Energy Storage Requirements for Hybrid Fuel Cell Vehicles

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Presentation Outline

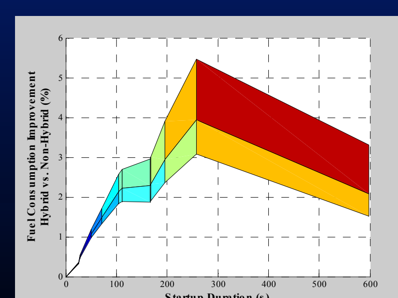
- Objectives
- Previous Studies
- Current Approach
- Results
  - Technical Results
  - Cost Analysis
- Conclusions

Objectives

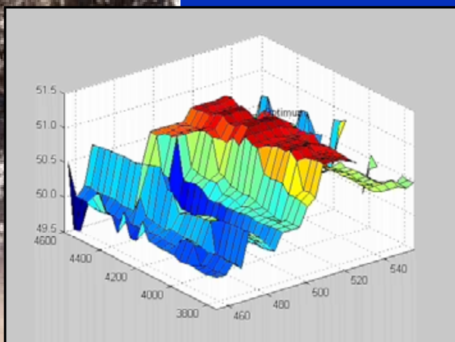
- Extend previous studies to determine how the fuel cell and battery sizing choices can impact not only efficiency but also cost, mass, and volume constraints.
- Analyze the fuel cell and energy storage system demands under drive cycle and performance tests for two vehicle platforms using ADVISOR™.
- Consider several sizing scenarios and energy storage technologies.
- Support the FreedomCAR technical teams in defining energy storage requirements for fuel cell vehicles.

Previous Studies

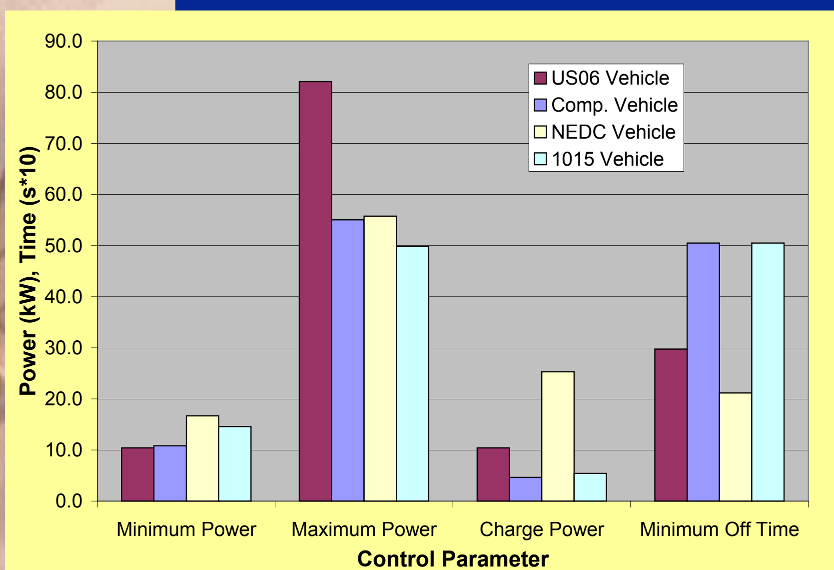
- **Hybridization of a fuel cell vehicle with energy storage improves fuel economy and make it practical (UCD, VTech, NREL)**
  - Smaller fuel cell - lower cost
  - Fuel cell or reformer warm up
  - Improving transient response
  - Capturing regenerative breaking
- **Pre-production prototype fuel cell vehicles are hybrids**
  - Toyota FCHV – (NiMH)
  - Honda FCX – (ultra-capacitors)



Optimization of Fuel Cell Vehicle Design Provides Insight into System Trade-offs



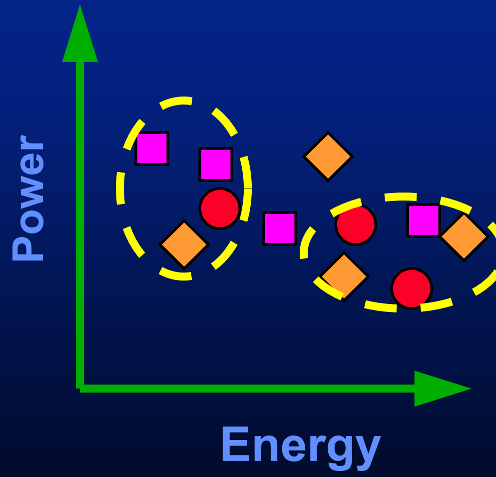
ADVISOR 2002
Advanced Vehicle Simulator



- Derivative-free optimization algorithms necessary for complex design space of HEVs
- Drive cycle influences optimal degree of hybridization and control parameters
  - NEDC provides robust design
- Fuel cell transient response capability critical for "pure" fuel cell vehicle
- An optimized hybrid design can nullify the effects of fuel cell transient response
- Fuel economy impact of gasoline reformer warm-up may be substantial
- Relatively small energy storage system can overcome warm-up limitations of reformer

Approach for This Study

- Summarize Study Assumptions
- Determine the Potential Roles of the Battery
- Run Simulations to Quantify Requirements Associated with Individual Roles
- Compile the Battery Requirements
- Compare Requirements to Existing Technology



Vehicle and Performance Assumptions

Vehicle Characteristics

Assumption Description	Units	mid-size SUV	mid-size Car
Vehicle Description	--	Rear wheel drive mid-size SUV	Front wheel drive mid-size car
Base Conventional Vehicle Mass	*kg*	1865	1480
Base Vehicle Glider Mass	*kg*	1276	1074
Cargo Mass	*kg*	136	136
Fuel Cell Vehicle Mass	*kg*	1923	1553
Aero. Drag Coef.	--	0.41	0.33
Frontal Area	*m^2*	2.6	2
Rolling Resistance Coef.	--	0.012	0.009
Wheel Radius (effective)	*m*	0.343	0.314
Vehicle Range	*mi (km)*	300 (483)	300 (483)

Performance

Assumption Description	Units	mid-size SUV	mid-size Car
0-60 mph (0-97 kph)	*s*	<=11.2	<=12
40-60 mph (64-97 kph)	*s*	<=4.4	<=5.3
0-85 mph (0-137 kph)	*s*	<=20.0	<=23.4
Grade @ 65mph (105kph) for 20min. @ Curb Mass + 408kg	%	>=6.5	>=6.5
Drive Cycle Tolerance	*mph (kph)*	<=2 (3.2)	<=2 (3.2)
SOC Balancing	%	<=0.5%	<=0.5%

Energy Storage System Assumptions

Assumption Description	Units	PbA	NiMH	Li-Ion	Ultra-capacitor
Energy Storage Energy Density	*Wh/L*	75	100	190	5
Energy Storage Specific Energy	*Wh/kg*	35	55	100	4
Energy Storage Energy Density	*W/L*	1600	2000	2800	4500
Energy Storage Specific Energy	*W/kg*	550	1000	1300	3500
Energy Storage Cost (power)	*$/kW*	$10.00	$40.00	$60.00	$15.00

DOE-OTT High-Power Vehicle Energy Storage Target	Units	
Energy Storage Cost (energy)	*$/kWh*	$1,666.67
Energy Storage Cost (power)	*$/kW*	$20.00

Fuel Cell and Hydrogen Storage Assumptions

Fuel Cell System

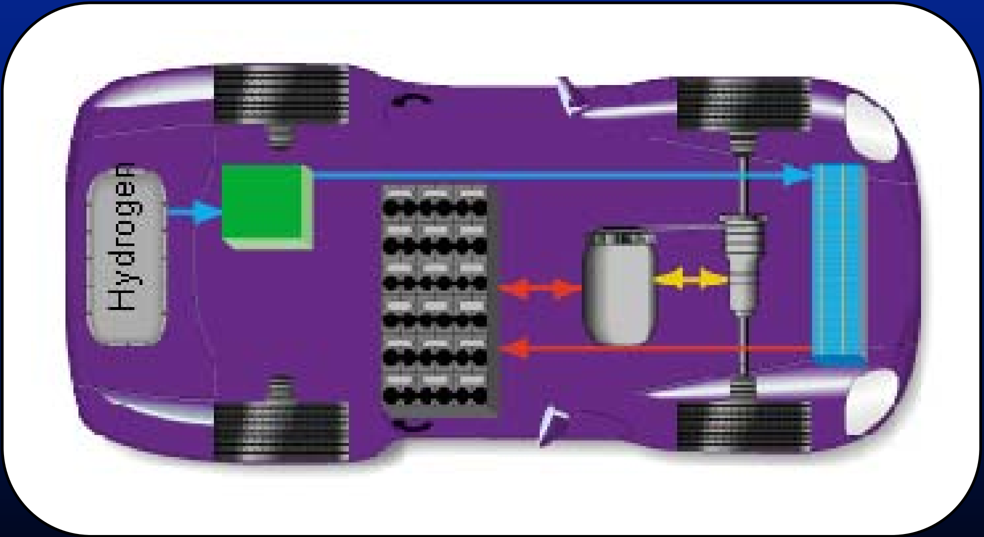
Assumption Description	Units	2005	2010
Fuel Type	--	hydrogen	hydrogen
Fuel Cell Peak Efficiency	%	62.9	62.9
Fuel Cell Efficiency at 25% Power	%	60	60
Fuel Cell Efficiency at Rated Power	%	53.6	53.6
Fuel Cell System Specific Power	W/kg	500	650
Fuel Cell System Power Density	W/L	500	650
Fuel Cell System Cost	$/kW	96	27
Fuel Cell System 10-90% Power Transient Response Capability	s	2	1

Hydrogen Storage

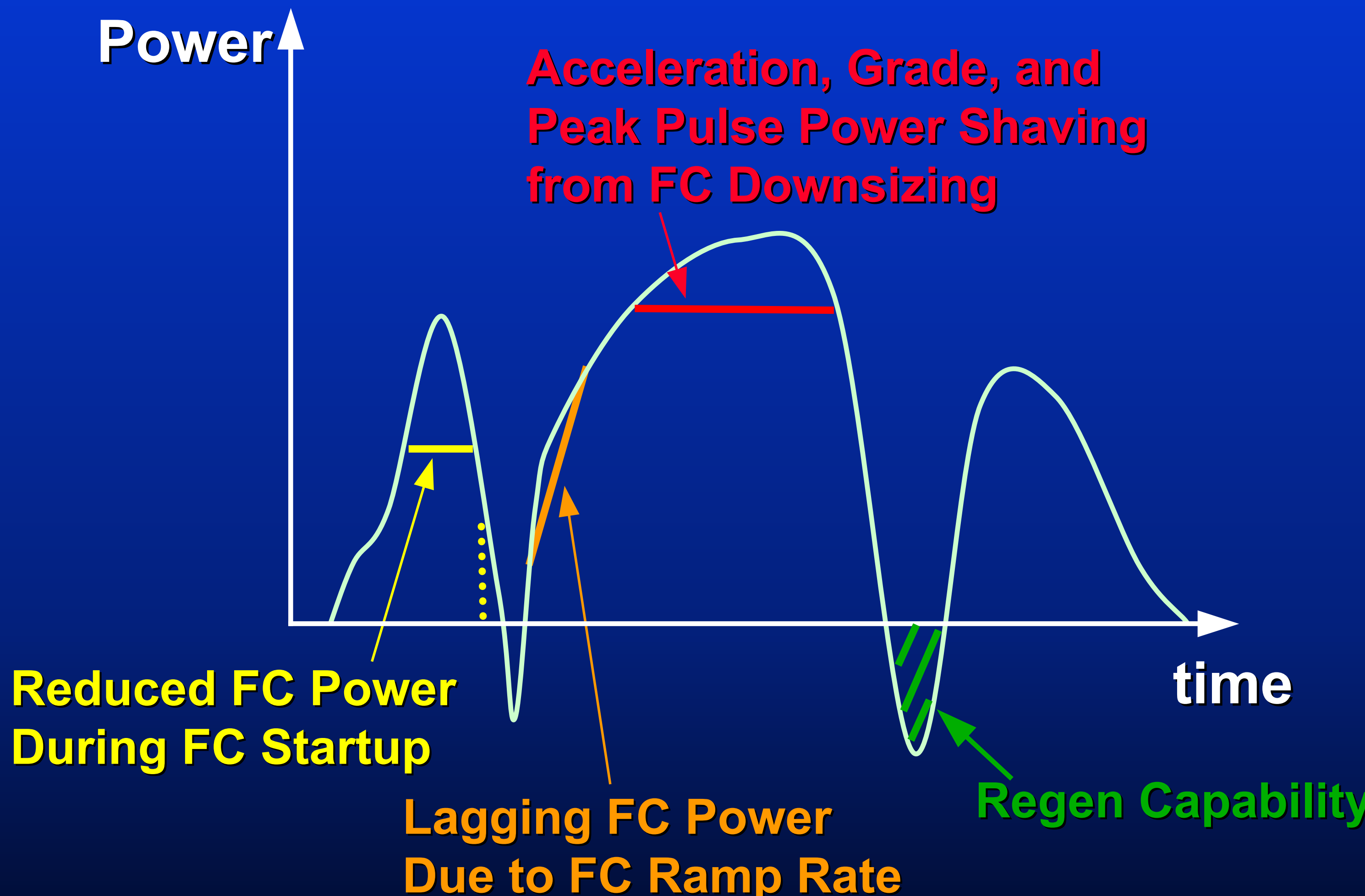
Assumption Description	Units	2005	2010
H2 Storage Energy Density	kWh/L	1.2	1.5
H2 Storage Specific Energy	kWh/kg	1.5	2
H2 Storage Cost	$/kWh	6	4

Roles of the Energy Storage System

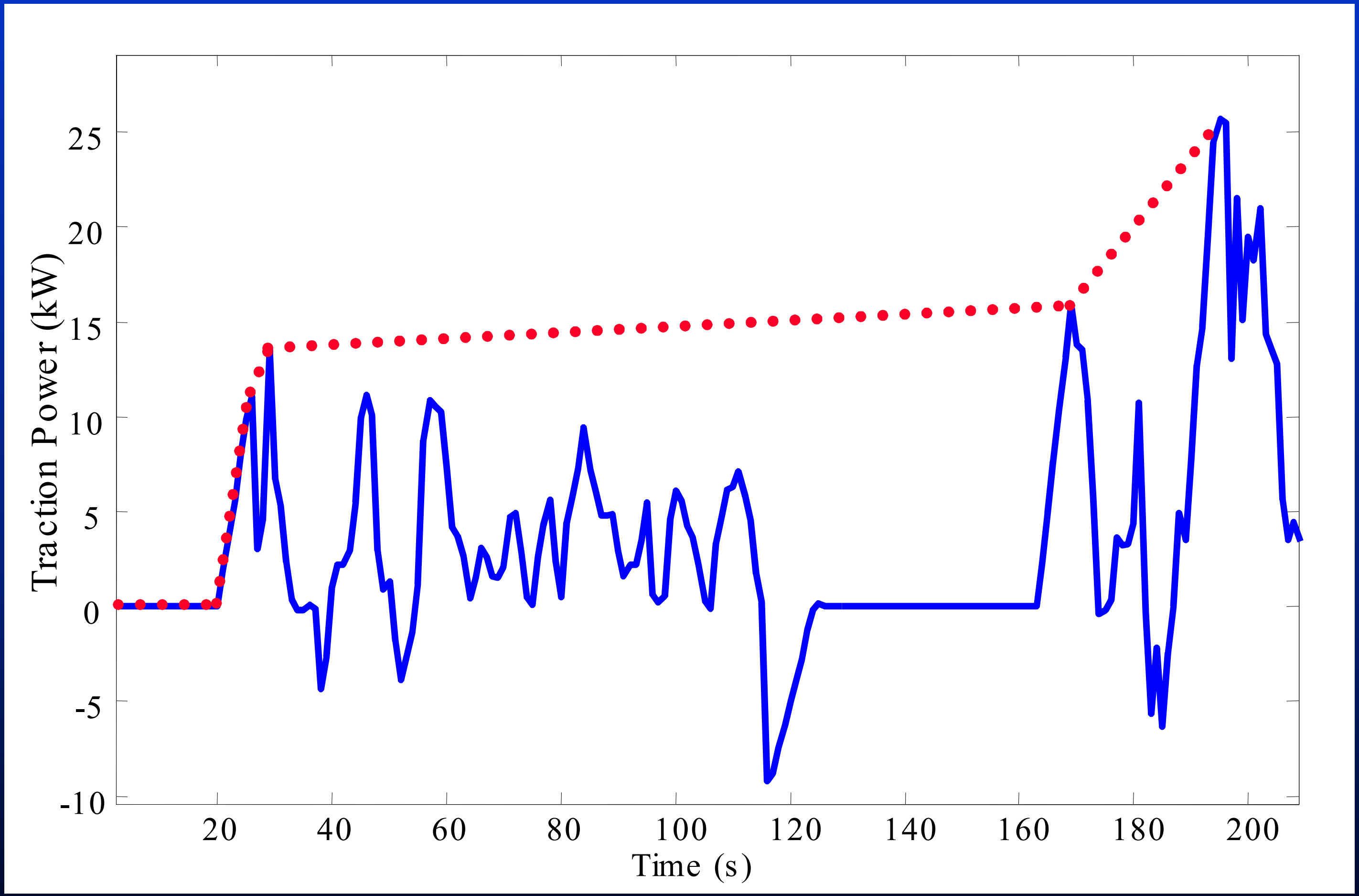
- Traction power during fuel cell startup
- Power-assist during drive cycles
- Regenerative braking recapture
- Gradeability performance
- Acceleration capability
- Electrical accessory loads
- Fuel cell startup and shutdown



Pictorial Description of Roles of the Energy Storage System

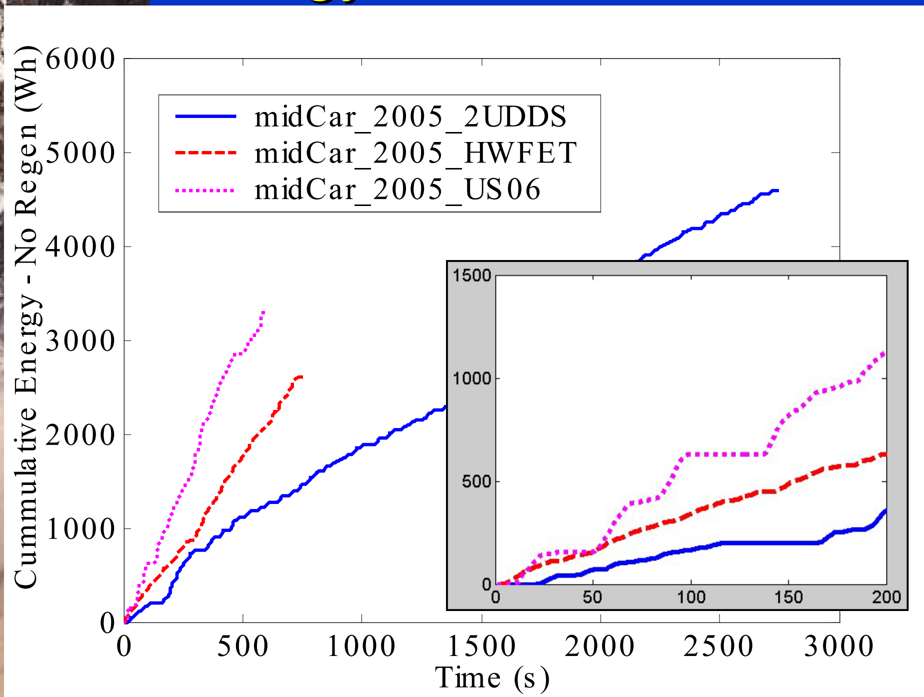


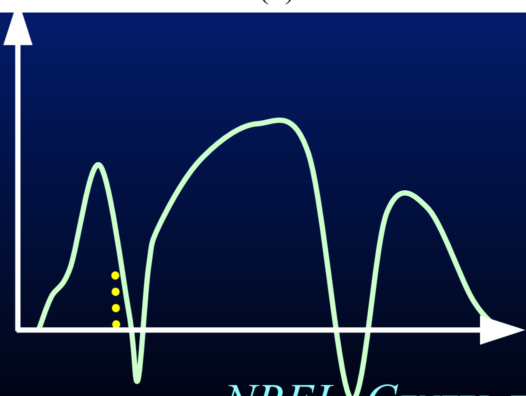
Drawing Power Envelope during a Drive Cycle



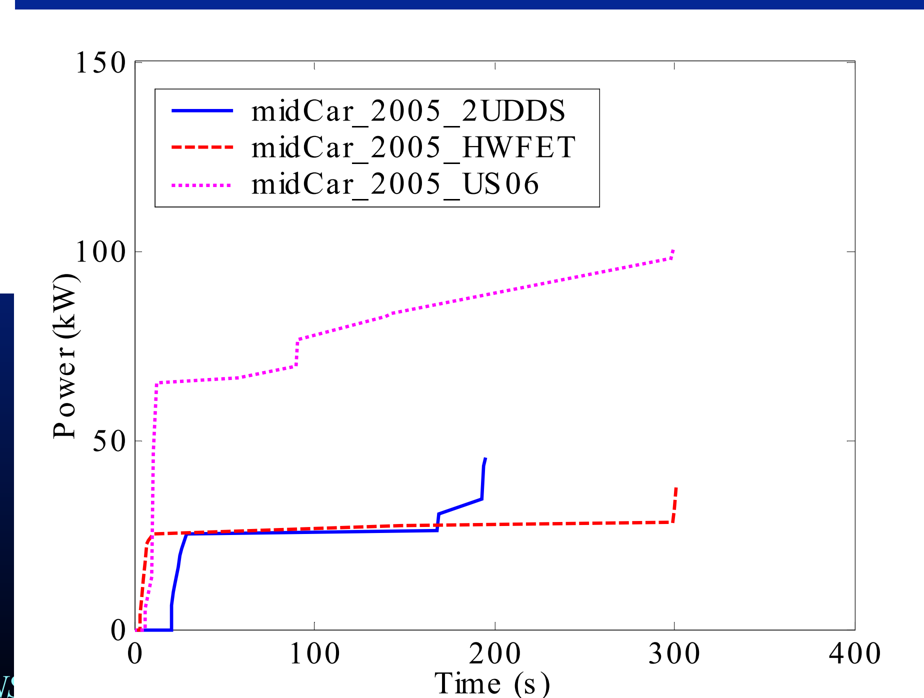
Traction Power During Fuel Cell Startup

Energy Mid Car 2005



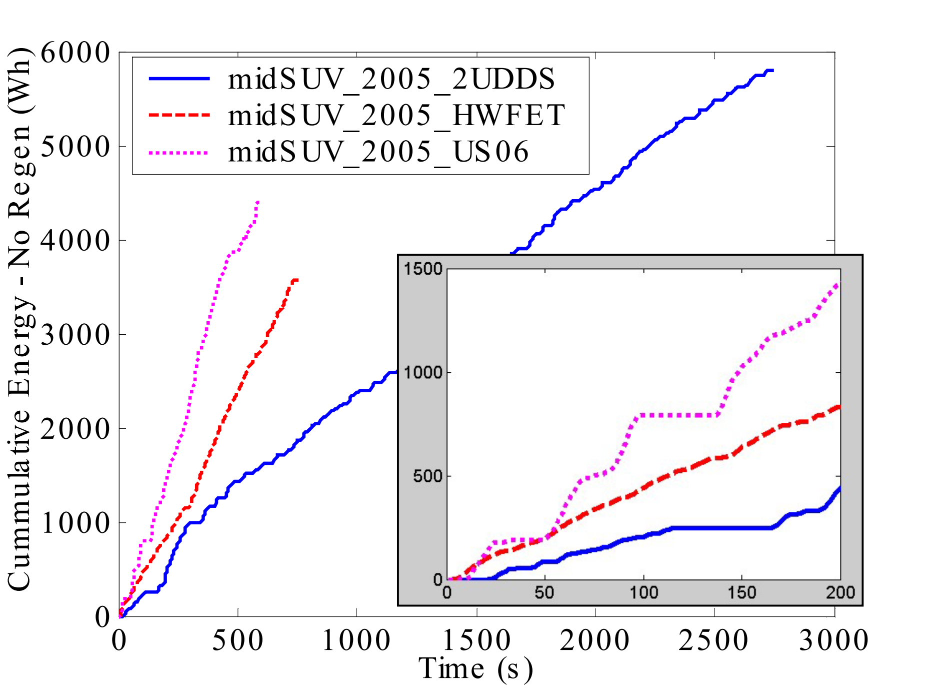


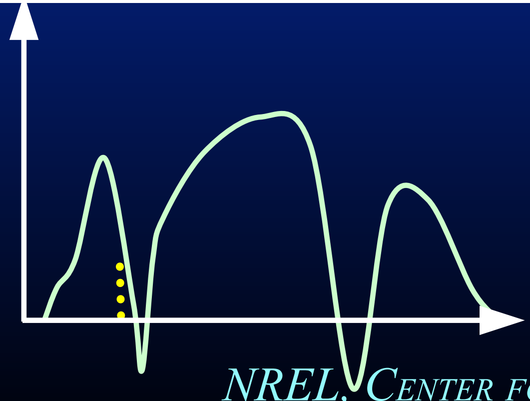
Power Mid Car 2005



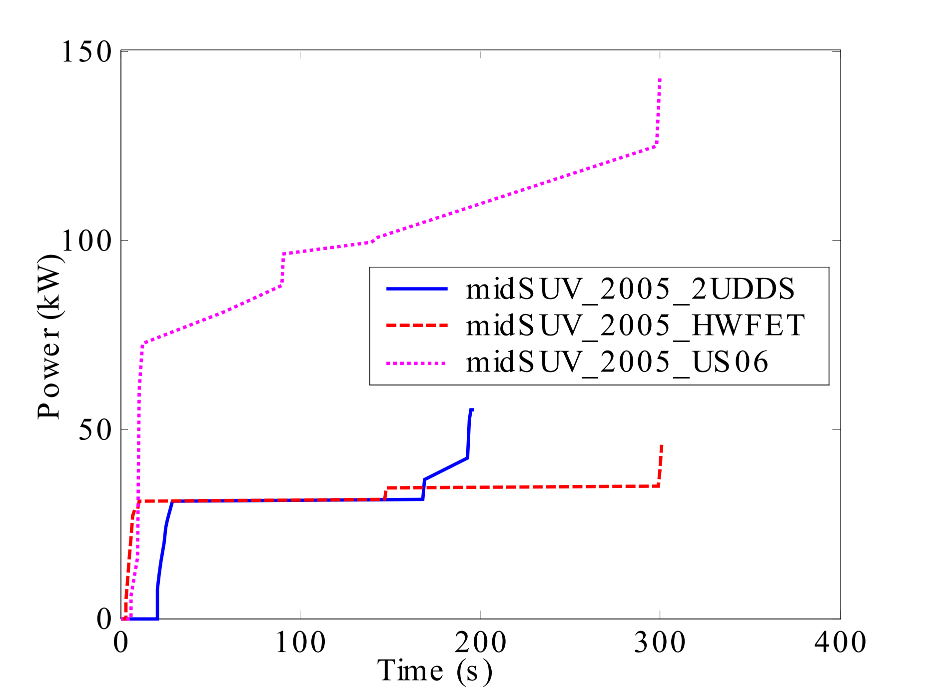
Traction Power During Fuel Cell Startup

Energy Mid SUV 2005



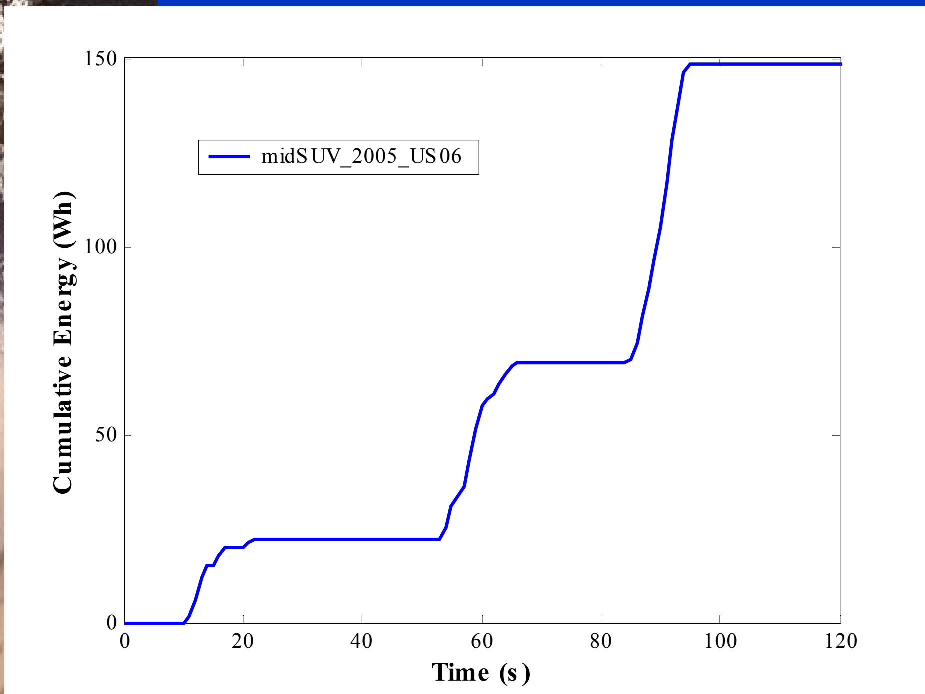


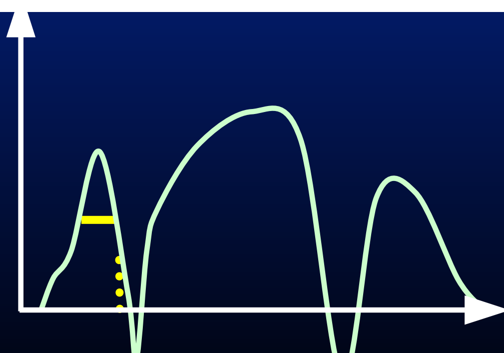
Power Mid SUV 2005



100kW Example - Energy Storage Traction Power/Energy During Fuel Cell Startup

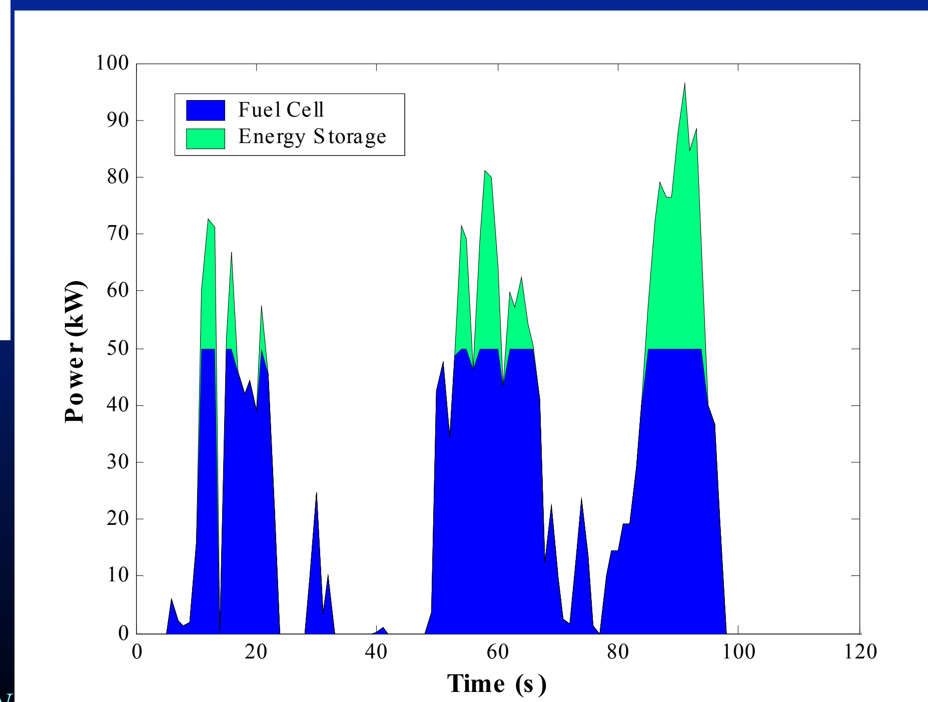
Energy





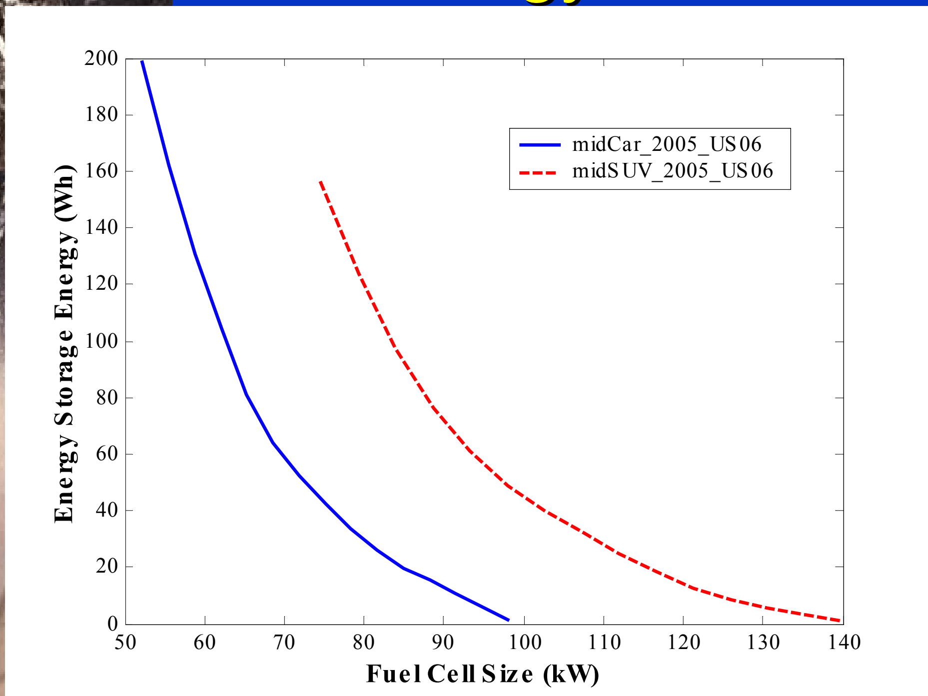
SUV requirements during the US06 assuming limited fuel cell performance

Power



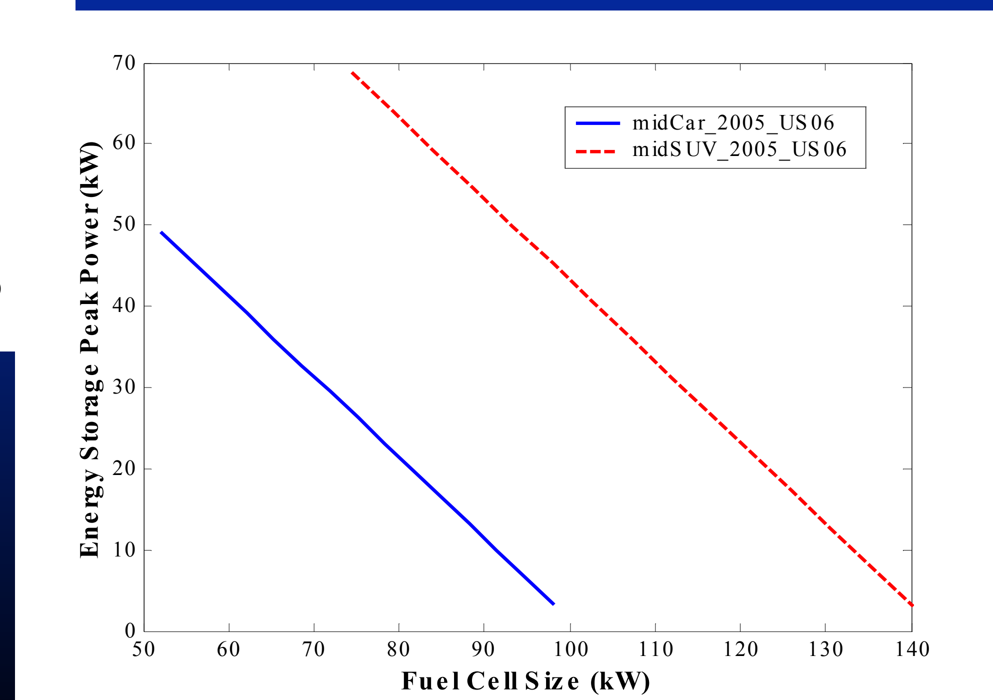
Traction Power Assist During US06 Drive Cycle

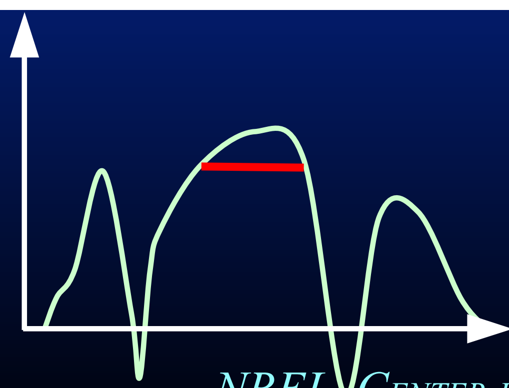
Energy



Battery provides peak shaving capability during the US06 drive cycle

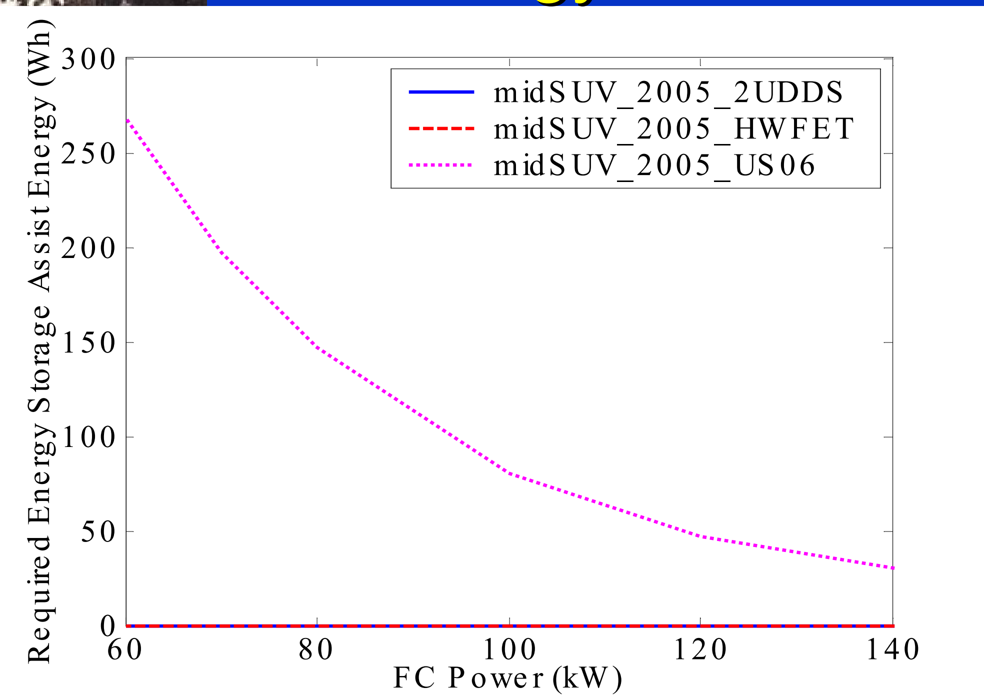
Power





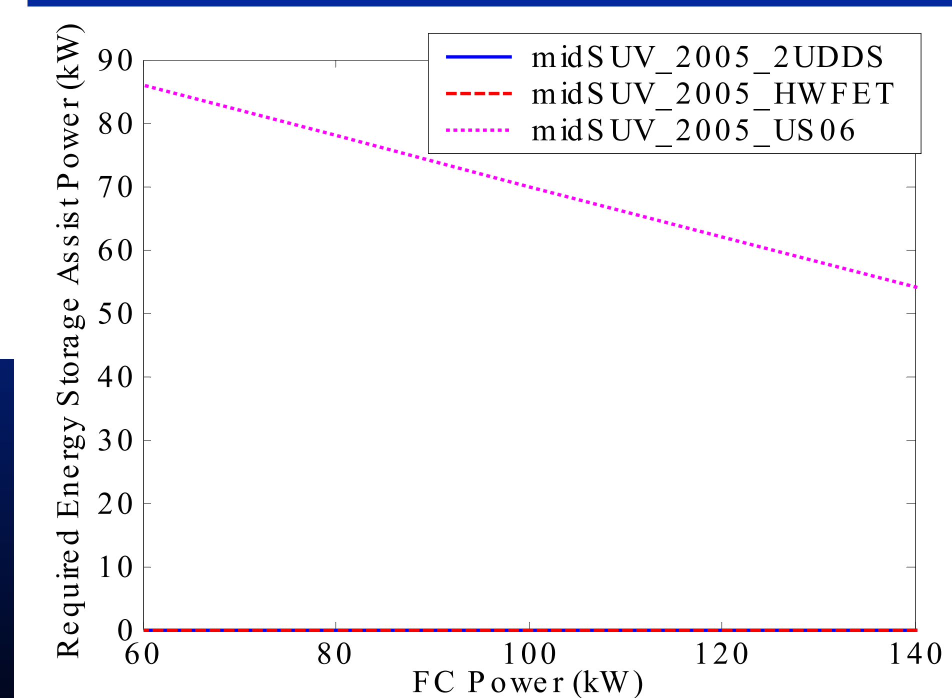
Traction Power/Energy Requirements Due to 2s Fuel Cell Power Response Capability

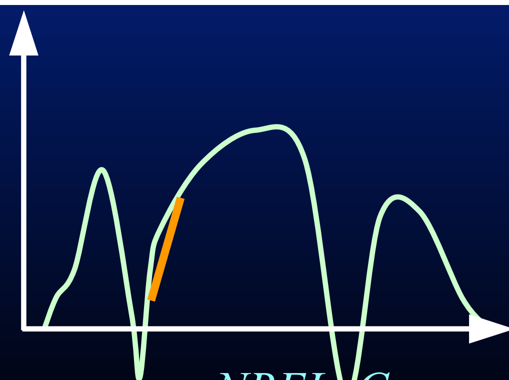
Energy



Battery provides ramp rates greater than fuel cell's ramp capability

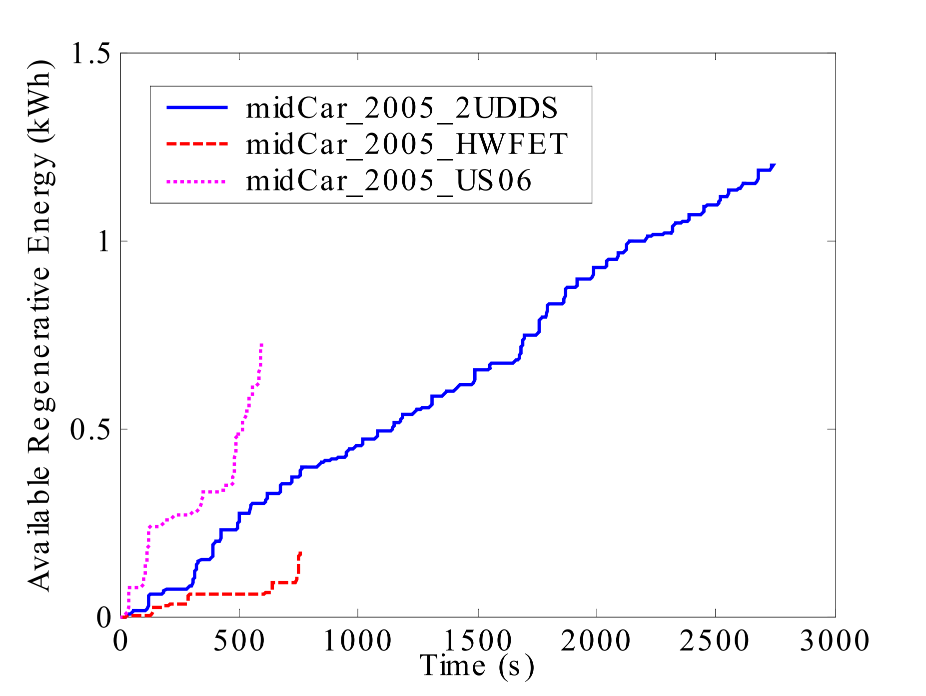
Power



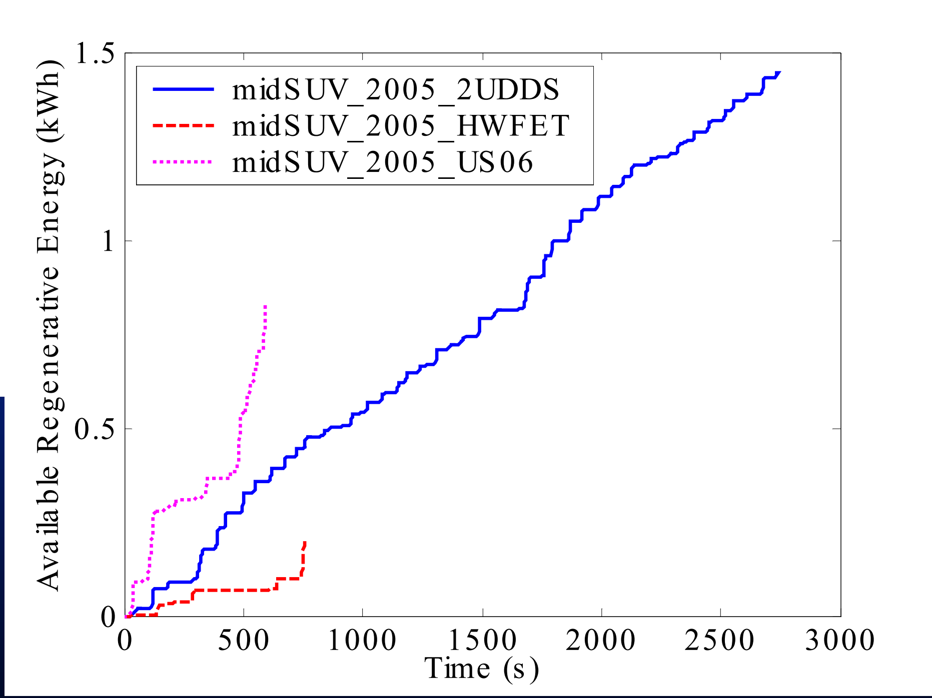


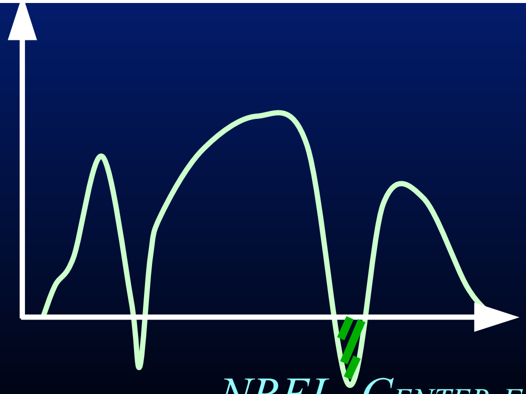
Total Available Regenerative Braking Energy possible for Recapture

Car



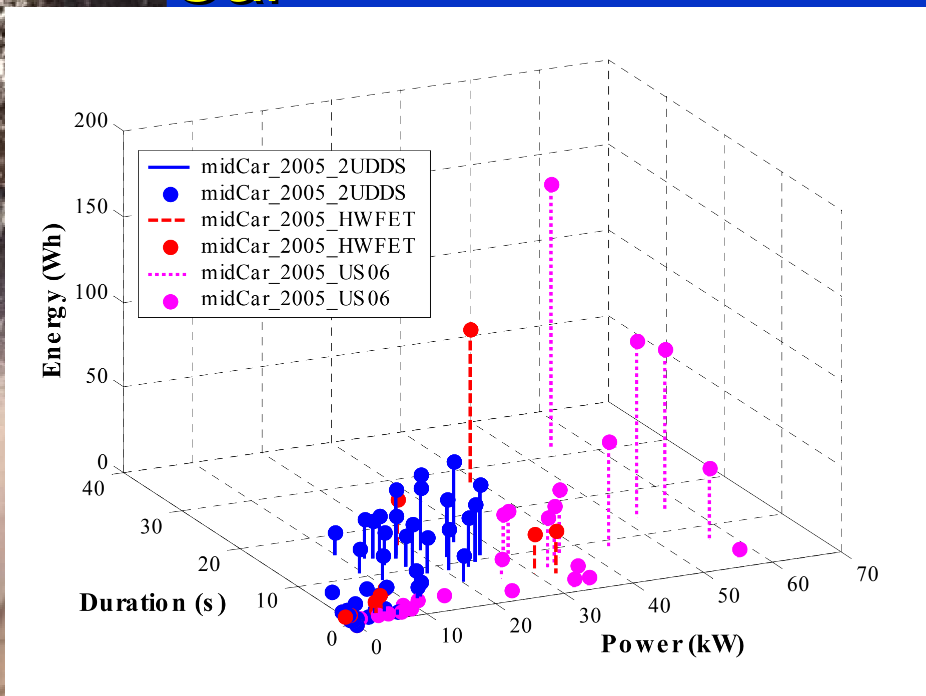
SUV



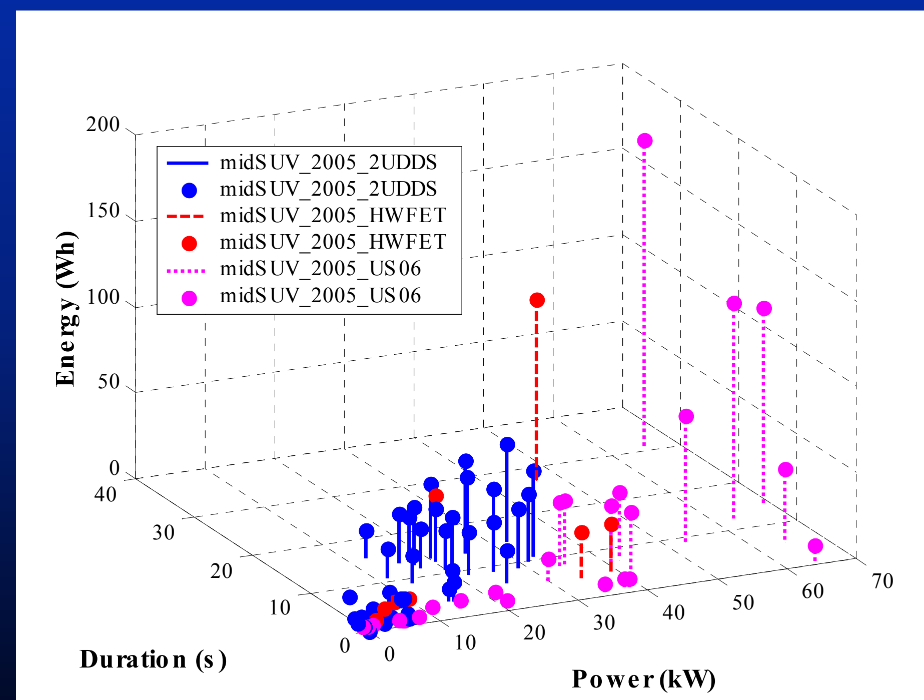


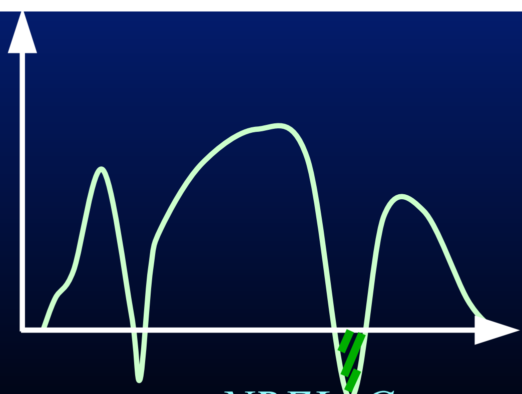
Regenerative Braking Event Analysis

Car



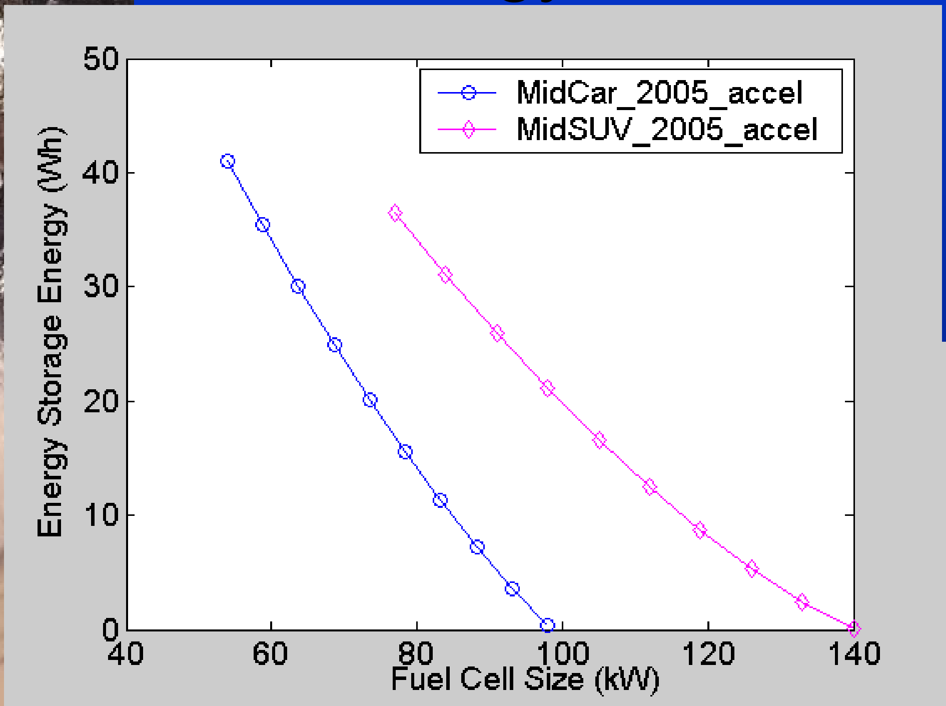
SUV





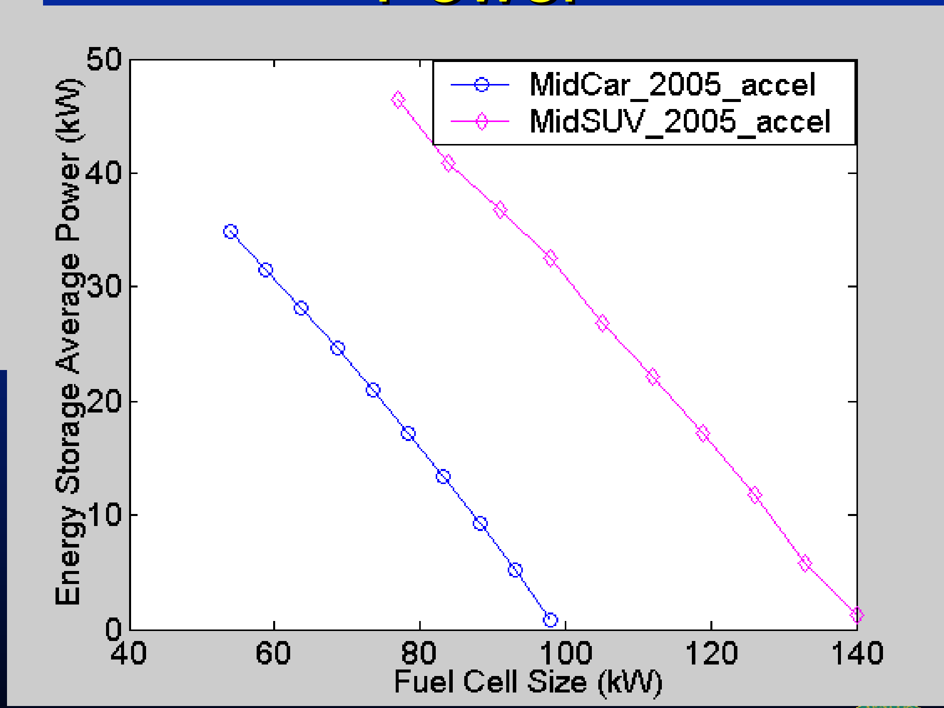
Acceleration Performance – Power Demanding

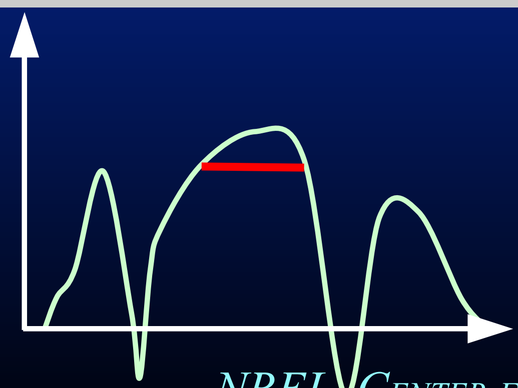
Energy



During 0-60 (0-97kph) mph maximum acceleration

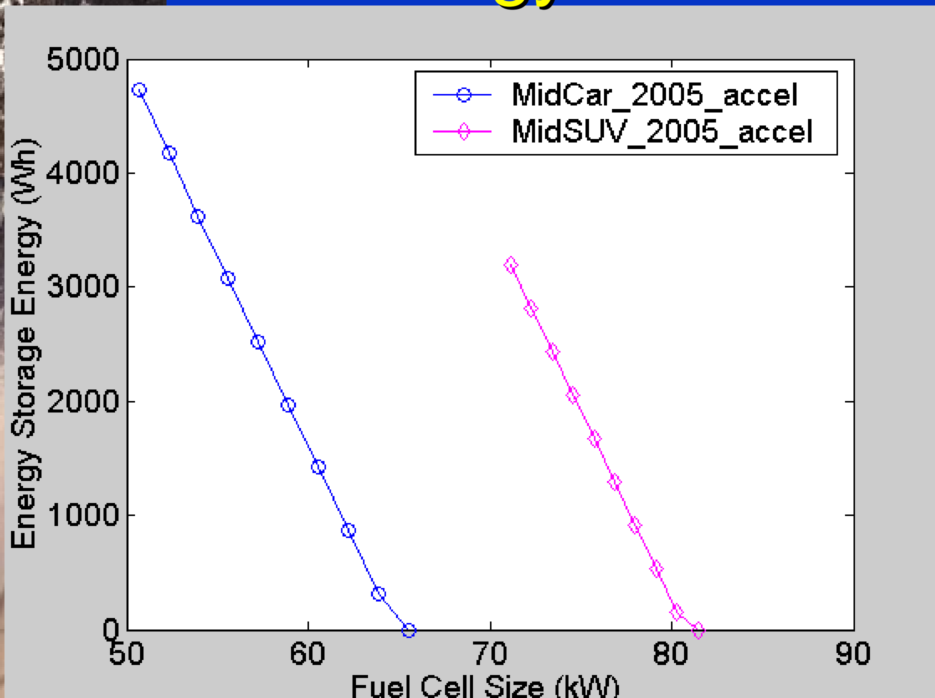
Power





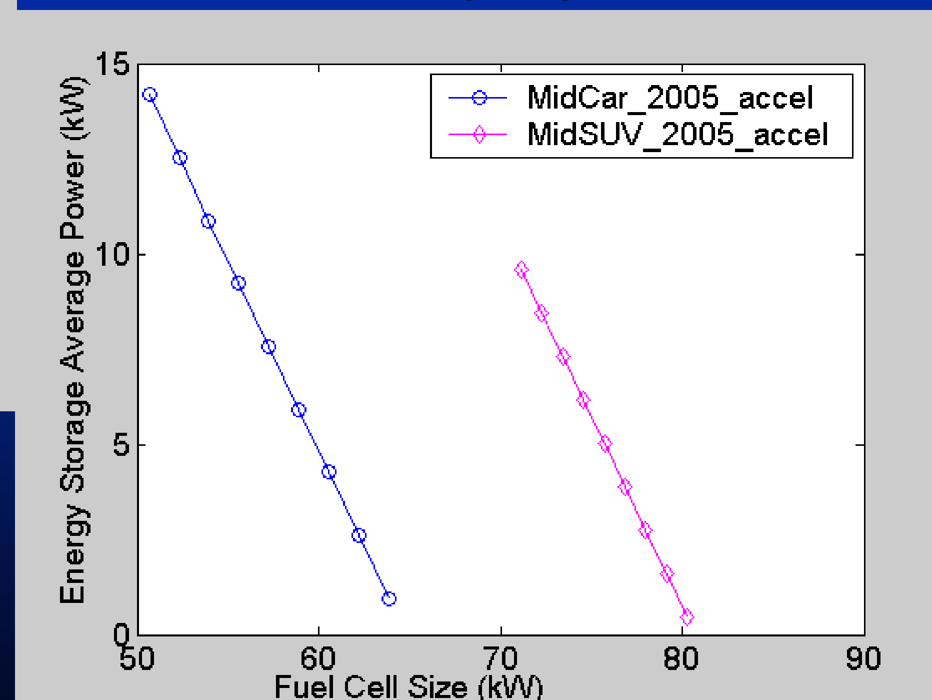
Gradeability Performance – Energy Demanding

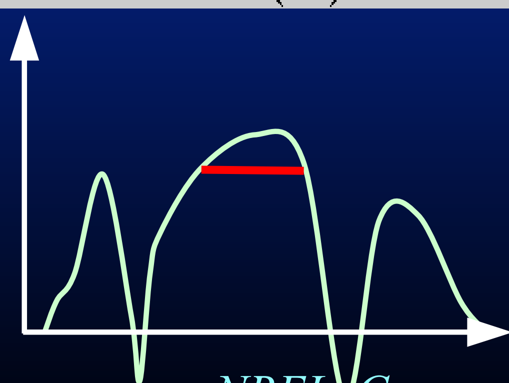
Energy



6.5% Grade @ 65 mph
(105kph) for 20 minutes
At curb mass + 408kg

Power

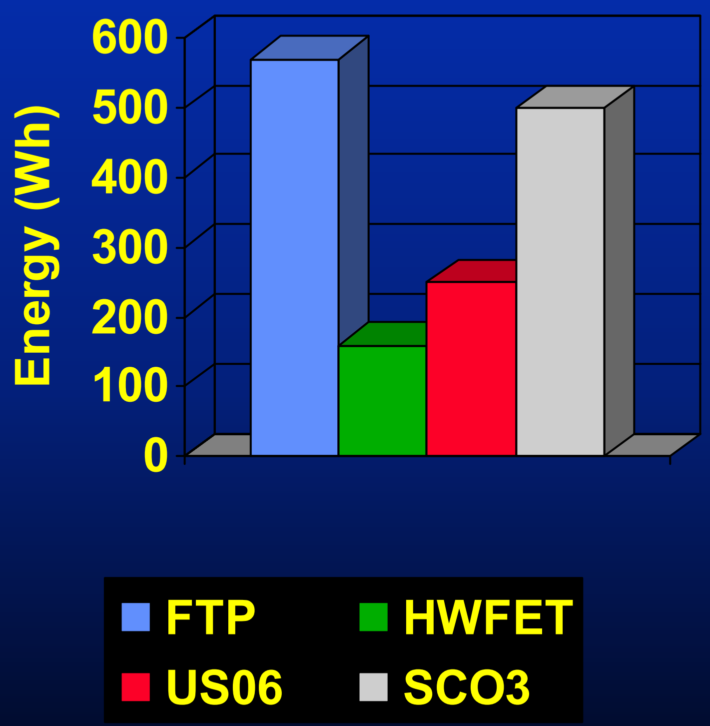




Accessory Loads

- FTP
  - 750 W for 2738 s
    - 570 Wh
- HWFET
  - 750 W for 765 s
    - 159 Wh
- US06
  - 1500 W for 600 s
    - 250 Wh
- SC03
  - 3000 W for 600 s
    - 500 Wh

Battery for Accessory Loads



Summary of Energy Storage Requirements for SUV (for 100kW Fuel Cell Case)

	Event Description	Peak Power (kW)	Duration (s)	Cumulative Energy (kWh)	Comments
A	**Startup Traction Loads**	46.4	<11	0.15	50% rated power,120s warm-up over 2UDDS, HWFET, & US06
B	**Power-assist (response)**	70.0	<3	0.08	2 second 10%-90% FC response (ramp) rate (during 2UDDS, HWFET, & US06)
C	**Power-assist (downsize)**	43.3	<3	0.05	During 2UDDS, HWFET, & US06. US06 is limiting case
D	**Gradeability (see Table 2)**	0.0	1200	0.00	81.4 kW sustained load for 1200s
E	**Acceleration**	40.0	20	0.22	140 kW sustained load for 20s
F	**Accessory Loads**	1.5	600-2800	0.10	US06 peak power, energy is for US06 4 min, or FTP 8 min
G	**Fuel Cell Shutdown**	N/A	N/A	N/A	-
H	**Regenerative Braking**	70.0	<30	1.50	Pmax is during US06, energy is FTP cycle max

Required:
Power = 71.5kW,
Energy = 1.33kWh
(from Case 2 below)

- Power Requirement = max(A,B,C,D,E) + aux. load if applicable
- Energy Requirement = greatest of four cases

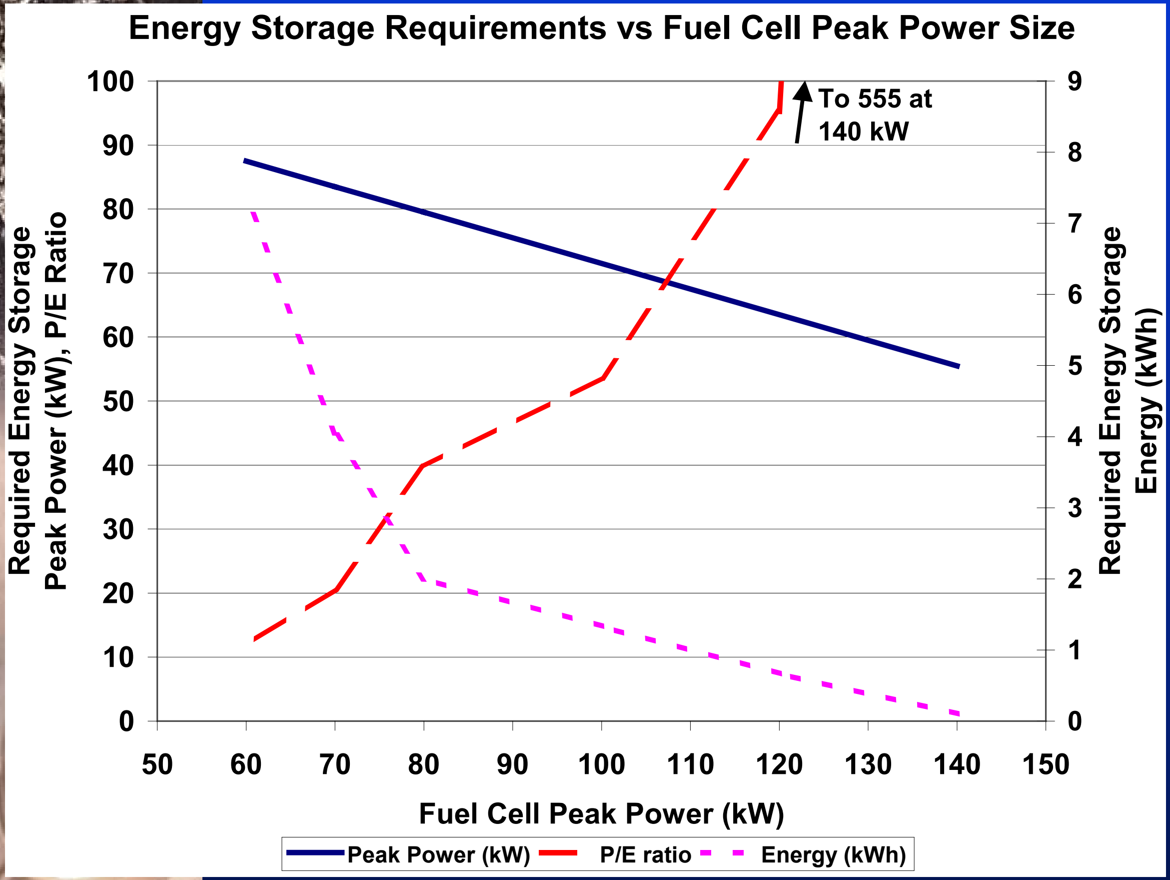
Case(1) The energy required to sustain the continuous grade power, plus a 750W accessory power for 20 minutes;

Case(2) The energy required to sustain the energy storage power requirement over six consecutive acceleration tests;

Case(3) The energy required to sustain the Highway or FTP accessory load for eight minutes, or the US06 accessory load for 4 minutes;

Case(4) The summation of the energies in A, B, and C. Minus overlap in cases A and C,cases A and B are additive (neglecting slight overlap).

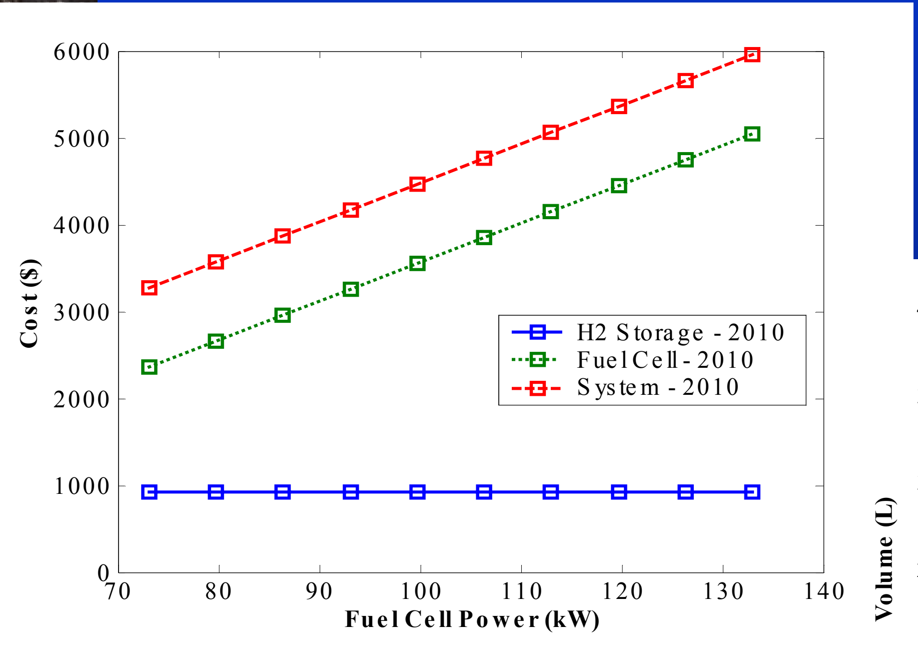
Summary of Energy Storage Requirements for SUV (for varying Fuel Cell Size)



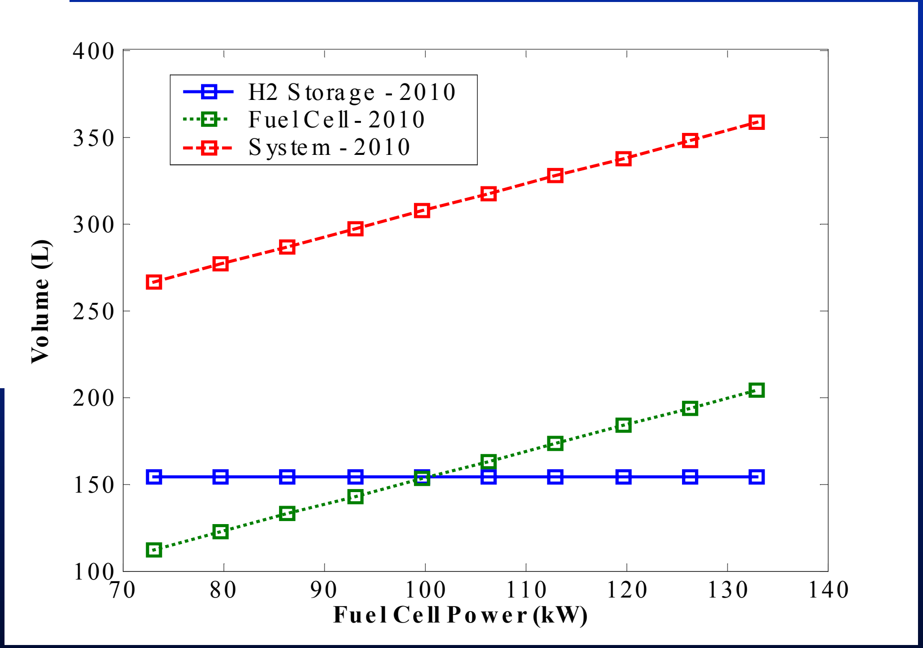
- Energy storage power (P), energy (E), and P/E ratio are compiled for many fuel cell sizes.
- Plot illustrates how P,E, and P/E change while the fuel cell is downsized.

Fuel Cell Cost and Volume - 2010

Cost

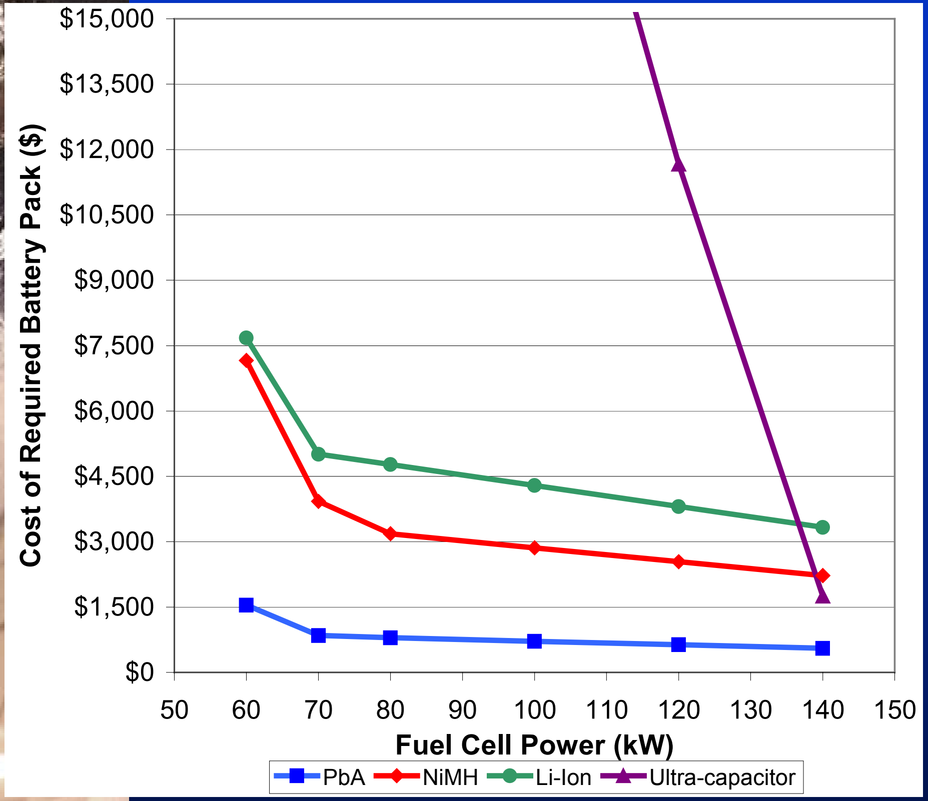


Volume

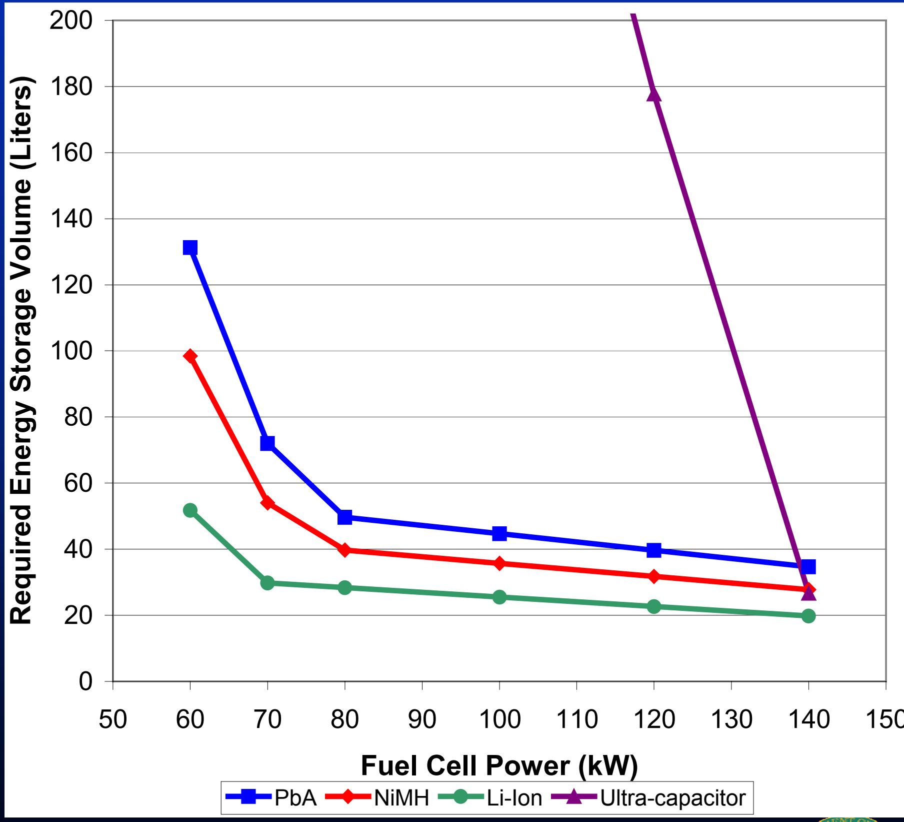


Chemistry Dependent Energy Storage System Cost and Volume

Cost

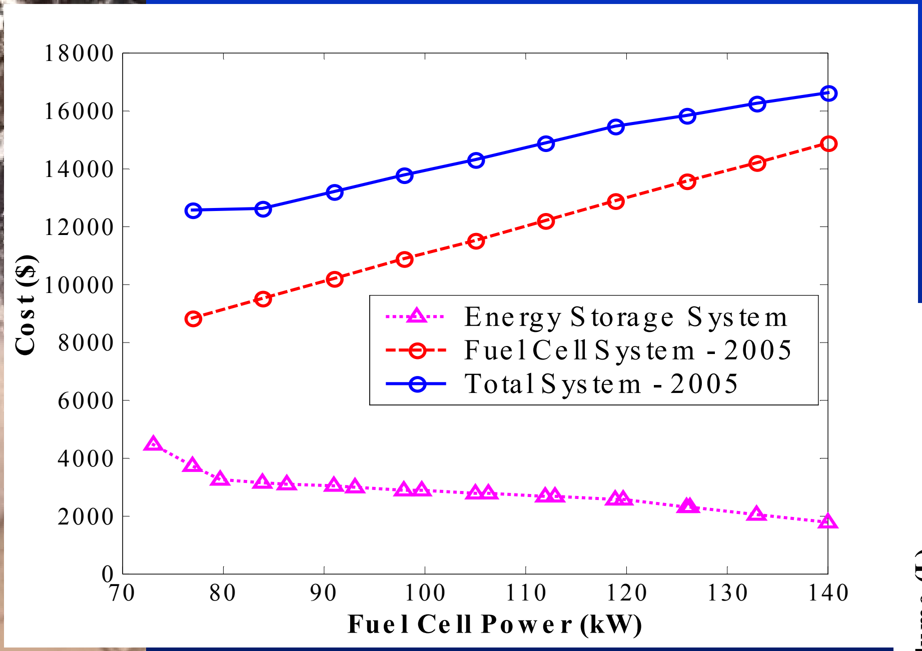


Volume

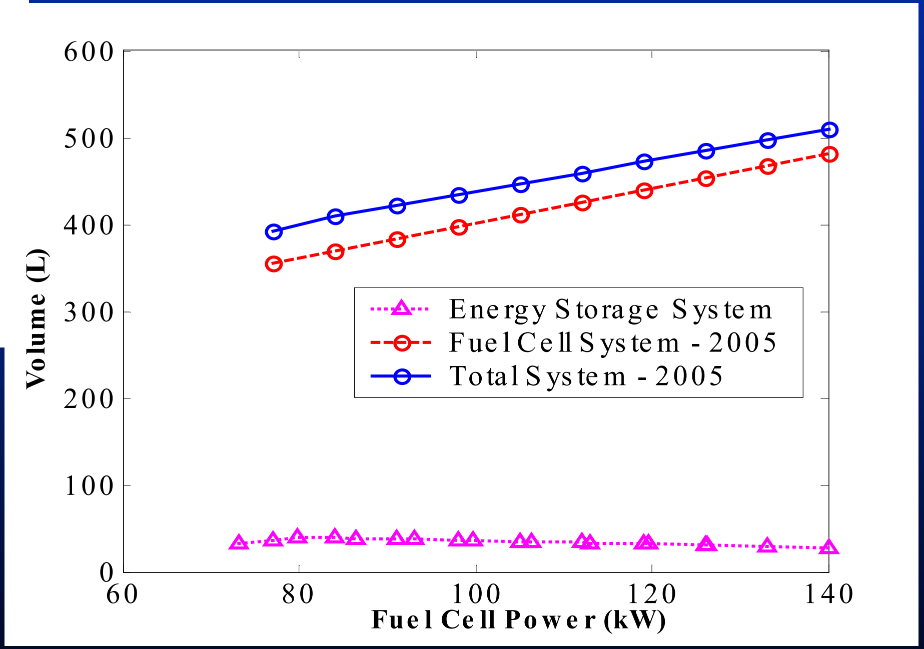


Powertrain System Cost and Volume - 2005

Cost

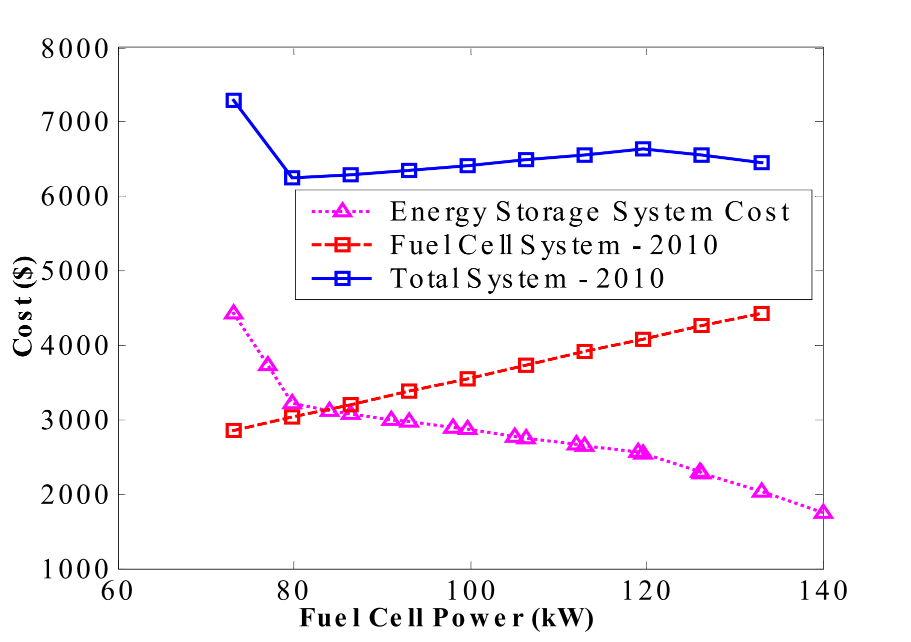


Volume

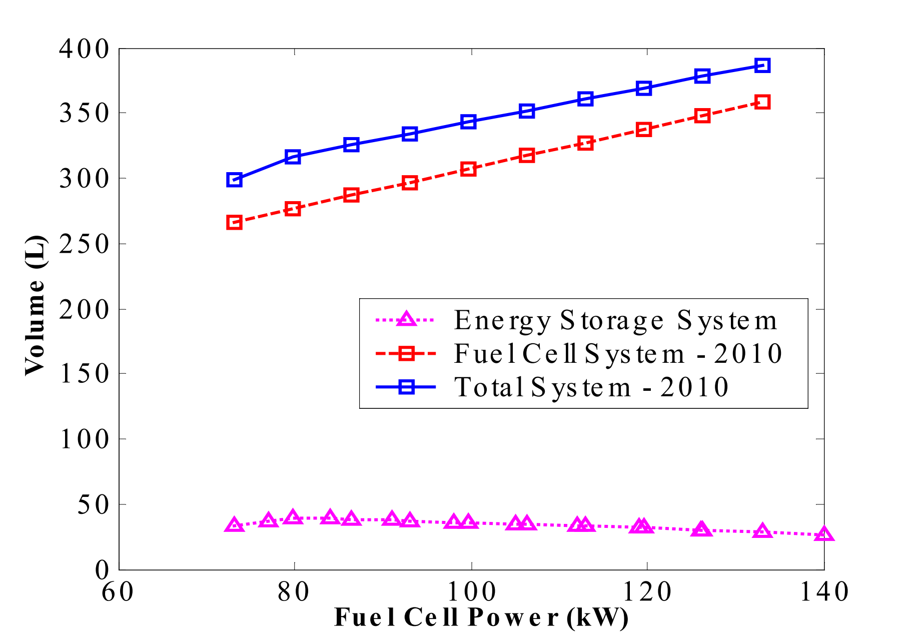


Powertrain System Cost and Volume - 2010

Cost



Volume



Conclusions

- A methodology has been developed for determining the requirements of an energy storage system to be included in a fuel cell hybrid vehicle.
- Requirements depends on the energy storage system's expected roles.
- This study's energy storage system requirements for a mid-size SUV ranged from 40-85 kW and 0.05-7 kWh depending on fuel cell system size and the role of the energy storage system.
- The best choice for energy storage chemistry may be different depending on the level of fuel cell downsizing.
- Downsizing fuel cell beyond the power level required for continuous gradeability led to dramatically increased energy requirements (and thus predicted cost) for the energy storage system.
- Short term costs drive design toward smaller fuel cell and larger battery while cost is less influential in long-term design scenarios

Future Work

- Refine vehicle and components assumptions to support identifying energy storage requirements for fuel cell vehicles
- Perform more detailed startup and shutdown load data for present/future fuel cell systems.
- Investigate use of ultracapacitors for hybrid fuel cell vehicles.
- Define the bounds for future optimization problems in which cost, volume, and mass constraints can all be evaluated simultaneously while maximizing fuel economy.

Acknowledgements

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- We appreciate the technical discussions we had with several FreedomCAR Technical Teams during the course of this study.

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