Plant/Control Optimization of a PEM Hybrid Fuel Cell Vehicle to Grid (V2G) System

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Outline

- Introduction
- Modeling
  - Fuel Cell System & Battery
  - Supervisory Controller
  - System Level Block Diagram & Power Cycle
- Optimization Problem Summary
- Model Analysis
  - DOE study
  - Monotonicity Analysis
  - Surrogate Model
- Optimization Study
  - Optimal Solution and Constraint Activity
  - Lagrange Multipliers and Constraint Relaxation
- Parametric Study
- Discussion of Results

Introduction

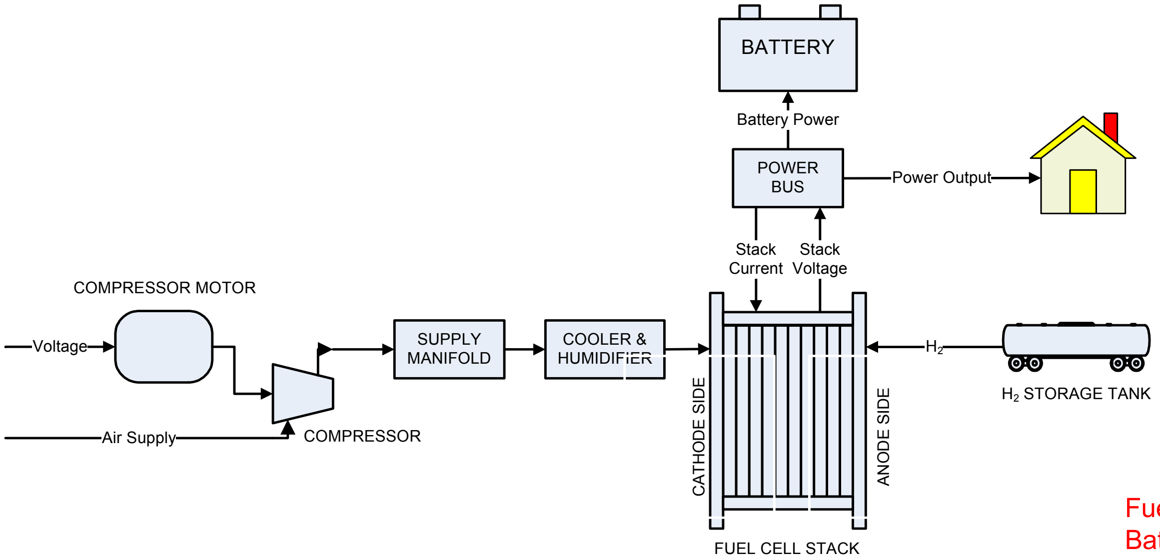
- Fuel Cell technology
  - Abundant energy source H_2
  - High efficiency (50-70%)
  - Clean energy source (zero emissions)

- Hybrid Technology
  - Hybrid concept is developing in many engineering fields, esp. the auto industry
  - Fuel Cell/Battery leverages advantages of each energy source

- V2G Concept
  - Enables the use of renewable energy sources
  - Adds energy storage capacity element to grid
  - Distributed generation (DG) decentralizes grid
  - 5% of California's vehicle fleet can provide 10% peak power for entire state [1]
  - Consumer may sell power back to the grid
  - More expensive FCV becomes a more profitable investment

[1] W. Kempton, J. Tomic, S. Letendre, A. N. Brooks and T. Lipman, "Vehicle-to-grid power: Battery, hybrid, and fuel cell vehicles as resources for distributed electric power in California," California Air Resources Board, Tech. Rep. UCD-ITS-RR-01-03, June 2001, 2001.

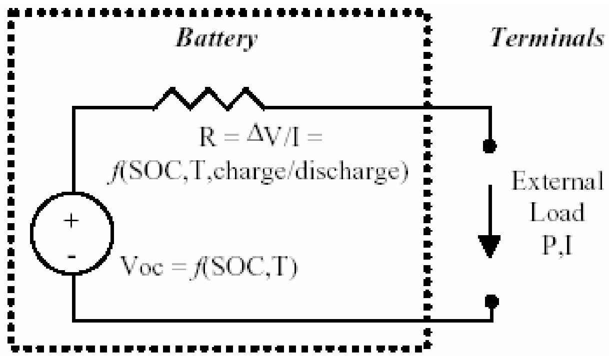
Fuel Cell System & Battery



- List of components
  - FC stack
  - Humidifier
  - Supply Manifold
  - Compressor

Fuel Cell stack model from Jay Pukrushpan
Battery model from ADVISOR

Resistive Equivalent Circuit Model



Isothermal Operation Assumption

- Main functions of battery model

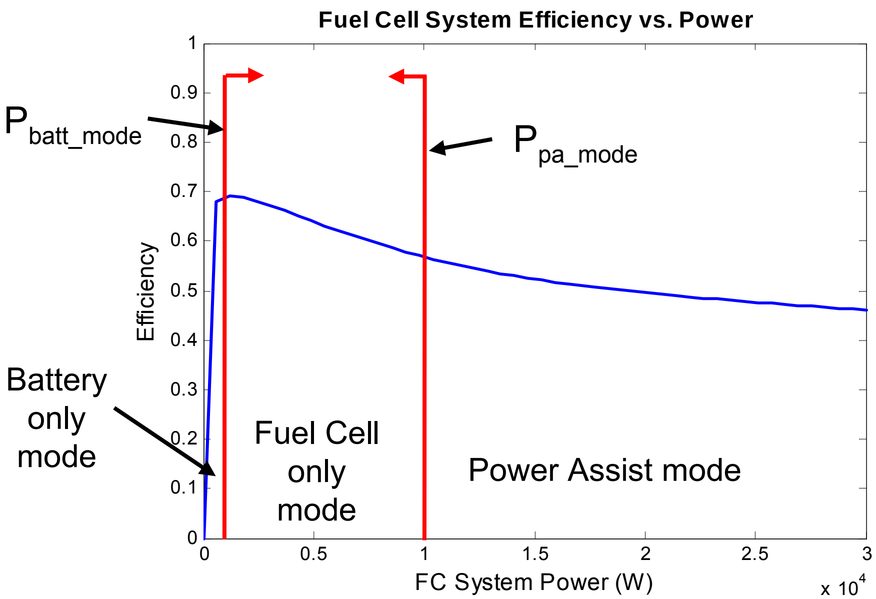
$$V_{oc} = f(soc, T), \quad R_{int} = f(soc, T)$$

$$P_{batt} = f(soc, V_{oc}, R_{int})$$

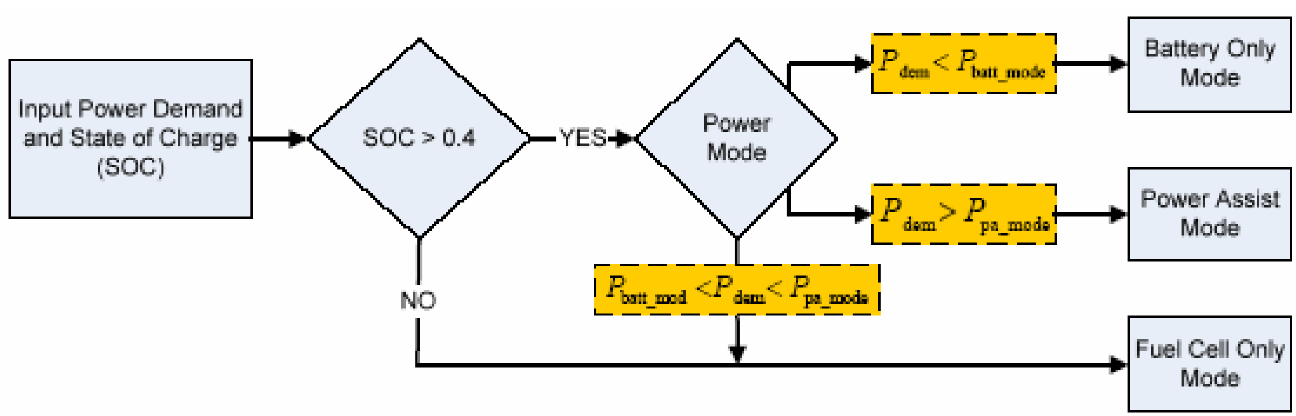
$$I_{batt} = -\frac{V_{oc} - \sqrt{V_{oc}^2 - 4P_{batt}R_{int}}}{2R_{int}}$$

$$\dot{SOC} = -\frac{I_{batt}}{Q_{max}} \Rightarrow SOC = \frac{Q_{max} - \int I_{batt}\,dt}{Q_{max}}$$

Rule-based Controller



- The idea of the rule-based control is to operate the fuel cell within a desired operating region that achieves high efficiency.
- For low power demand, battery provides all necessary power and fuel cell is turned off.
- For high power demand, battery assists fuel cell providing power to grid, which allows FC operate in higher efficiency region.



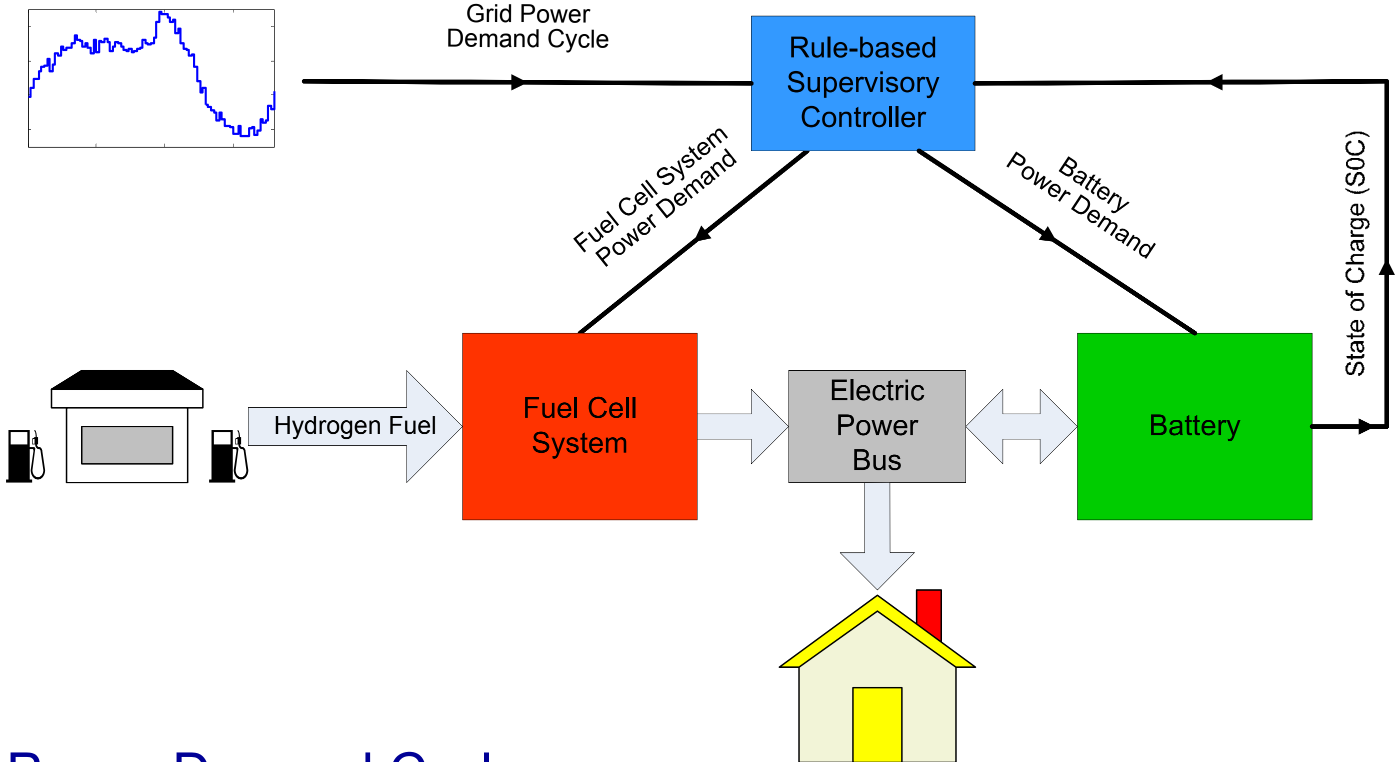
$$P_{fc} = 0,\ P_{batt} = P_{dem}$$

$$P_{fc} = P_{pa\_mode},\ P_{batt} = P_{dem} - P_{pa\_mode}$$

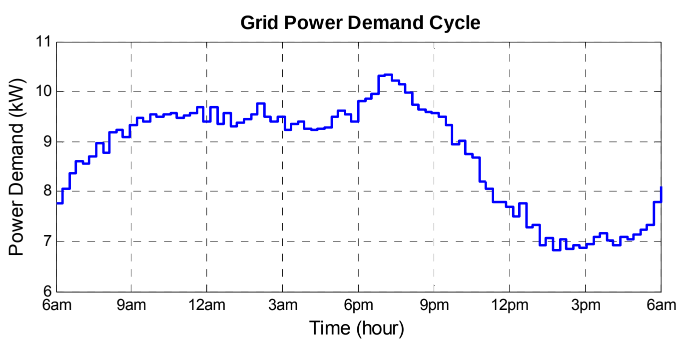
$$P_{fc} = P_{dem} + P_{charge},\ P_{batt} = -P_{charge}$$

where $P_{charge} = K_{charge}\left(SOC - SOC_{des}\right)$

System Level Block Diagram & Power Cycle



Grid Power Demand Cycle



- Representative grid power demand cycle
- Adapted from CAISO daily demand forecast
- Scaled for medium size office or apartment complex
- Augmented with white Gaussian noise to simulate stochastic nature of power demand

Optimization Problem Summary

Minimize hydrogen fuel consumption

$$\min f(\mathbf{x}) = m_{H_2}\left(\lambda_{CP}, n_{FC}, n_{BATT}, P_{pa}, P_{batt}, K_{ch}\right)$$

with respect to

6 Design Variables

- Number of fuel cells in stack, n_{fc}
- Number of battery modules, n_{batt}
- Compressor size, λ_{cp}
- Power Assist (PA) mode threshold, P_{pa}
- Battery mode threshold, P_{batt}
- Controller Gain, K_{ch}

subject to

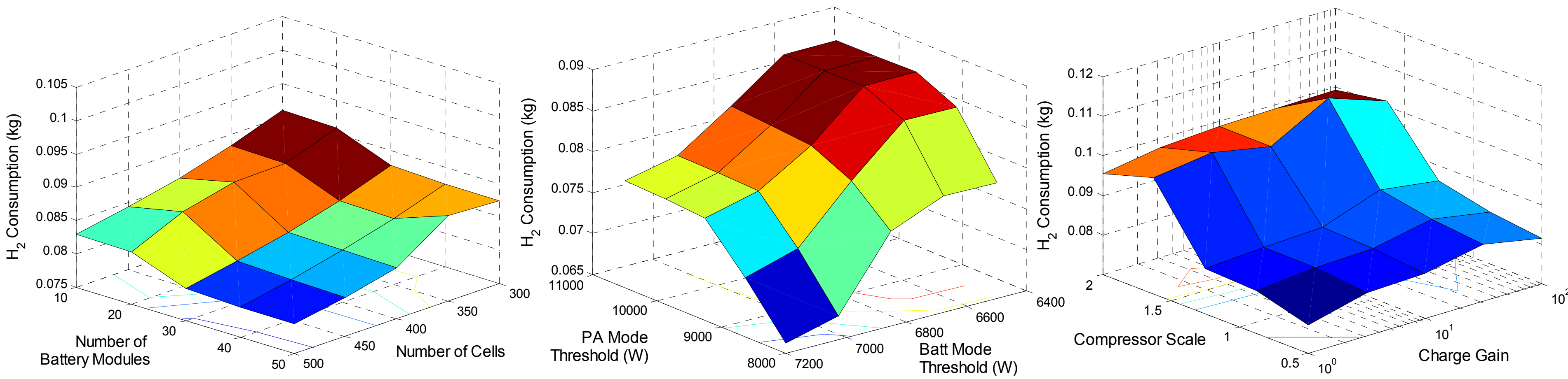
10 Constraints

- Fuel cell stack length
- Battery weight
- Stack heat generation
- Parasitic losses
- Fuel cell efficiency
- Oxygen excess ratio
- Max/Min SOC
- Start/End SOC deviation

DOE Study

Purpose: Determine general trends and possible monotonic relationships

- Sensitivity
  - Most sensitive to variations of power threshold values
  - Least sensitive to number of cells & battery modules
- Critical Role of Control
  - Optimal control allows the use of less efficient component sizes
- Monotonicity
  - Power threshold variables
  - Number of cells & battery modules (if fluctuations are ignored)
- Optimal Solution
  - Fluctuations indicate possible local minima



(a) (b) (c)

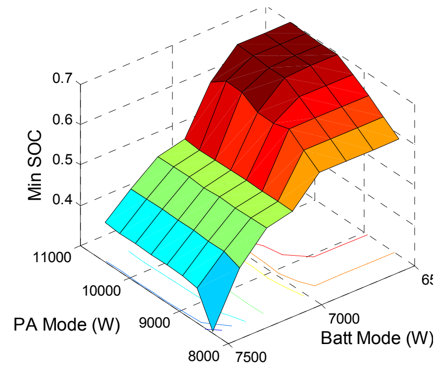
Monotonicity Analysis

- Active Constraints
  - Fuel Cell Stack Length ACTIVE MP1 wrt n_{fc}
  - Battery Weight ACTIVE by MP1 wrt n_{batt}
  - Minimum SOC ACTIVE by MP1 wrt $\{n_{fc}\ \lambda_{cp}\ P_{pa}\ \ P_{batt}\ K_{ch}\}$
- Solutions

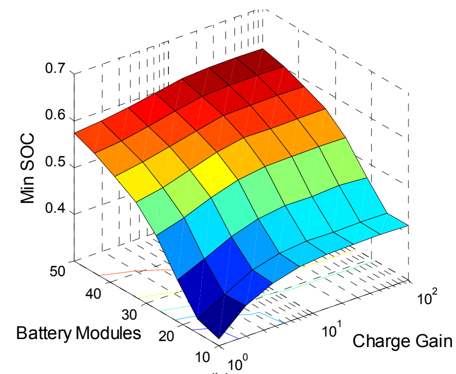
$$n_{fc}^* = 421$$

$$n_{batt}^* = 34$$

		n_{FC}	n_{BATT}	λ_{CP}	P_{pa}	P_{batt}	K_{ch}	Suspected Activity
Fuel consumption	$f(\mathbf{x})$	-	-	+ or -	+	-	?	N/A
Fuel Cell Stack Length	g_{16}	+						ACTIVE by MP1 wrt n_{FC}
Battery weight	g_{17}		+					ACTIVE by MP1 wrt n_{BATT}
Minimum SOC	g_{23}	?	-	?	?	+	-	ACTIVE by MP1 wrt at least one variable

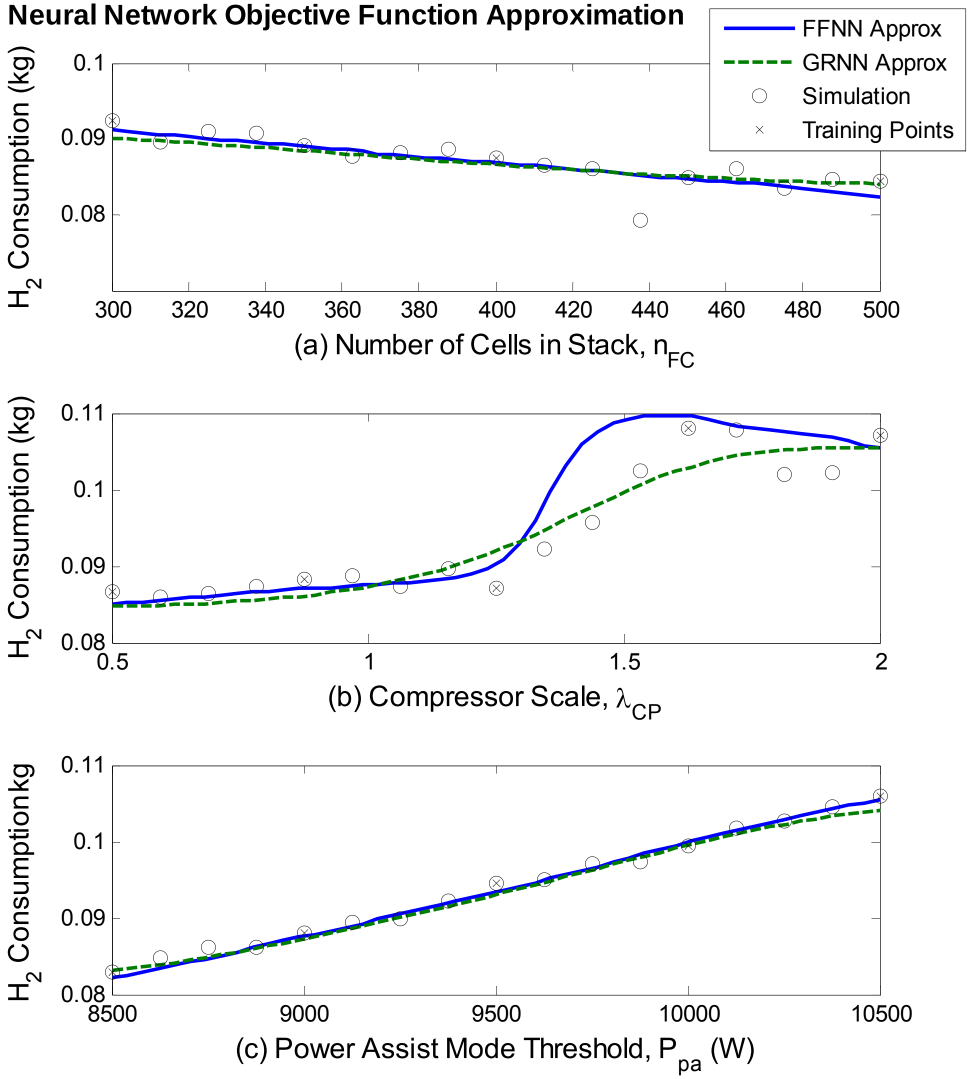


(a)



(b)

Surrogate Model



- Motivation
  - Noisy objective function
  - Gradient-based optimization is best suited for continuous, smooth objective functions
- Artificial Neural Network (ANN)
  - Two-layer feed-forward neural network (FFNN)
  - Generalized regression neural network (GRNN)
  - Trained via Levenberg-Marquardt algorithm, a quasi-Newton optimization technique
- Input/Output Model
  - 6 inputs (design variables)
  - 1 output (objective function)
  - 5^6 = 15625 total training sets

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Optimal Solution and Constraint Activity

Surrogate Model

Design Variable	Optimal Value
Number of Fuel Cells in Stack, n_{FC}	422
Number of Battery Modules, n_{BATT}	32
Compressor Scale, λ_{CP}	0.5
Power Assist Mode Threshold, P_{pa}	8074 W
Battery Only Mode Threshold, P_{batt}	6662 W
Charge Gain, K_{ch}	1.412
H_2 Fuel Consumption, m_{H_2}	0.0756 kg

Inconsistent Solutions

Neural Net captures general trends, but not local optima

Simulation Model

Design Variable	Optimal Value
Number of Fuel Cells in Stack, n_{FC}	422
Number of Battery Modules, n_{BATT}	23
Compressor Scale, λ_{CP}	0.92367
Power Assist Mode Threshold, P_{pa}	8792 W
Battery Only Mode Threshold, P_{batt}	6755 W
Charge Gain, K_{ch}	22.7115
H_2 Fuel Consumption, m_{H_2}	0.0847 kg

Active Constraints (4)

- Compressor Scale Lower Bound
- Fuel Cell Stack Length
- Battery Weight
- Minimum SOC

Observations

- Feasible for surrogate, infeasible for simulation
- Verifies monotonicity analysis
- Active model validity constraint, λ_{cp}
- Excellent fuel consumption

Active Constraints (1)

- Fuel Cell Stack Length

Nearly Active Constraints (3)

- Fuel Cell Efficiency
- Oxygen Excess Ratio
- Minimum SOC

Observations

- Battery weight not active
- Nominal compressor size is nearly optimal
- A single active constraint suggests local optima
- Notably worse fuel consumption than surrogate

Lagrange Multipliers & Constraint Relaxation

Lagrange Multipliers

Karush Kuhn Tucker Conditions

Stationarity: $\nabla f_* + \lambda^T \nabla \mathbf{h}_* + \mu^T \nabla \mathbf{g}_* = \mathbf{0}^T$

Feasibility: $\mathbf{h}(\mathbf{x}_*) = 0$

Transversality: $\mu^T \mathbf{g} = 0$

Multipliers: $\lambda \neq 0$, $\mu \geq 0$

Post-Optimality Sensitivity Analysis

$$\left(\frac{\partial f}{\partial \mathbf{h}}\right)_* = -\lambda^T$$

Active Constraints			Lagrange Multiplier Values, μ, at Optimum
λ_{CP} lower bound	g_1 :	$0.5 - \lambda_{CP} \leq 0$	3.857
Fuel cell stack length	g_{16} :	$L_{st}(n_{fc}) - 1.2 \leq 0$	9.551
Battery weight	g_{17} :	$m_{batt}(n_{batt}) \cdot g - 75 \leq 0$	19.549
Minimum SOC	g_{24} :	$SOC_{\min} - \min_k\{SOC(k)\} \leq 0$	53.102

Most Sensitive to Minimum SOC

Constraint Relaxation

- Relax minimum SOC to 0.5
- 2.62 % decrease in fuel consumption
- P_{pa} is second most sensitive constraint

Design Variable	Optimal Value for Relaxed Problem
Number of Fuel Cells in Stack, n_{FC}	423
Number of Battery Modules, n_{BATT}	32
Compressor Scale, λ_{CP}	0.5
Power Assist Mode Threshold, P_{pa}	8000 W
Battery Only Mode Threshold, P_{batt}	6708 W
Charge Gain, K_{ch}	1
H_2 Fuel Consumption, m_{H_2}	0.077277 kg

Active Model Validity Constraints

2.62 % reduction in fuel consumption

2nd Most Sensitive to P_{pa}

Active Constraints			Lagrange Multiplier Values, μ, at Optimum
λ_{CP} lower bound	g_1 :	$0.5 - \lambda_{CP} \leq 0$	2.6485
P_{pa} lower bound	g_7 :	$8000 - P_{pa} \leq 0$	20.4713
K_{ch} lower bound	g_{11} :	$1 - K_{ch} \leq 0$	0.1495
Fuel cell stack length	g_{16} :	$L_{st}(n_{fc}) - 1.2 \leq 0$	6.0449
Battery weight	g_{17} :	$m_{batt}(n_{batt}) \cdot g - 75 \leq 0$	1.3036
Maximum SOC displacement	g_{25} :	$\frac{\lvert SOC(1) - SOC(N)\rvert}{SOC(1)} - \Delta SOC_{\max} \leq 0$	0.5491

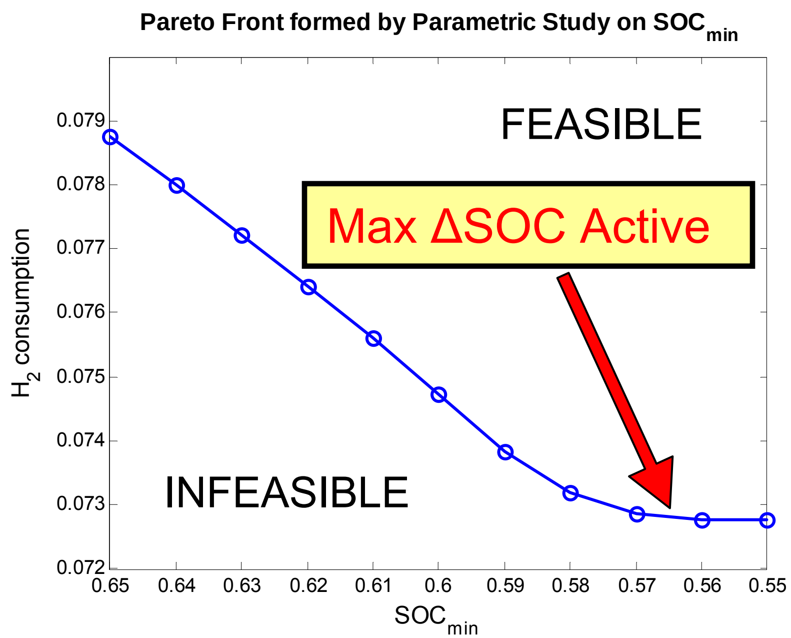
Note: Post-optimality sensitivity analysis shown here is performed on surrogate model.

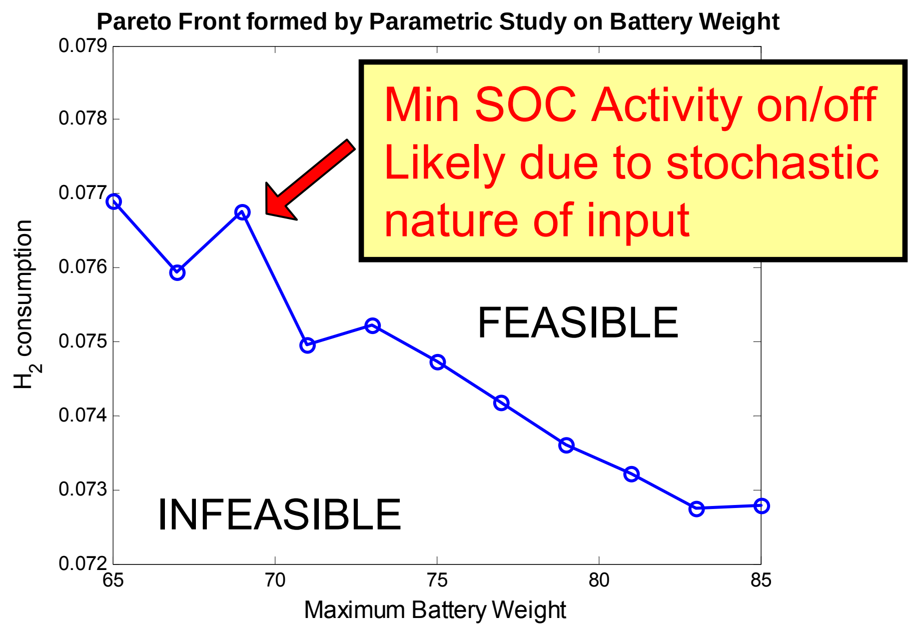
Parametric Study

- Formulate Multi-objective Optimization Problem
  - Parameterize constraint on Minimum SOC
  - Parameterize constraint on Maximum Battery Weight

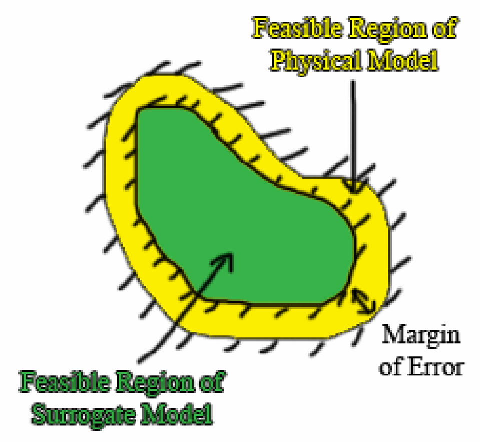
- Parametric Study on Minimum SOC
  - Decreasing Minimum SOC results in further decrease in H_2 consumption
  - Beyond SOC = 0.57, maximum ΔSOC becomes active

- Parametric Study on Battery Weight
  - Increasing battery weight results in further decrease in H_2 consumption
  - Battery weight and Minimum SOC are NOT mutually dependent





Discussion of Results



- Surrogate Modeling
  - Enables gradient-based optimality analysis
  - Eliminates "noise" in objective function
  - Local minima are not captured
  - Impose more aggressive constraints on surrogate model than actual model
- Combined Plant/Control Optimization
  - Component sizing and control parameters may be strongly coupled
  - An excellent control design can compensate for inefficient component sizes (and vice versa)
- Vehicular vs. Stationary Applications
  - Control represents larger obstacle than component sizing
  - Vehicle application constraints (FC length, battery weight) often constrain the optimal design

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Key References

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