Drive-Cycle Performance and Life-Cycle Costs of Automotive Fuel Cell Systems

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Drive-Cycle Performance and Life-Cycle Costs of Automotive Fuel Cell Systems

2010 study: Cost reduction with moderate decrease in fuel economy

2011 study: Life-cycle cost of fuel-cell hybrid electric vehicles (HEV)

- Initial cost of fuel cell propulsion system (FCS), energy storage system (ESS) and electric drivetrain
- Fuel cost over real-world drive cycles, 15 years

Outline

- Reference fuel-cell system configuration
- FCS efficiency, performance and cost
- HEV configuration, component specifications, and cost assumptions
- Energy management and real-world drive cycles
- Net present value definition and optimization
- Optimum battery size and FCS control parameters
- Fuel economy
- Sensitivity to fuel cost

Approach

Trade-off between initial and operating costs

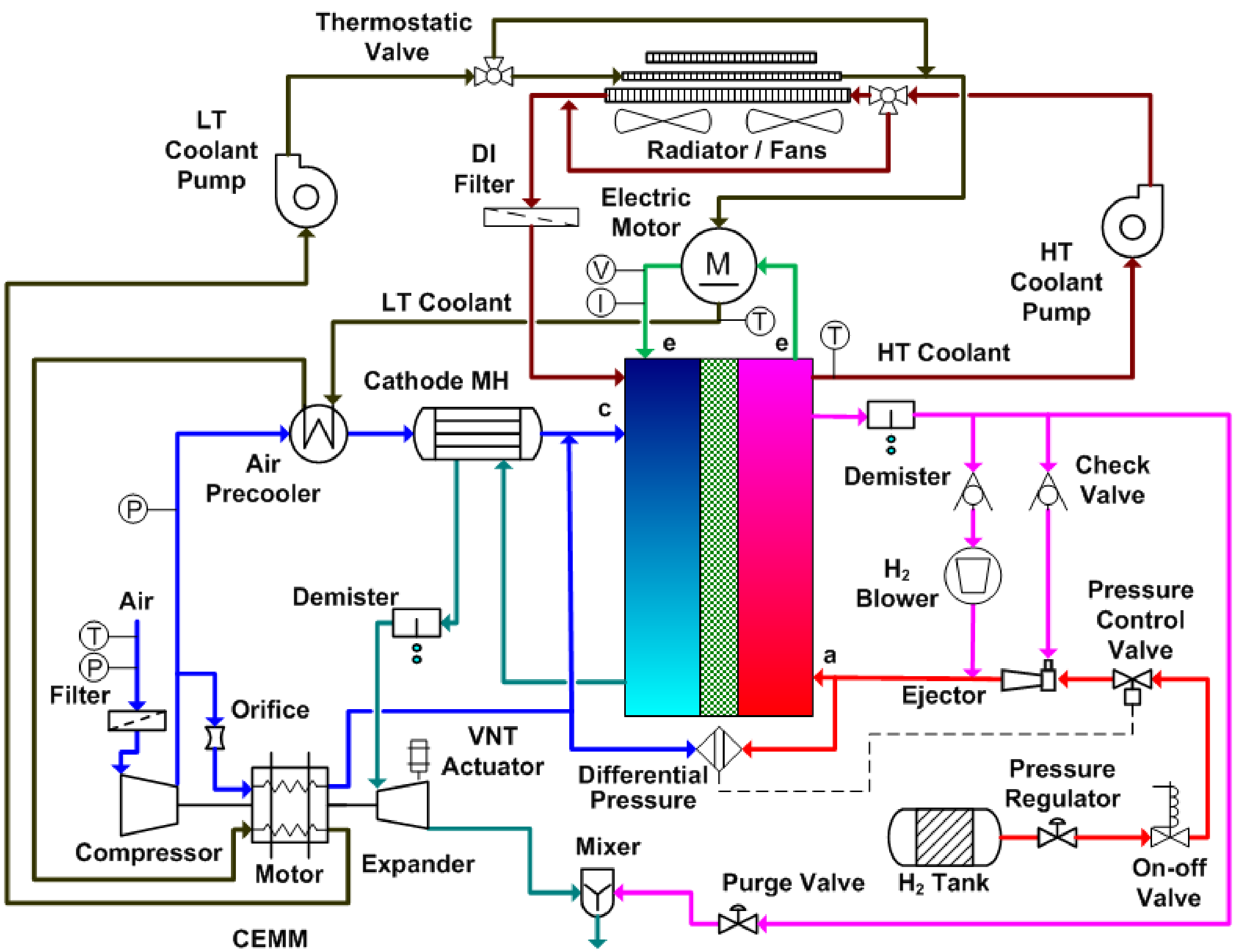
- FCS variables: rated power (65-120 kW), efficiency at rated power (35-50%)
- ESS variable: maximum discharge power (20-35 kW), fixed storage capacity (1.4 kWh)
- Weight penalty

Approach

- Fuel cell system with low-Pt loading
- FCS operated in load-following mode
- ESS operated in charge-sustaining mode
- Single FCS and ESS over vehicle lifetime with degradation in battery performance
- Real-world drive cycles from the EPA Kansas City Test Program
- Net present value: net of future fuel savings and incremental cost of FCS and ESS over a reference ICE powertrain

Argonne 2011 FCS Configuration

- S1 – Pressurized FCS, 2.5 atm stack inlet pressure at rated power
- S2 – Low-pressure FCS, 1.5 atm stack inlet pressure at rated power
- Dynamic performance of the components and the system



2011 FCS

MEA
- 3M NSTFC MEA
- 20-µm 3M membrane
- 0.05(a)/0.1(c) mg/cm^2 Pt
- Metal bipolar plates

Air Management System
- Honeywell CEMM
- Air-cooled motor/AFB

Water Management System
- Cathode MH with precooler

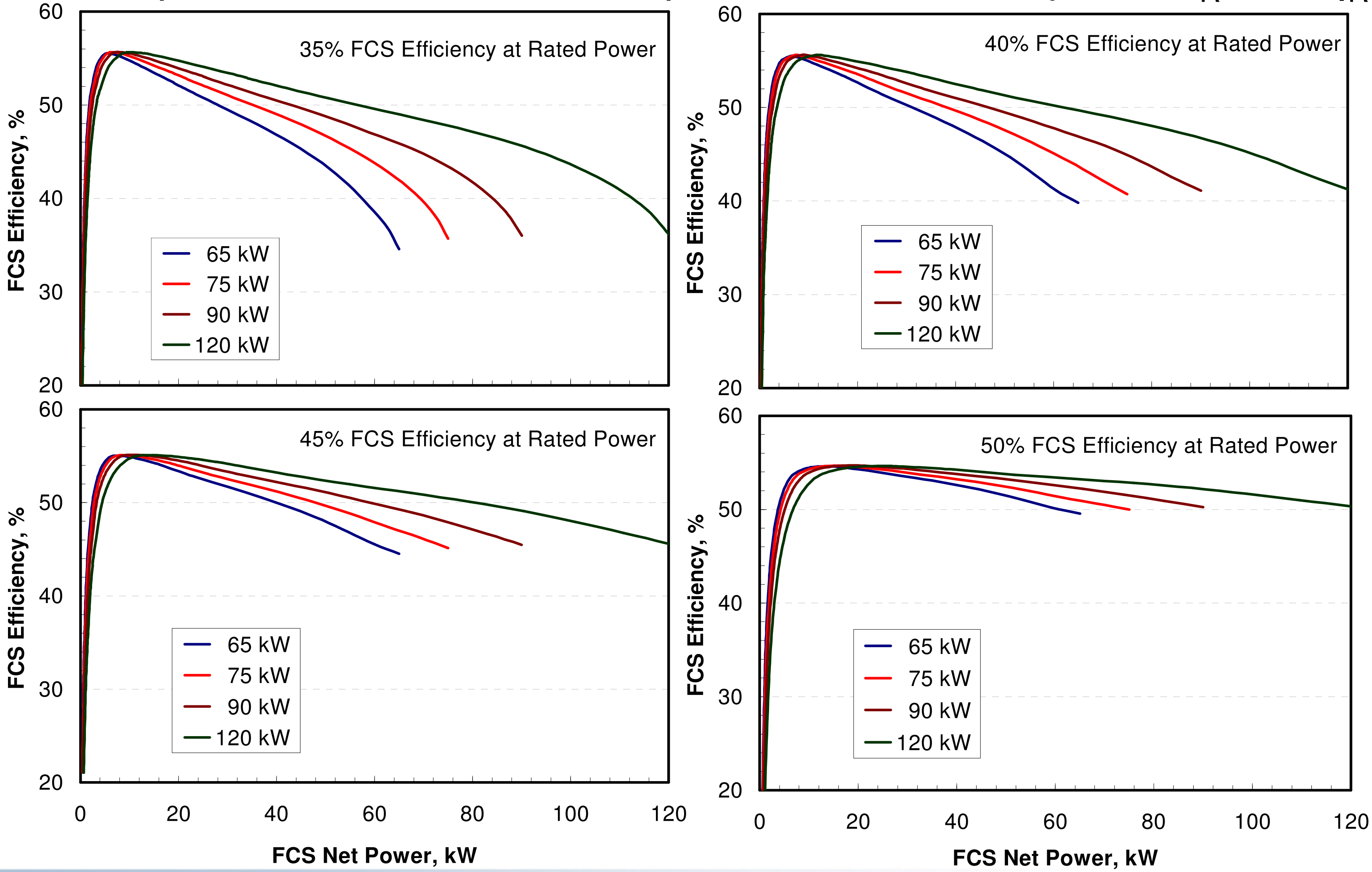
Thermal Management System
- Advanced 40-fpi microchannel fins

Fuel Management System
- Parallel ejector-pump hybrid

FCS Efficiency Maps

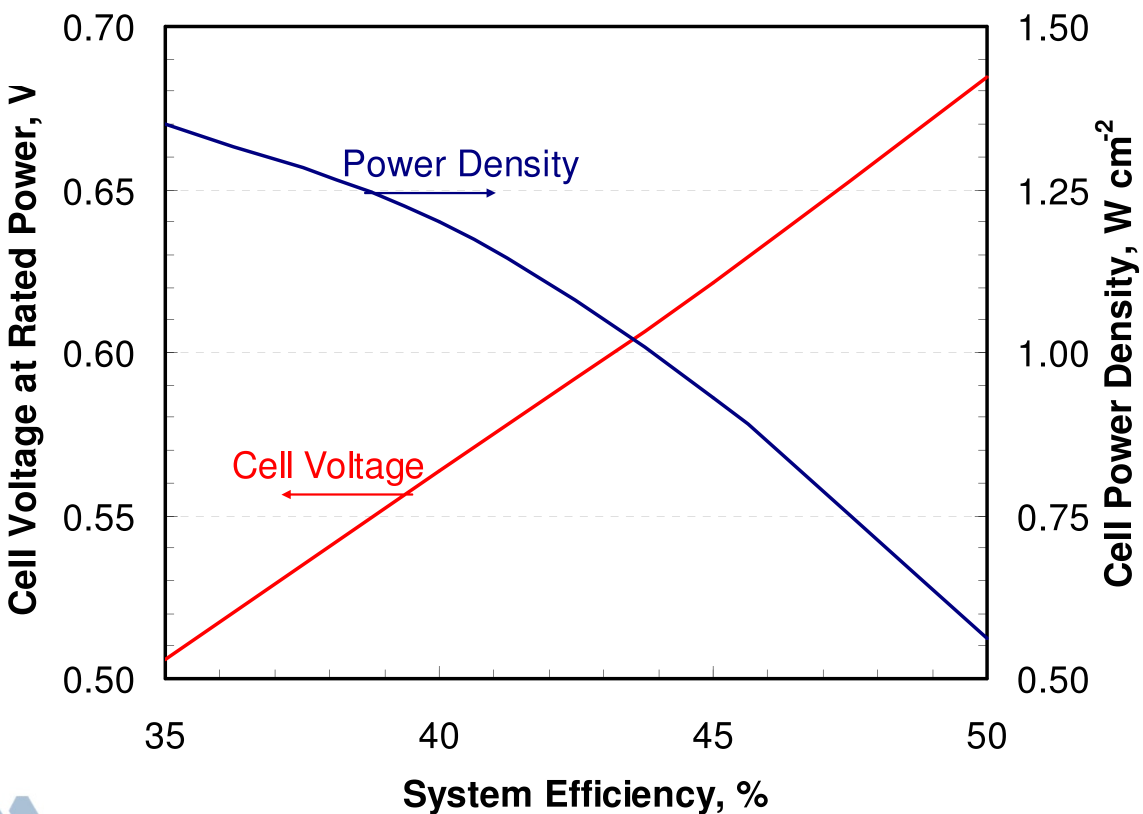
Modeled efficiency maps (GCtool), LHV basis

- Peak efficiency (η_M) and FCS power at η_M functions of P_R and η_R
- At low power, inverse relationship between efficiency and P_R and η_R



Stack Performance at Rated Power

- Cell voltage at rated power and power density primarily function of η_R
  - Cell voltage 505 mV at η_R =35%, 685 mV at η_R =50%
  - Current density > 2 A cm^{-2} at 505-mV cell voltage
  - Ohmic and mass transfer overpotentials become significant for >2 A cm^{-2} current density



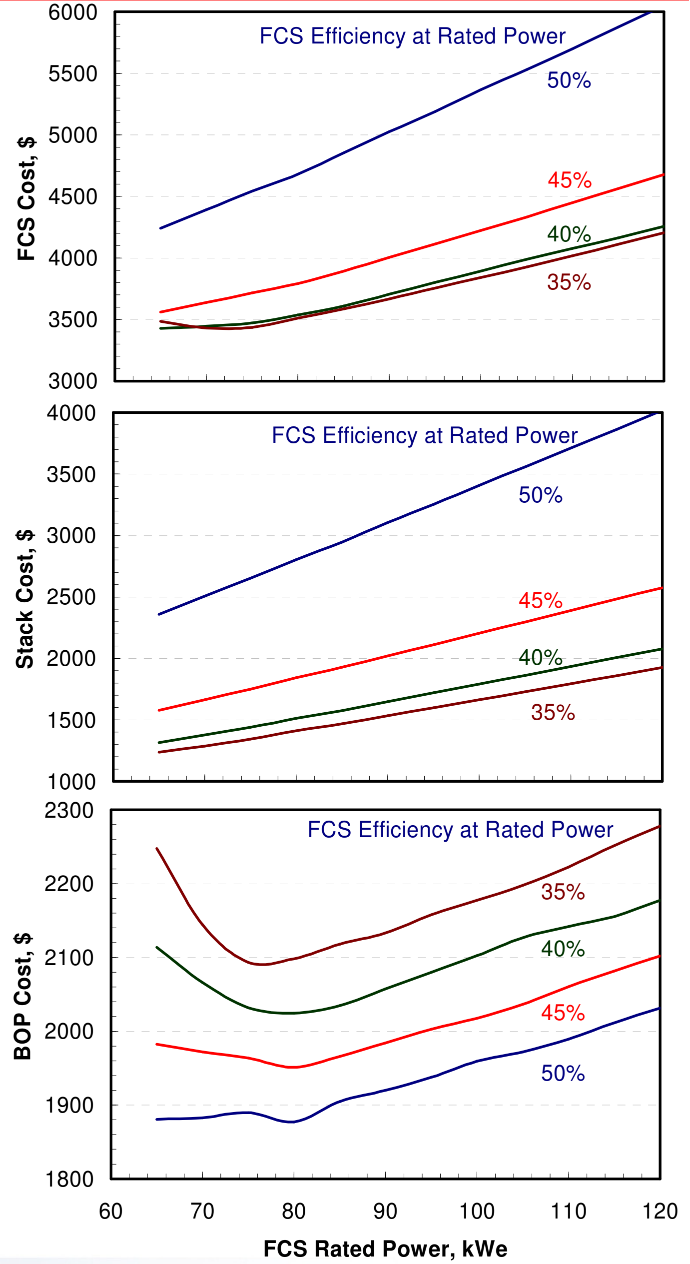
Conditions at Rated Power

Counter-flowing H_2 and air
Co-flowing air and coolant
1.5 atm stack inlet pressure
65°C coolant inlet T, 10°C ΔT
Inlet T_{DP}: 61°C(c), 53°C(a)
50% H_2/O_2 utilization

FCS Cost at High Volume Manufacturing

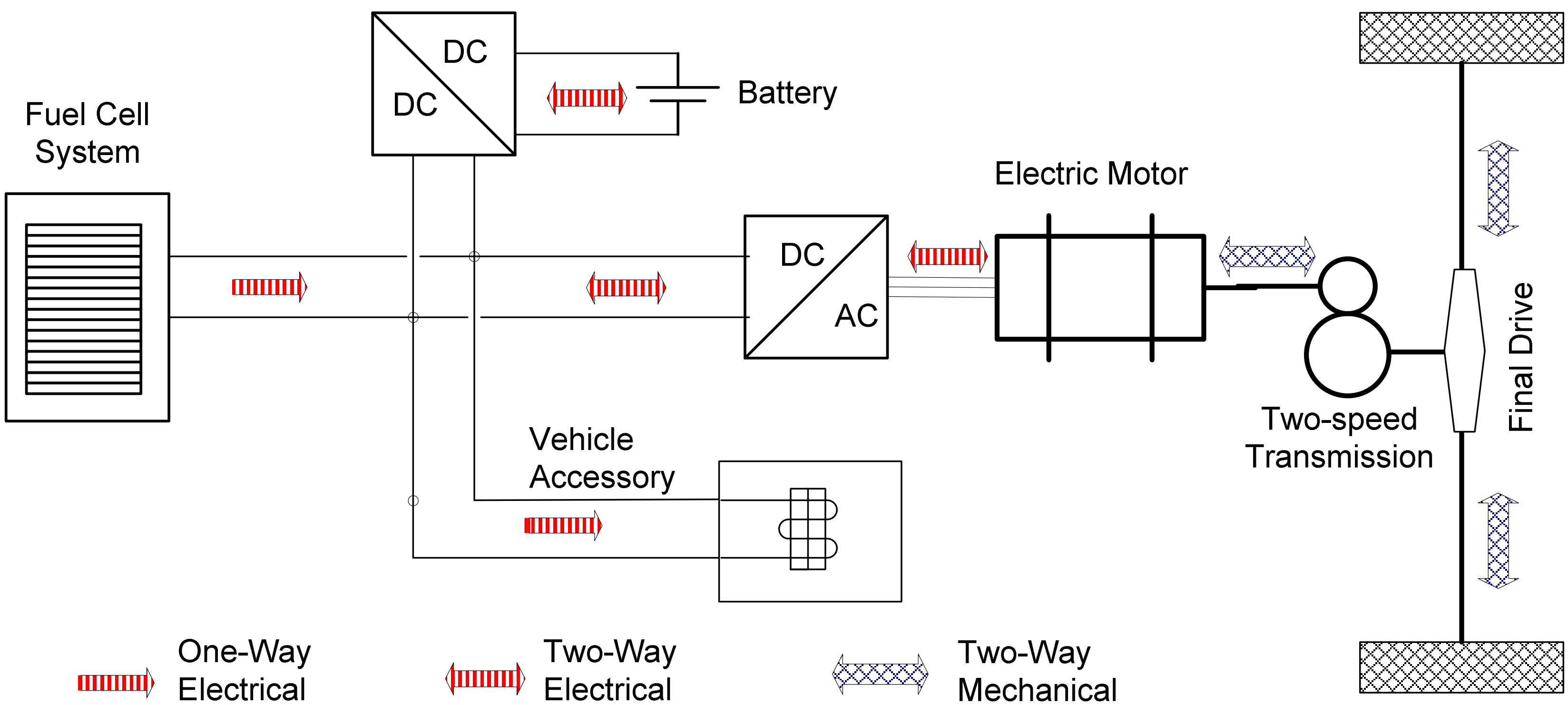
Cost correlations from multi-variable regression analysis by SA

- Stack Cost
  active membrane area, catalyst loading, Pt price, stack V
- Air Management System Cost
  compressor discharge P, flow rate
- Water Management System Cost
  membrane area, pre-cooler Q, ΔT
- Thermal Management System Cost
  heat duty, ΔT, radiator fan power
- Fuel Management System Cost
  blower power
- Balance of System



Series FC HEV Configuration

- Charge-sustaining hybrid electric vehicle (HEV) with load-following fuel cell system
- Simulated modes of operation
  - FCS operated in load-following mode (LFM)
  - FCS operated as a battery-charger (BCM)



HEV Component Specifications

Mid-size vehicle platform

- Li-ion battery pack: 1.4 kWh storage capacity, 20-40 kW max power
- FCS: 65-120 kW (P_R), 35-50% efficiency at rated power (η_R)

Component	Weight (kg)	FC HEV Specifications
Transmission	75	2-Speed manual = 1.86, 1
		Peak efficiency = 97.5%
Final Drive	25	Ratio = 4.44, constant efficiency = 97.5%
Wheels	120	Wheel radius = 0.317 m
		Rolling resistance = 0.0075 (C_0), 0.00012 (C_1)
Vehicle	998 (glider)	Cargo = 136 kg, Passengers = 140 kg
		C_D = 0.26, A_F = 2.2 m^2
Traction Motor	120	Ballard IPT 300 V, Peak efficiency = 95%
		Peak power = 97.8 kW
Power Electronics	18	
H_2 Storage	108	
ESS	57	Storage capacity = 1.4 kWh
		Performance degradation = 4%/yr after 6 yrs
FCS	95 - 181	Rated power = 65 - 120 kW
		Rated power efficiency = 35-50%
DC-DC Converter		Constant efficiency = 95%

HEV Cost Assumptions

Mid-size vehicle platform

- Gasoline ICE and powertrain component costs from Ricardo study
- FCS cost from SA correlations for high-volume manufacturing
- H_2 storage system cost from ANL-TIAX study
- Fuel costs from DOE targets and assumptions

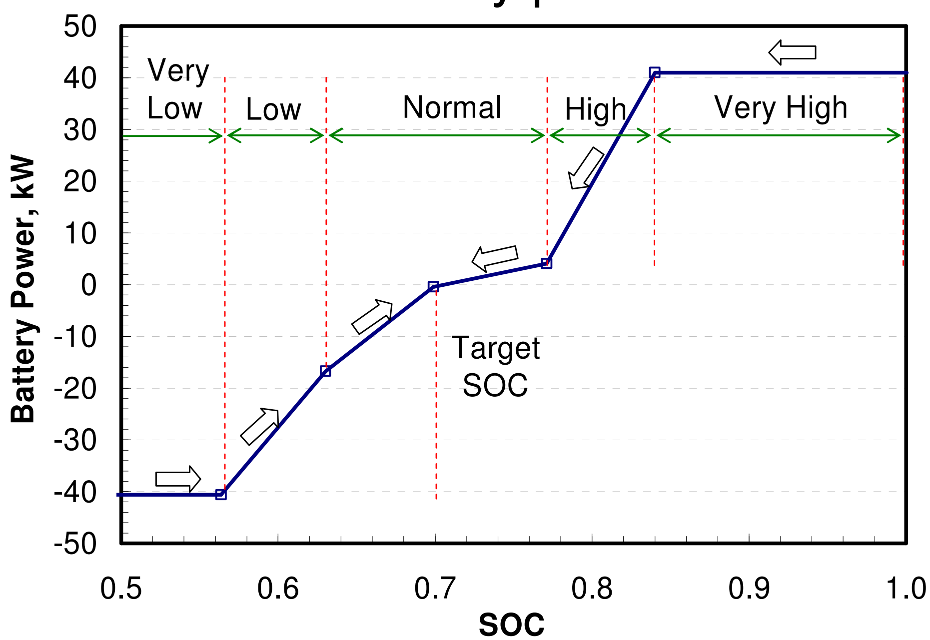
	Cost (Without Taxes)		
Component	**ICEV**	**FC HEV**	**Comments**
Engine	$2,000	$3,300-5,900	123 kW gasoline engine, 65-120 kW FCS
H_2 Storage	-	$3,530	5.6 kg H_2 at 700-bar, IJHE 36 (2011) 3037-3049
Electric Motor	-	$1,420	118-kW electric motor and controller, $12 kW^{-1}
Battery	$64	$700-880	12 V startup battery for ICEV
			Li-ion battery pack, 1.4 kWh storage capacity
Glider	$9,890	$9,890	
Transmission	$1,300	$840	
Tires	$320	$320	
Final Drive	$200	$200	
OEM Markup	1.5	1.5	50% OEM markup on all vehicle components
Fuel Cost	$3.70 gal^{-1}	$5.00 gge^{-1}	gge: gallon gasoline equivalent
O&M	$0.043 mile^{-1}	$0.043 mile^{-1}	Operating and maintenance expense

Energy Management

Load-following mode: FCS propels vehicle, maintains acceptable SOC

- FCS provides the vehicle accessory loads (250 W)
- Once started, FCS never turned off during a drive cycle. At idle, FCS provides power to BOP components and vehicle accessory loads.
- 1 MJ energy for start-up (SU) and shut-down (SD), 2 SUSDs per day
- FCS charges ESS at maximum power if SOC drops below SOC_{min}
- ESS discharged at maximum power if SOC exceeds SOC_{max}

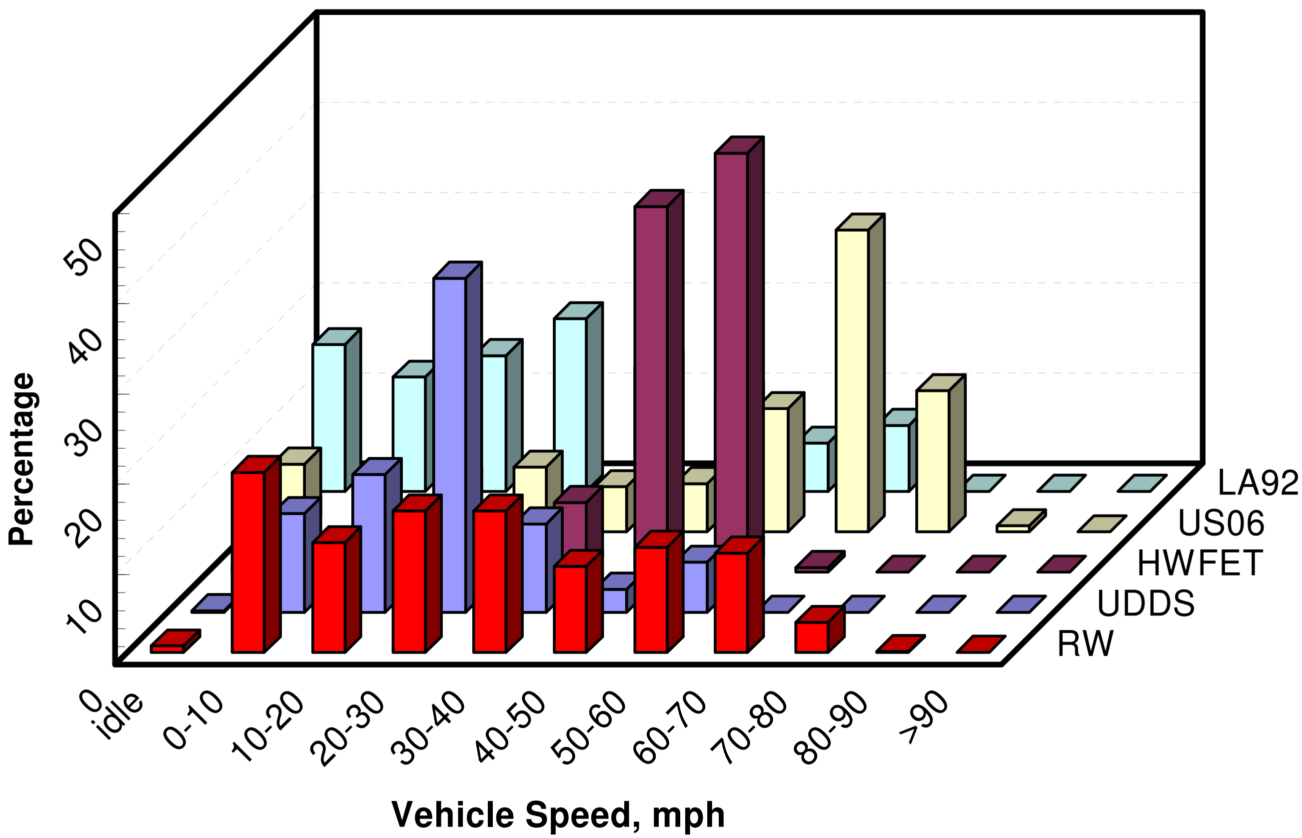
Look-up table determines the battery power demand to regulate SOC



Real-World (RW) Drive Cycles

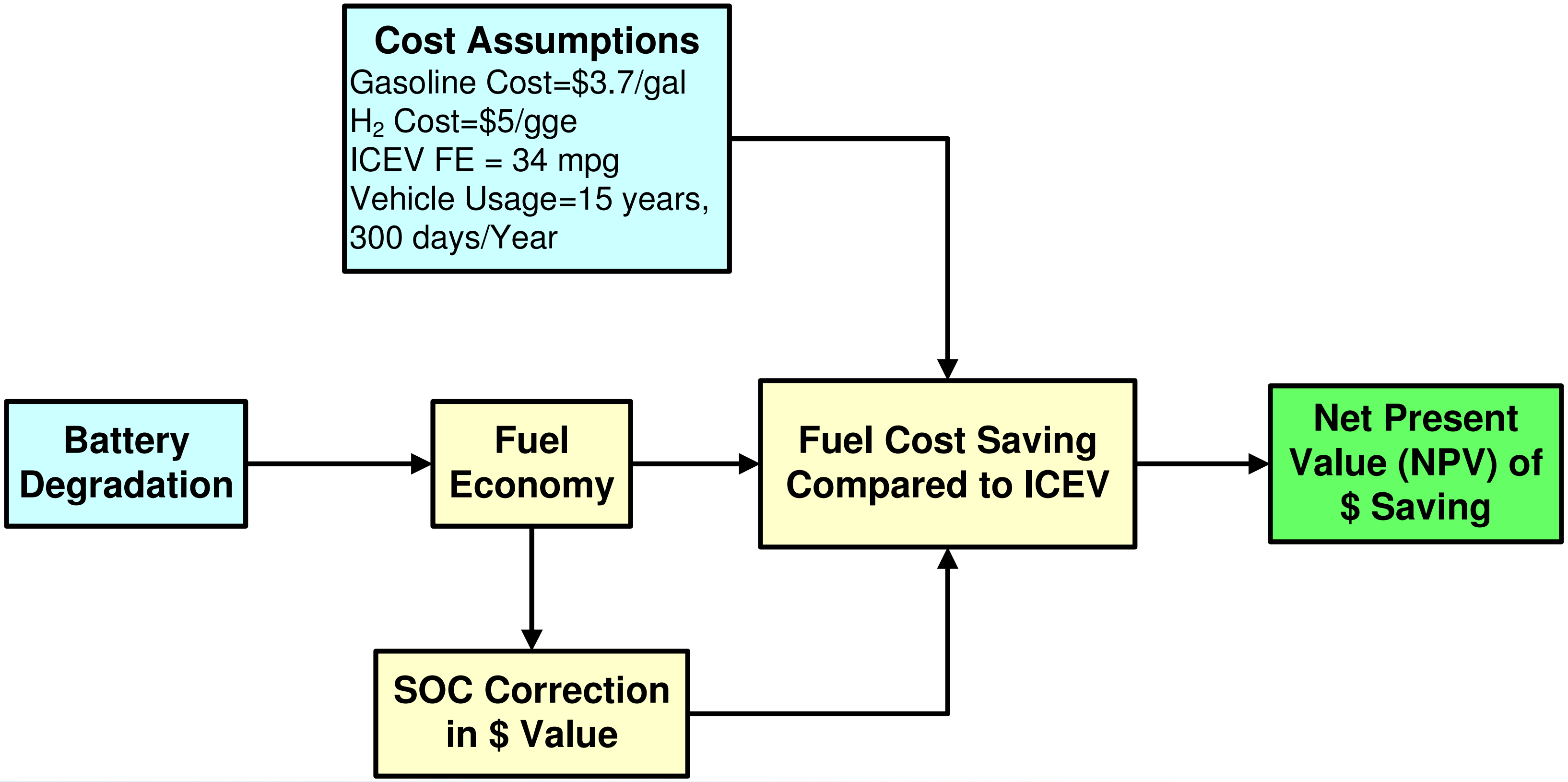
Kansas City Test Program conducted by EPA in association with NACAA, DOT and DOE/NREL

- 30 RW drive cycles sampled from database for light-duty vehicles
- Averages: 58 km daily driving distance, 52 km/h speed
- Speed distribution similar to LA92, but more even



Net Present Value (NPV)

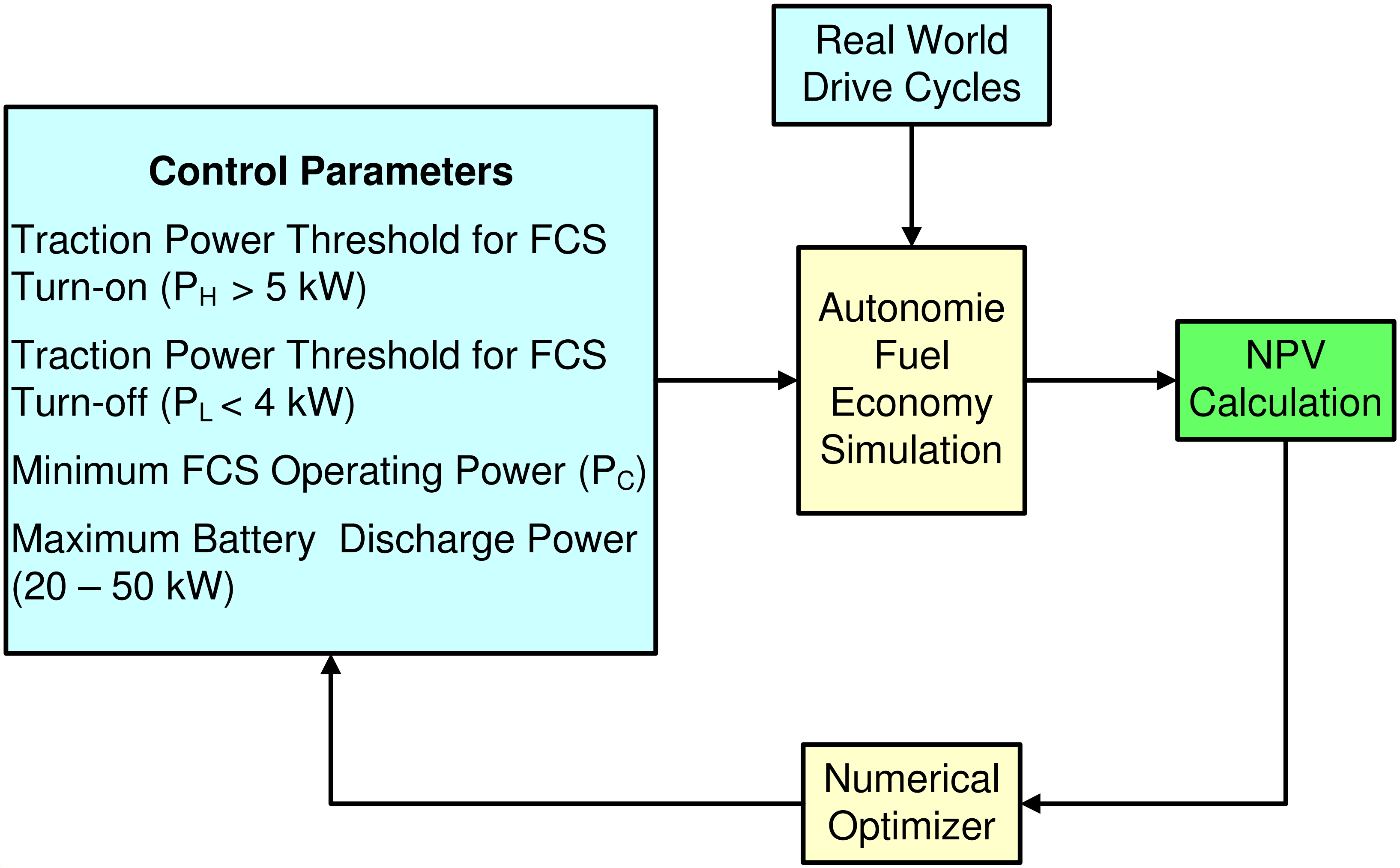
- Vehicle usage drive pattern over 15 years: 240,000 km
  - 0.7 factor applied to fuel economy of ICEV and FC HEV
- No battery or FCS replacement, no recycling cost
  - 4%/year degradation in battery performance after first 6 years
- Policy neutral study: tax incentives, fuel taxes, interest on initial cost not considered



NPV Optimization Algorithm

NPV maximized by varying battery power and FCS control parameters

- Direct search numerical optimizer, parallel computing workstations



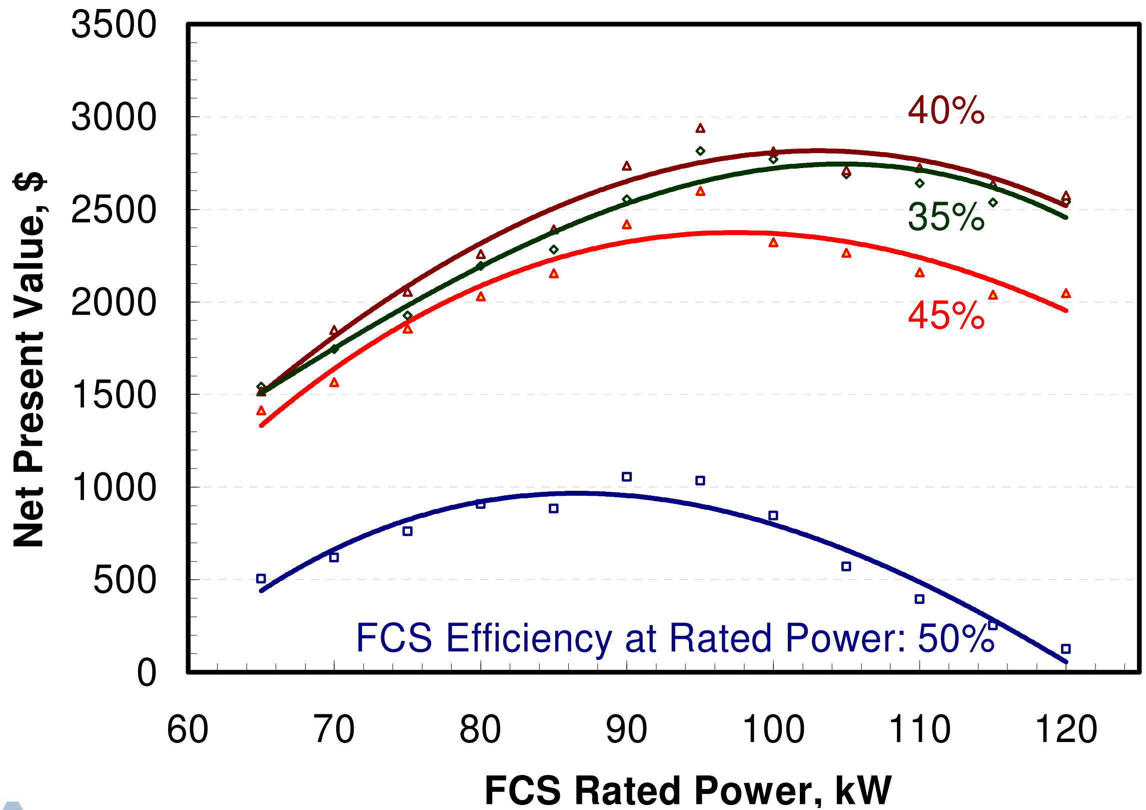
Optimum FCS Rated Power (P_R) and Efficiency (η_R)

Relationship between optimum η_R and P_R

- Optimum P_R lower for systems with higher η_R

Highest NPV for 100-kW FCS with 40% efficiency at rated power

- NPV smaller for 35% efficiency system due to higher fuel cost
- NPV smaller for 45-50% efficiency systems due to higher initial cost



Reference Conditions

Gasoline cost: \$3.70 gal^{-1}

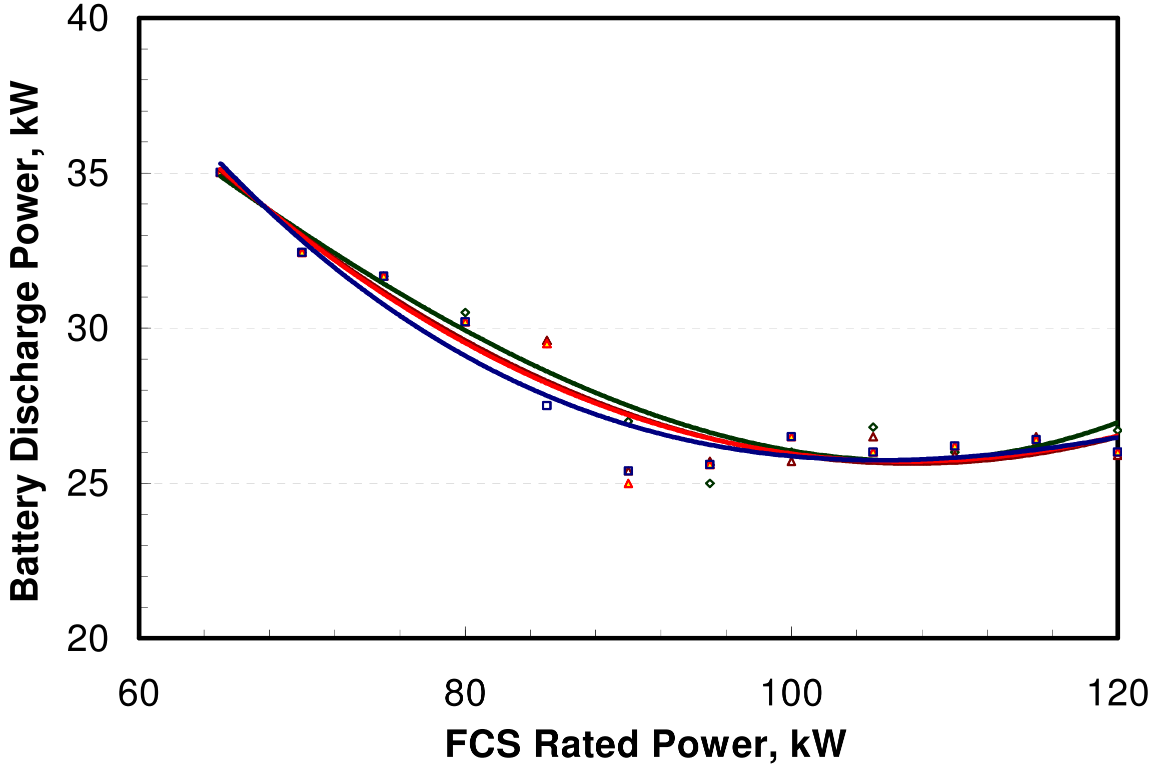
H_2 cost: \$5.00 gge^{-1}

ICEV adjusted FE: 23.8 mpg

Optimum Battery Discharge Power

Optimum battery discharge power generally decreases with increase in FCS power

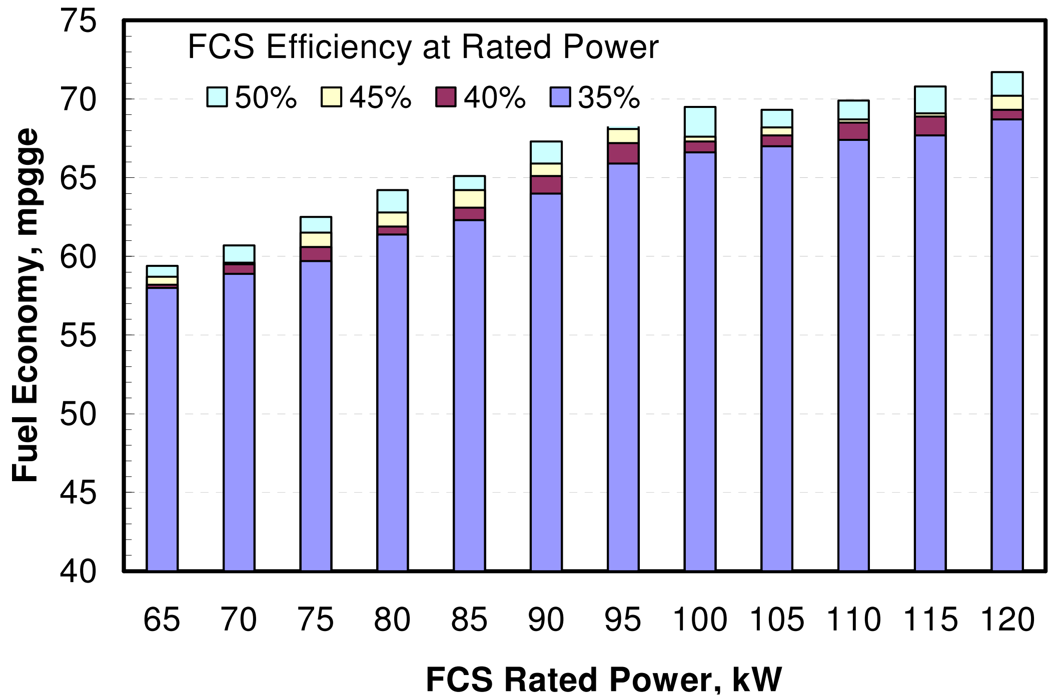
- Weak dependence on FCS efficiency at rated power
- Regenerative braking energy function of discharge power
- Acceleration depends on combined FCS and ESS power



Fuel Economy

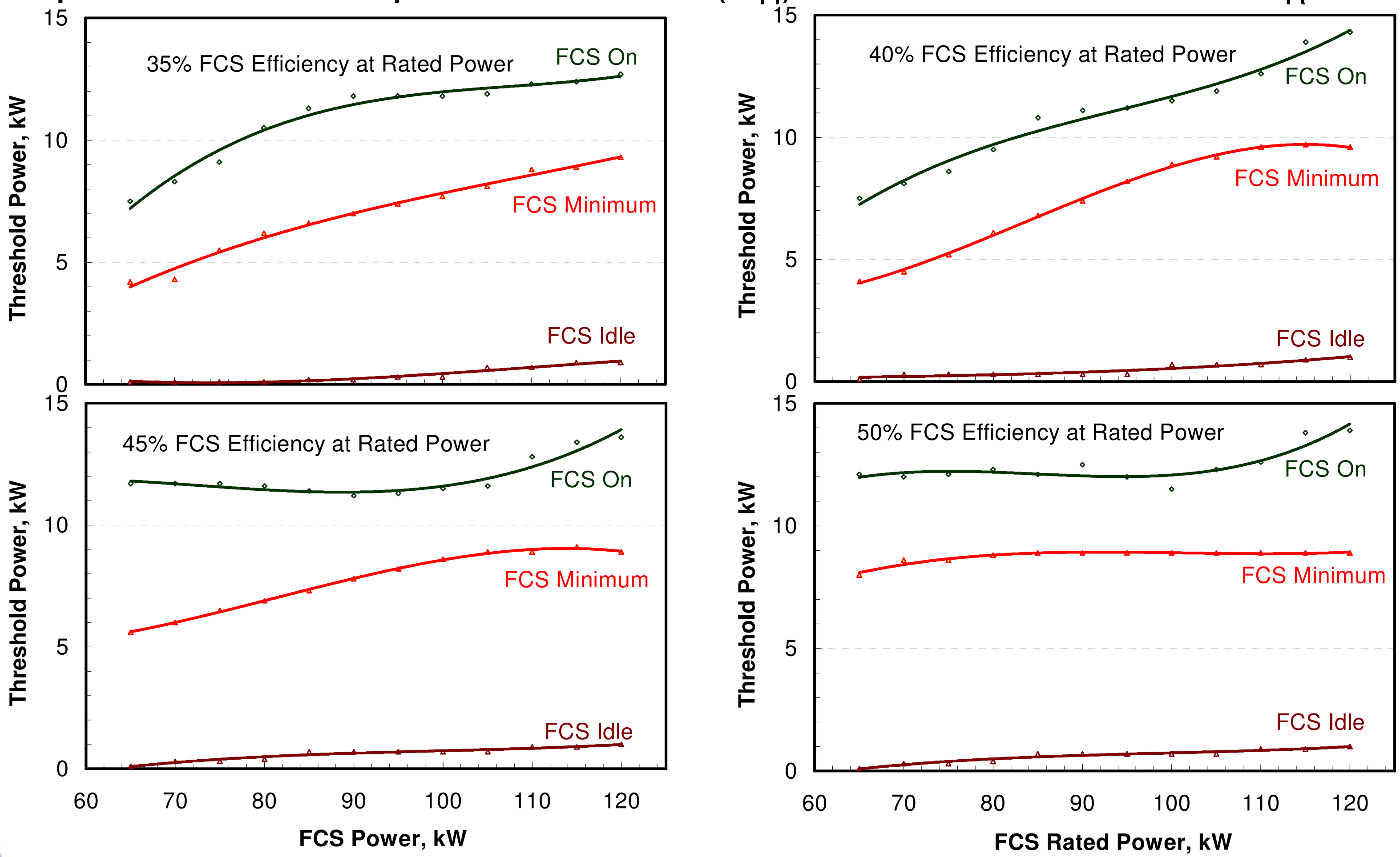
Average fuel economy over the 30 RW drive cycles and 15 years

- 0.7 factor applied to calculated FE to account for other accessory loads and ambient conditions
- Higher fuel economy for vehicles with larger FCS rated power (P_R)
- Fuel economy only weekly dependent on FCS efficiency at rated power (η_R)



Optimum FCS Control Parameters

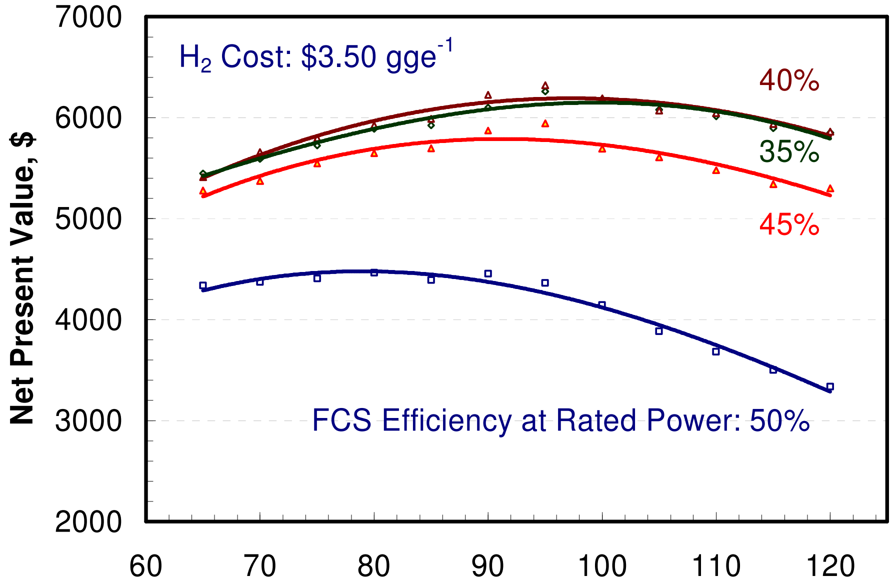
- Proper energy management strategy allows FCS to operate down to low traction loads (P_L)
- Minimum FCS power (P_C) close to but < FCS peak efficiency point (P_m)
- Optimum traction power for FCS (P_H) turn-on is function of P_R and η_R

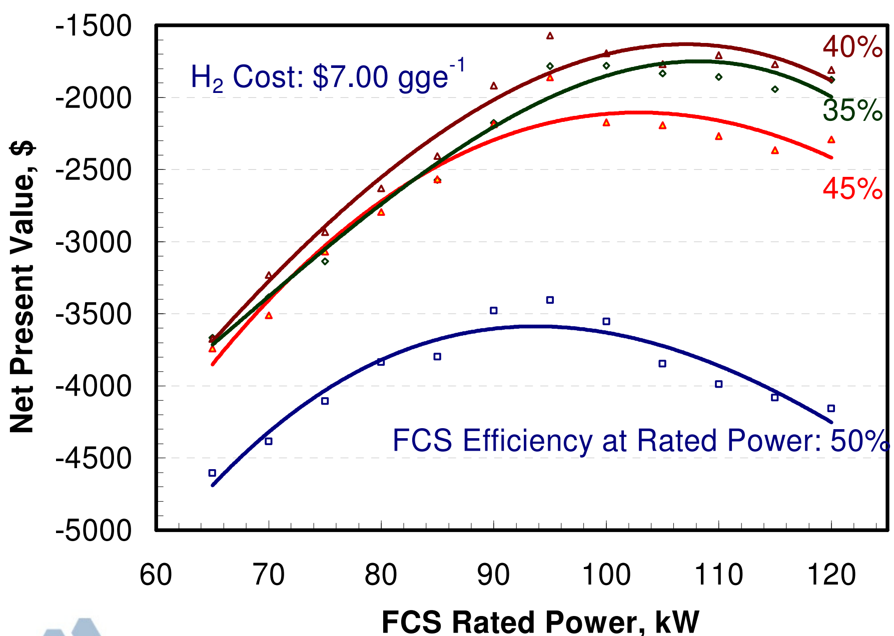


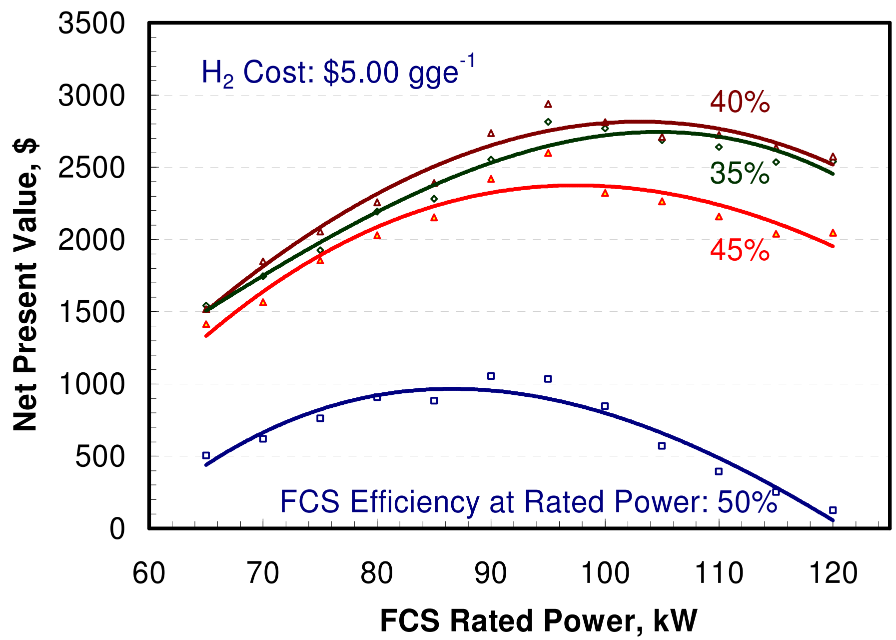
Optimum control strategy will also depend on stack/battery durability considerations

Sensitivity to Fuel Cost

- NPVs turn negative as H_2 cost increases to \$7.00 gge^{-1}
- No change in NPV trend over \$3.50-7.00 gge^{-1} H_2 cost - max NPV at 40% η_R
- Nearly 15 kW increase in optimum P_R with \$3.50 gge^{-1} increase in H_2 cost







Conclusions

Trade-off study to determine the effect of FCS rated power (P_R) and efficiency at rated power (η_R) on performance and life-cycle costs

- Lower peak efficiency in systems with higher P_R or η_R
- Proper energy management strategy allows FCS to operate down to low traction loads (P_L)
- Minimum FCS operating power (P_C) close to but < FCS peak efficiency point (P_M)
- Optimum traction power for FCS (P_H) turn-on function of P_R and η_R
- Higher fuel economy for vehicles with larger-P_R fuel cell systems
- Fuel economy rather insensitive to η_R
- Lowest ownership cost for 100-kW FCS with 40% η_R
- Positive NPV for $1.30/gge difference between the costs of gasoline and hydrogen

Supplemental Slides

Critical Assumptions and Issues – S1

PEFC Stack

- 2.5 atm at rated power
- 50% O_2 utilization
- 50% H_2 consumption per pass
- Cell voltage at rated power: 0.65 V
- 20-µm 3M membrane at 85°C
- 3M ternary alloy: 0.1/0.05 mg-Pt/cm^2 on cathode/anode
- GDL: 235-µm non-woven carbon fiber with MPL
- 1.1-mm metal bipolar plates, each with cooling channels
- 17 cells/inch

Fuel Management System

- Hybrid ejector-recirculation pump
- 35% pump efficiency
- 3 psi pressure drop at rated power

Air Management System

- Compressor-expander module
- Liquid-cooled motor
- Efficiencies at rated power: 72% compressor, 73% expander, 88% motor, 88% controller
- Turn-down: 20
- 5 psi pressure drop at rated power

Heat Rejection System

- Two circuits: 85°C HT, 10°C ΔT
  60°C LT coolant, 5°C ΔT
- 55% pump + 92% motor efficiency
- 45% blower + 92% motor efficiency
- 10 psi pressure drop each in stack and radiator

Water Management System

- Membrane humidifier, 64°C dew-point temperature at rated power

Stack T permitted to rise to 95°C for short durations under some driving conditions

Critical Assumptions and Issues – S2

PEFC Stack
- 1.5 atm at rated power
- 50% O_2 utilization
- 50% H_2 consumption per pass
- Cell voltage at rated power: 0.622 V
- 20-µm 3M membrane at 75°C
- 3M ternary alloy: 0.1/0.05 mg-Pt/cm^2 on cathode/anode
- GDL: 235-µm non-woven carbon fiber with MPL
- 1.1-mm metal bipolar plates, each with cooling channels
- 17 cells/inch

Fuel Management System
- Hybrid ejector-recirculation pump
- 35% pump efficiency
- 3 psi pressure drop at rated power

Air Management System
- Compressor-expander module
- Liquid-cooled motor
- Efficiencies at rated power: 73% compressor, 72% expander, 90% motor, 83% controller
- Turn-down: 20
- 5 psi pressure drop at rated power

Heat Rejection System
- Two circuits: 75°C HT, 10°C ΔT
  60°C LT coolant, 5°C ΔT
- 55% pump + 92% motor efficiency
- 45% blower + 92% motor efficiency
- 10 psi pressure drop each in stack and radiator

Water Management System
- Membrane humidifier, 61°C dew-point temperature at rated power

Stack T permitted to rise to 95°C for short durations under some driving conditions