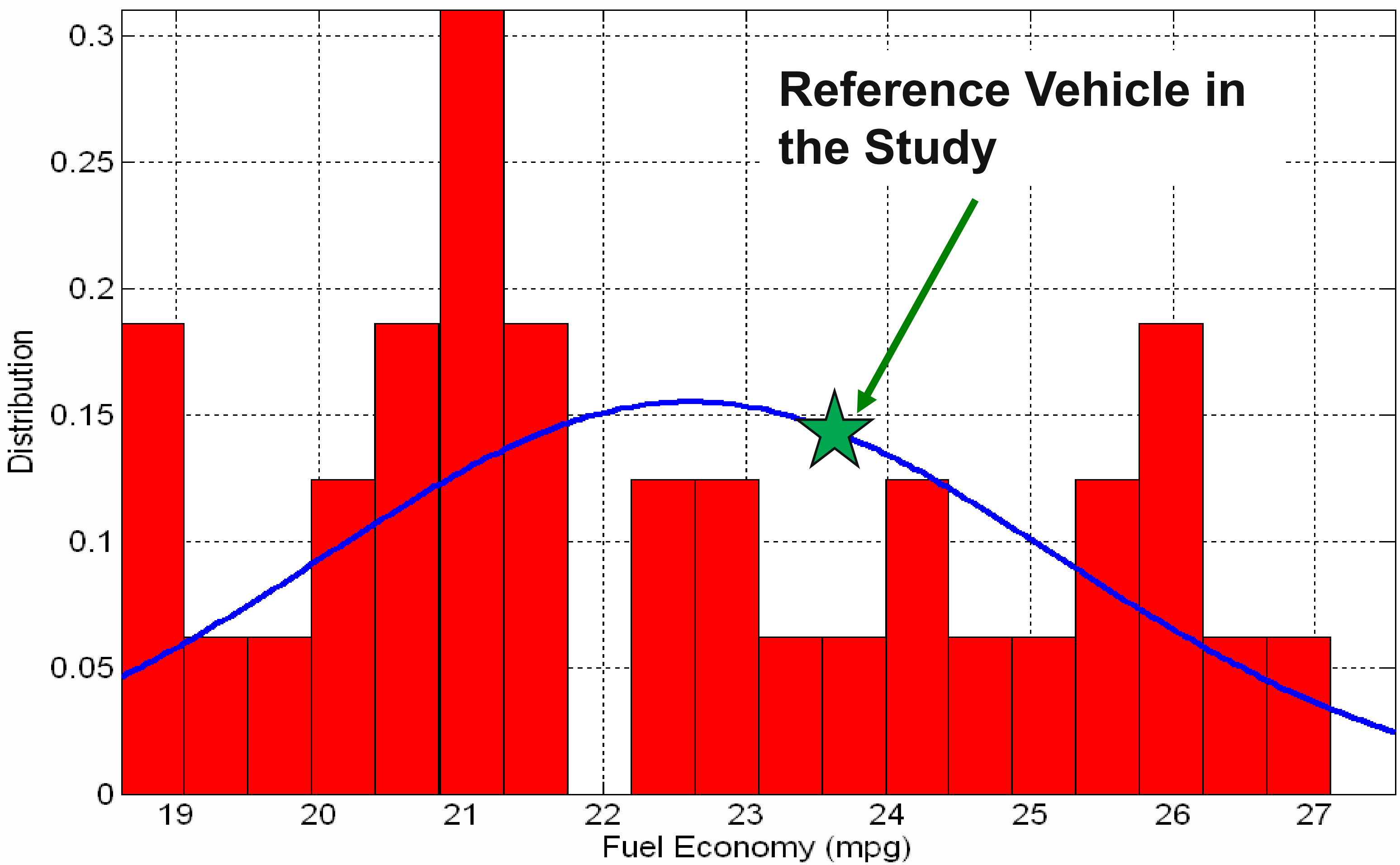
Component Average Power



Vehicle Test Mass Comparison

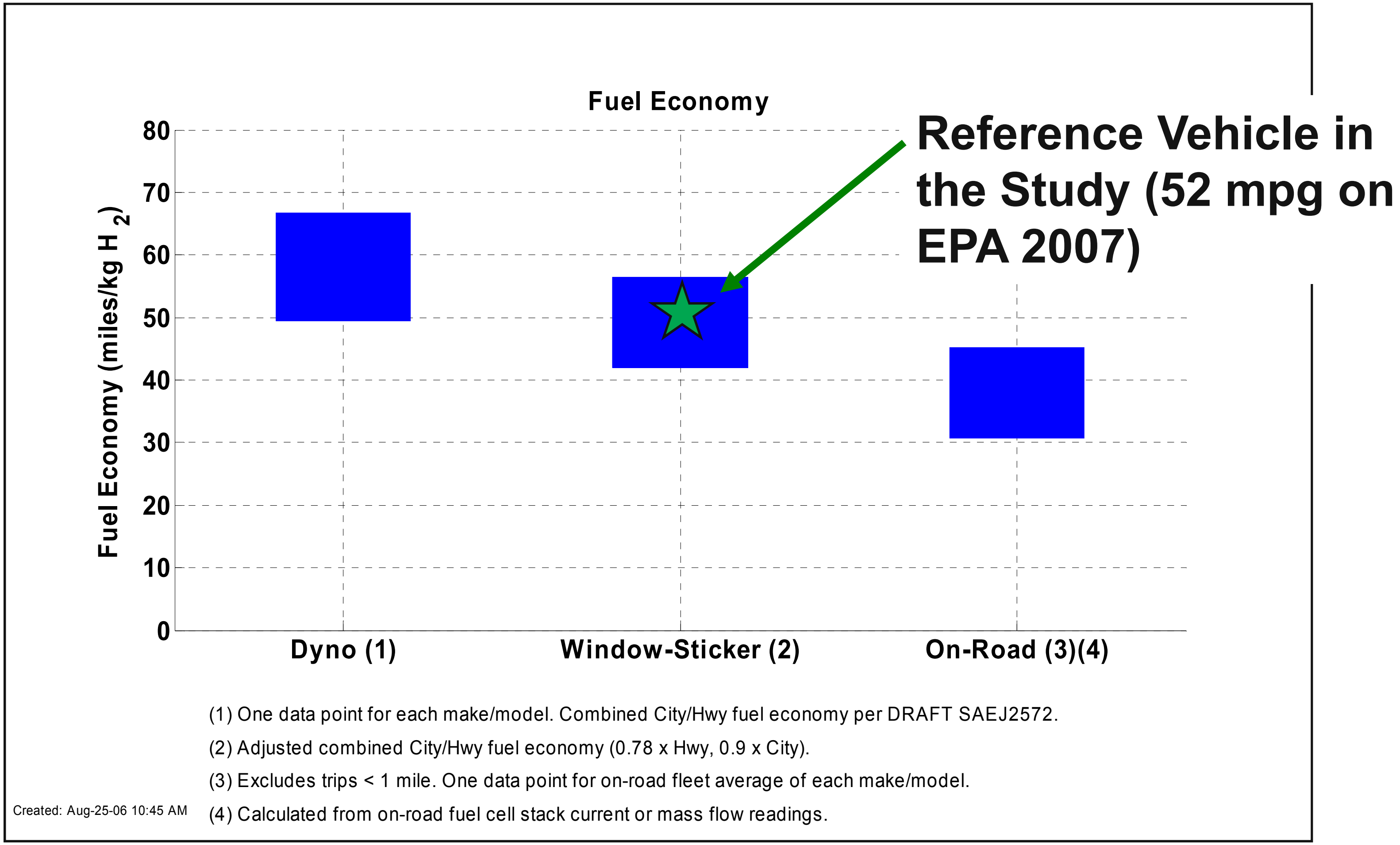


Reference Gasoline Vehicle
Comparison to Vehicles on the Market



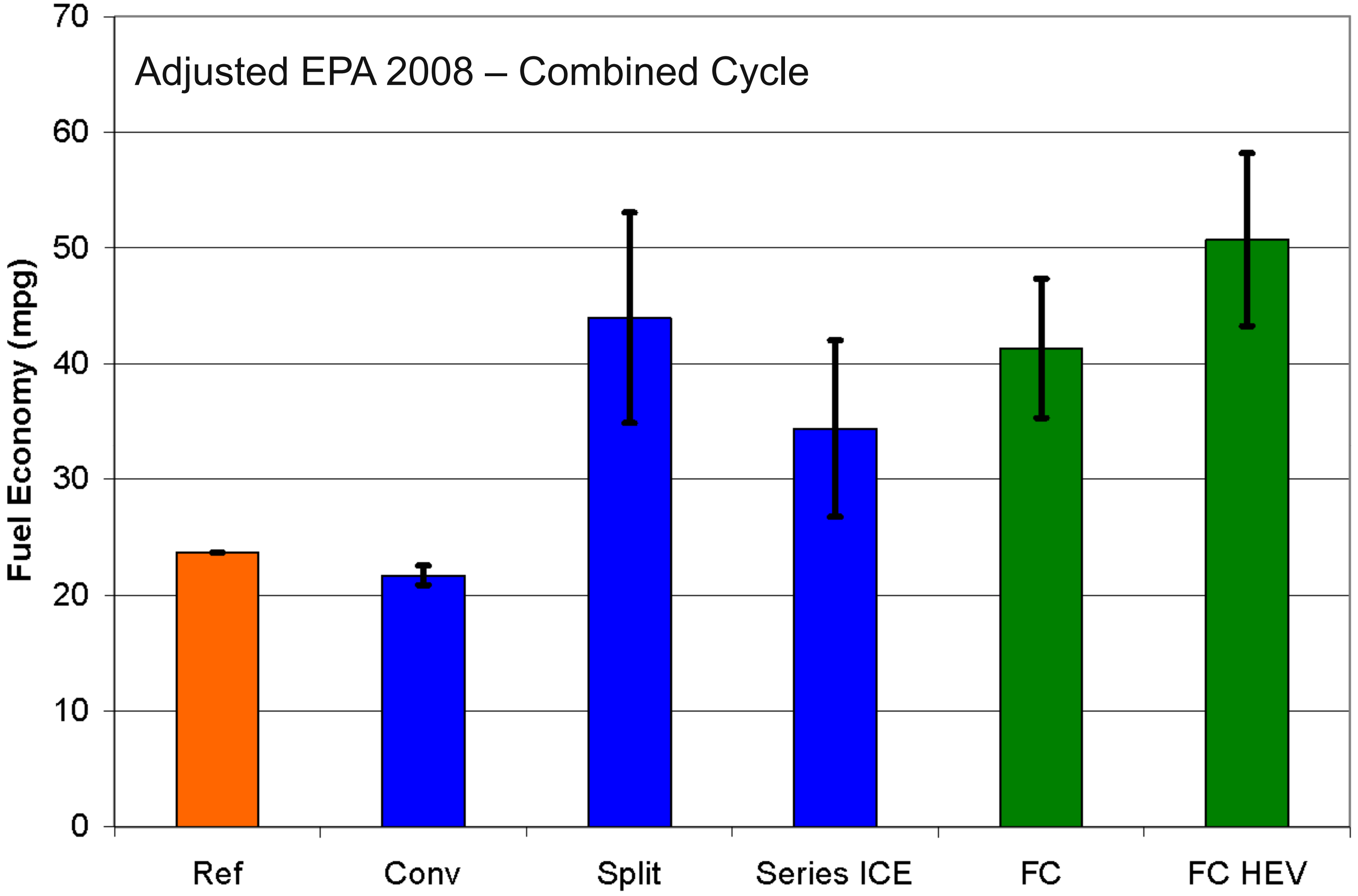
Distribution of current midsize gasoline vehicles fuel economy (2008 EPA)

Reference Fuel Cell HEV
Comparison to Vehicles on the Road

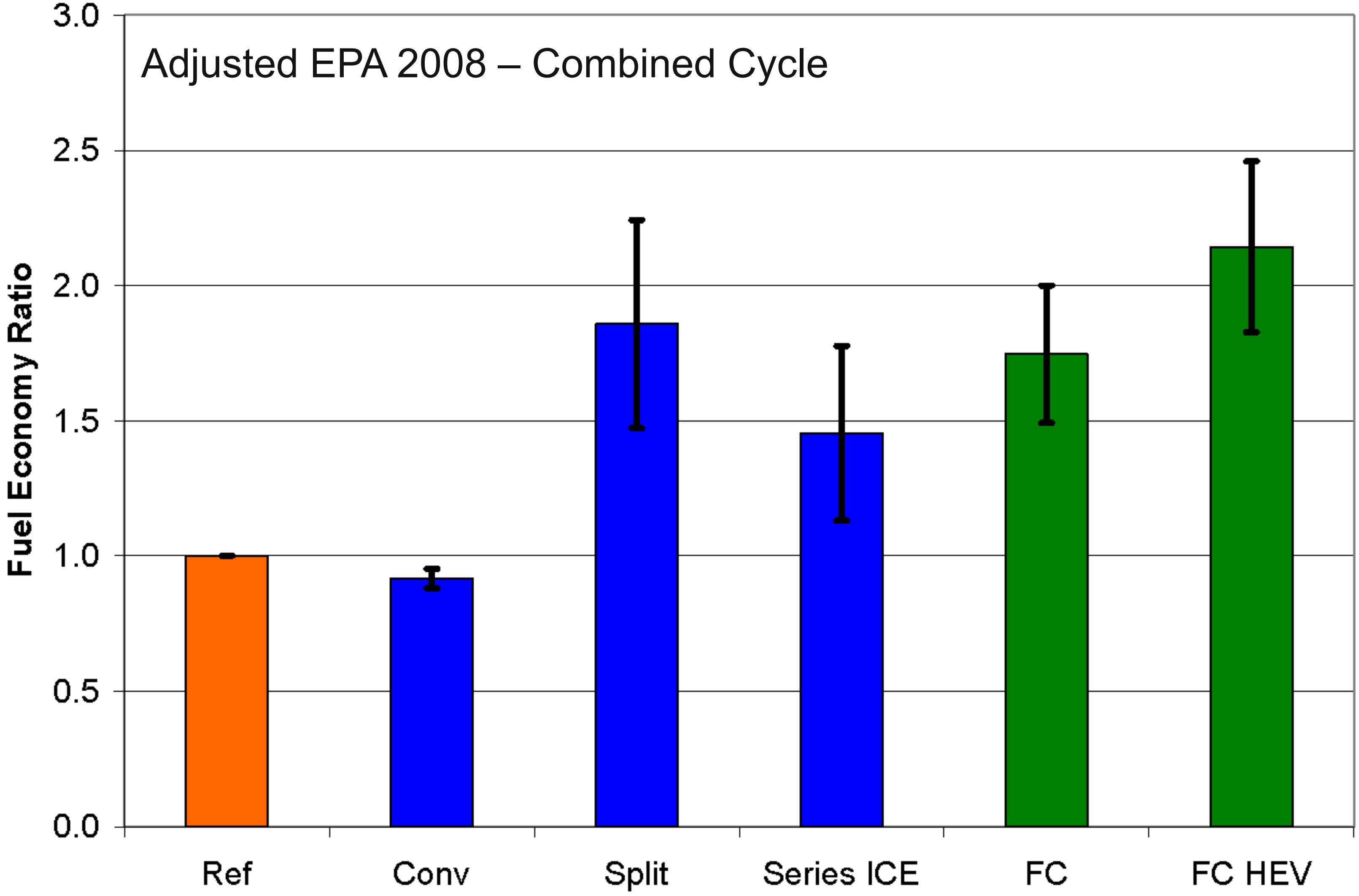


Source: NREL, Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, 2006

Fuel Economy Comparison



Fuel Economy Ratio



Results Summary – Combined Drive Cycles

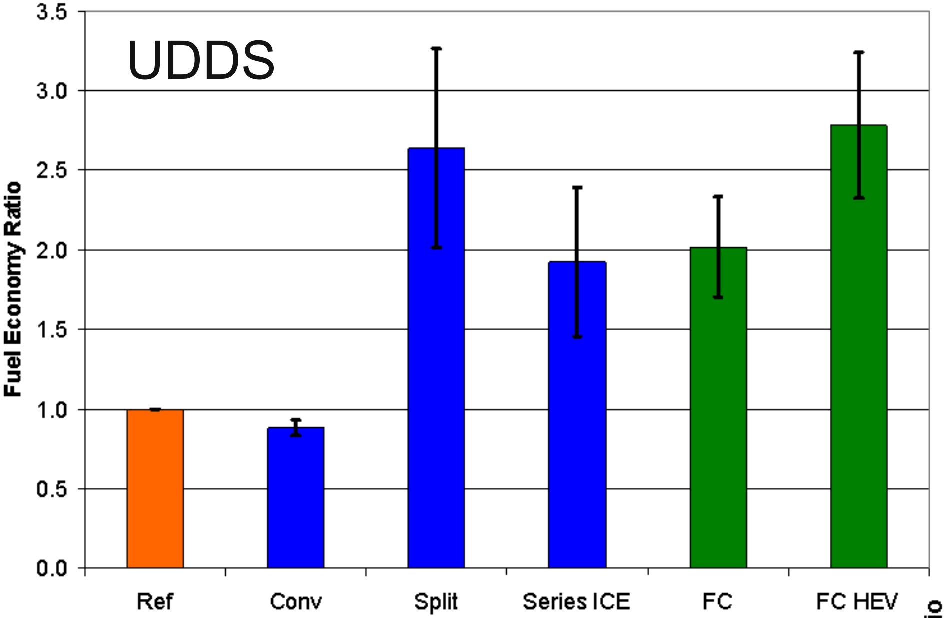
EPA 2008 Adjusted Fuel Economy (mpg)

	Ref	Conv	Split	Series ICE	FC	FC HEV
Current	23.66	20.84	34.86	26.74	35.30	43.24
Future	23.66	22.52	53.06	42.03	47.34	58.20
Average	23.66	21.68	43.96	34.39	41.32	50.72
Error bar	0.00	0.84	9.10	7.65	6.02	7.48

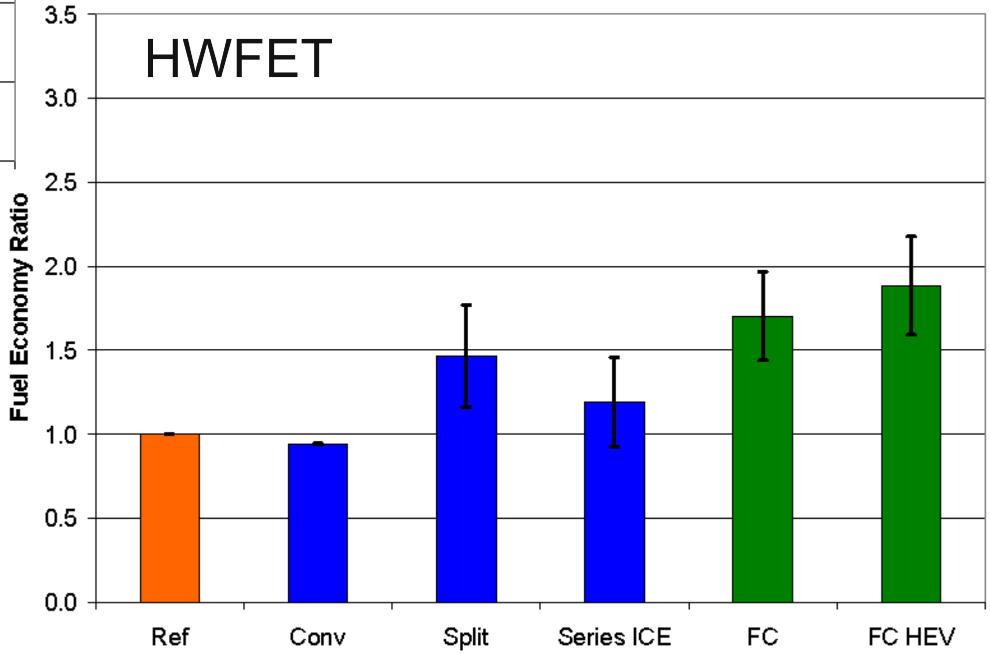
EPA 2008 Adjusted Fuel Economy Ratio

	Ref	Conv	Split	Series ICE	FC	FC HEV
Current	1.00	0.88	1.47	1.13	1.49	1.83
Future	1.00	0.95	2.24	1.78	2.00	2.46
Average	1.00	0.92	1.86	1.45	1.75	2.14
Error bar	0.00	0.04	0.38	0.32	0.25	0.32

Impact of Drive Cycles on Fuel Economy Ratios



- UDDS shows greater gains for all systems
- H2 ICE penalized more on the HWFET than the fuel cell vehicles



* Ratios are based on unadjusted values

Future work

- Further optimize hydrogen direct injection combustion strategies on single-cylinder research engine (ongoing project)
- Transfer single-cylinder results to a ground-up design for a dedicated efficiency optimized hydrogen multi-cylinder direct injection engine (proposed project)
- Use future steady-state results from a dedicated multi-cylinder hydrogen DI engine for additional simulation runs
- Transfer dedicated multi-cylinder hydrogen DI engine to Modular Advanced Technology Testbed for drive-cycle testing (proposed project)

Summary

- The DI H2-ICE has been defined based on a combination of four-cylinder and single cylinder data generated for different A/F ratios.
- H2 ICE has more potential than initially thought
- H2 ICE should be used within an HEV to utilize full efficiency potential
- Power split configuration offers the best fuel consumption when using H2-ICE due to added inefficiencies in the series configuration.
- Fuel cell systems benefit less from hybridization than the ICE due to their high system level efficiency
- The study confirms DOE position that H2 ICE is a bridging technology and might help the infrastructure development