



FCV Learning Demonstration: Factors Affecting Fuel Cell Degradation

Jennifer Kurtz, Keith Wipke, Sam Sprik

Fuel Cell Durability & Performance

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Fuel Cell Vehicle Learning Demonstration

- **Objectives**
 - Validate H₂ FC Vehicles and Infrastructure in Parallel
 - Identify Current Status and Evolution of the Technology
 - Assess Progress Toward Technology Readiness
 - Provide Feedback to H₂ Research and Development

Key Targets

Performance Measure	2009*	2015**
Fuel Cell Stack Durability	2000 hours	5000 hours
Vehicle Range	250+ miles	300+ miles
Hydrogen Cost at Station	\$3/gge	\$2-3/gge

* To verify progress toward 2015 targets

** Subsequent projects to validate 2015 targets



Learning Demonstration Partners



All 1st generation vehicles deployed
2nd generation introduction Fall '07

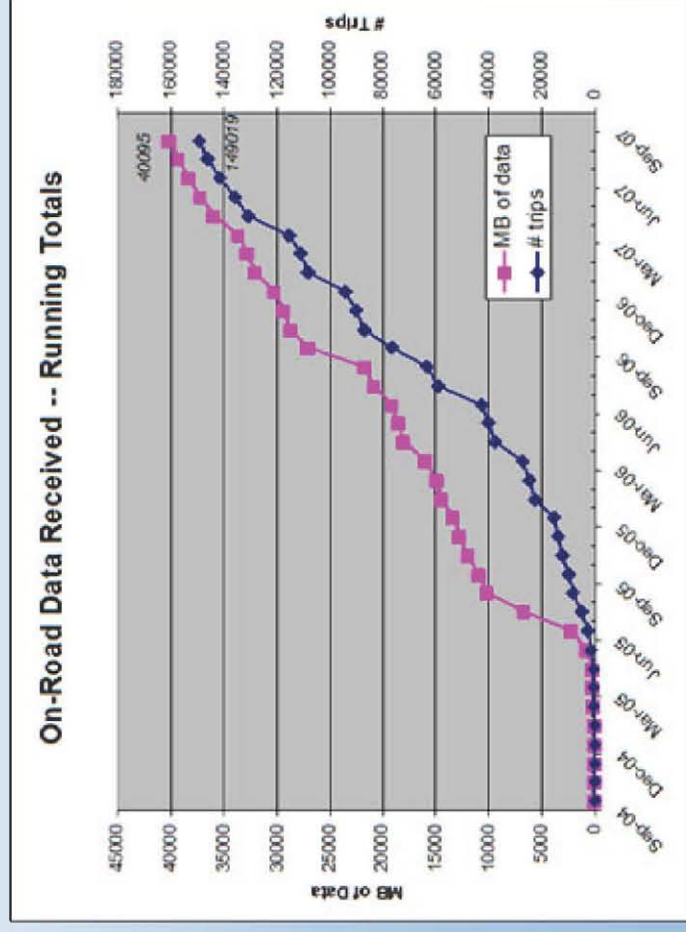


FC Degradation Analysis

Objectives

- Learn if there are **observable relationships** between the FCV Learning Demonstration **real world data** (driving and filling) and **fuel cell degradation**.
- Include fuel cell design and driving tendency factors
- Report on dominant factors (if there are any) affecting fuel cell degradation

Note: data not specifically controlled for a FC degradation study



Through August 2007:

- >149,000 individual vehicle trips
- 40 GB of on-road data
- >2 yrs data analyzed
- >2 yrs of data to gather

Multivariate Analysis Overview

- Why multivariate analysis?

- Uncontrolled degradation experiment
- Likely a combination of factors in real world applications
- A dominant single factor not apparent from Single Factor analysis step
- Reduction of factors

Data
Processing

Single Factor
GUI

Data
Processing

Multivariate
Analysis

- Why Partial Least Squares (PLS)?

- Concentration on observation, FC decay rate
- Latent Variables (LVs) assembled to explain maximum decay rate variance

Degradation
Model & Testing

Data Pre-Processing

- FC operation trip filters
- Sample (FC) filter
- Factors
 - FCV Learning Demonstration, Gen I available data.
 - Factors may vary between project partners.
 - Factor examples
 - Trip detail factors
 - Fuel cell performance factors
- Scaled & mean-centered data
- Data through September 2007
- Observation: FC Decay Rate
 - Voltage decay estimate
 - Low, average, or high decay rate classification

Data Set

Variable Categories

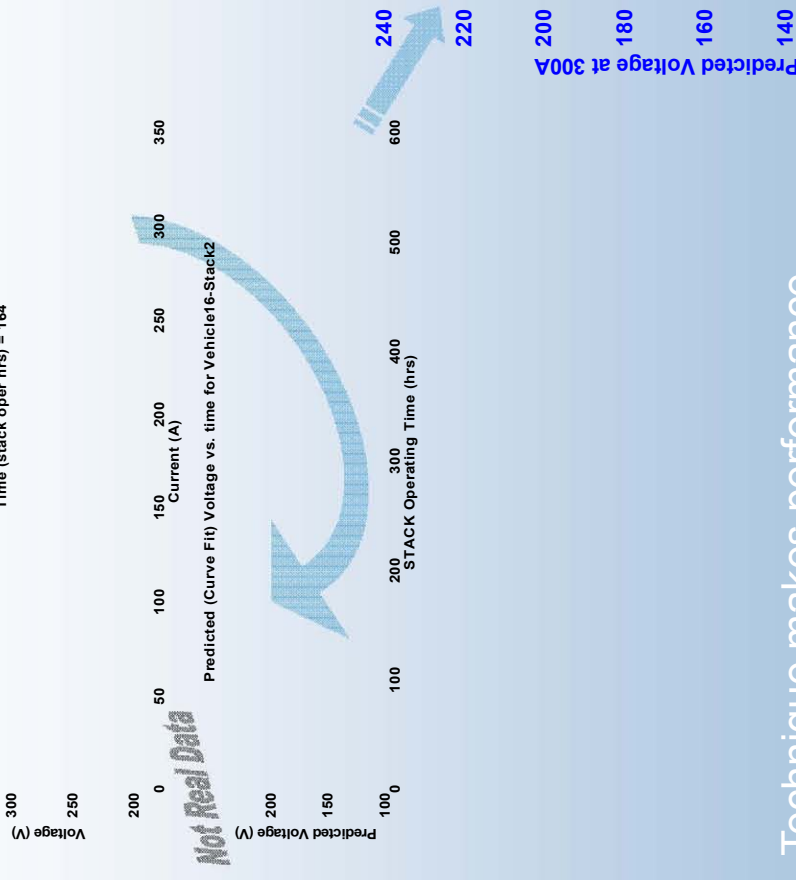
FC Power			
Install Date			
Starts/hr			
Idle Time			
Initial Condition			
Time Between Trips			
Trip Length			
Ambient Trip Temperature			
Filling Station H2 production method			
# of 0 speed trips			
Voltage			
Current			
Successful FC starts			

Simulated Data Set Example

Method for Projecting Time to 10% Fuel Cell Stack Voltage Degradation

Stack Degradation Analysis: Vehicle16-Stack2

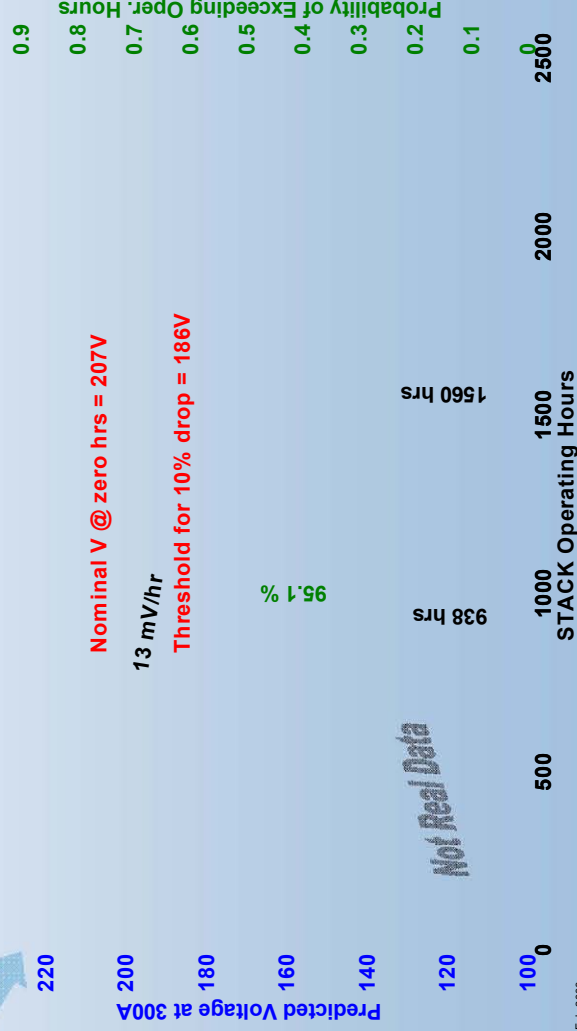
2400 data points per curve fit
Time (stack oper hrs) = 164



Technique makes performance projection based on all available FC data & includes confidence intervals.

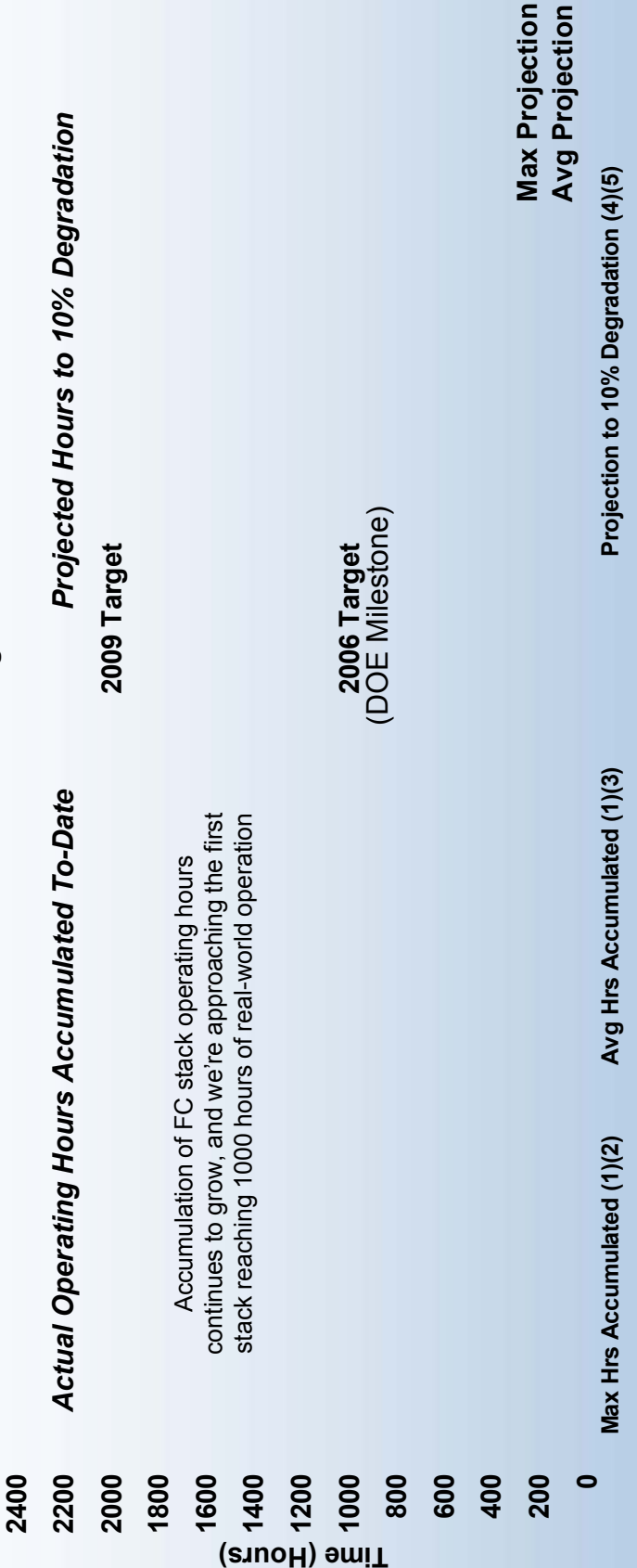
Created: 28-Feb-2006

Voltage vs. Operating Hours at 300A: Vehicle16-Stack2



As More Gen 1 Data Is Accumulated, Some Teams Are Demonstrating Long FC Durability

DOE Learning Demonstration Fuel Cell Stack Durability:
Based on Data Through 2007 Q2



Accumulation of FC stack operating hours continues to grow, and we're approaching the first stack reaching 1000 hours of real-world operation

(1) Range bars created using one data point for each OEM.
(2) Range (highest and lowest) of the maximum operating hours accumulated to-date of any OEM's individual stack in "real-world" operation.
(3) Range (highest and lowest) of the average operating hours accumulated to-date of all stacks in each OEM's fleet.
(4) Projection using on-road data -- degradation calculated at high stack current. This criterion is used for assessing progress against DOE targets, may differ from OEM's end-of-life criterion, and does not address "catastrophic" failure modes, such as membrane failure.
(5) Using one nominal projection per OEM: "Max Projection" = highest nominal projection, "Avg Projection" = average nominal projection.
The shaded green bar represents an engineering judgment of the uncertainty due to data and methodology limitations. Projections will change as additional data are accumulated.

What Factors are Important to the Model?

Regression Vector Example



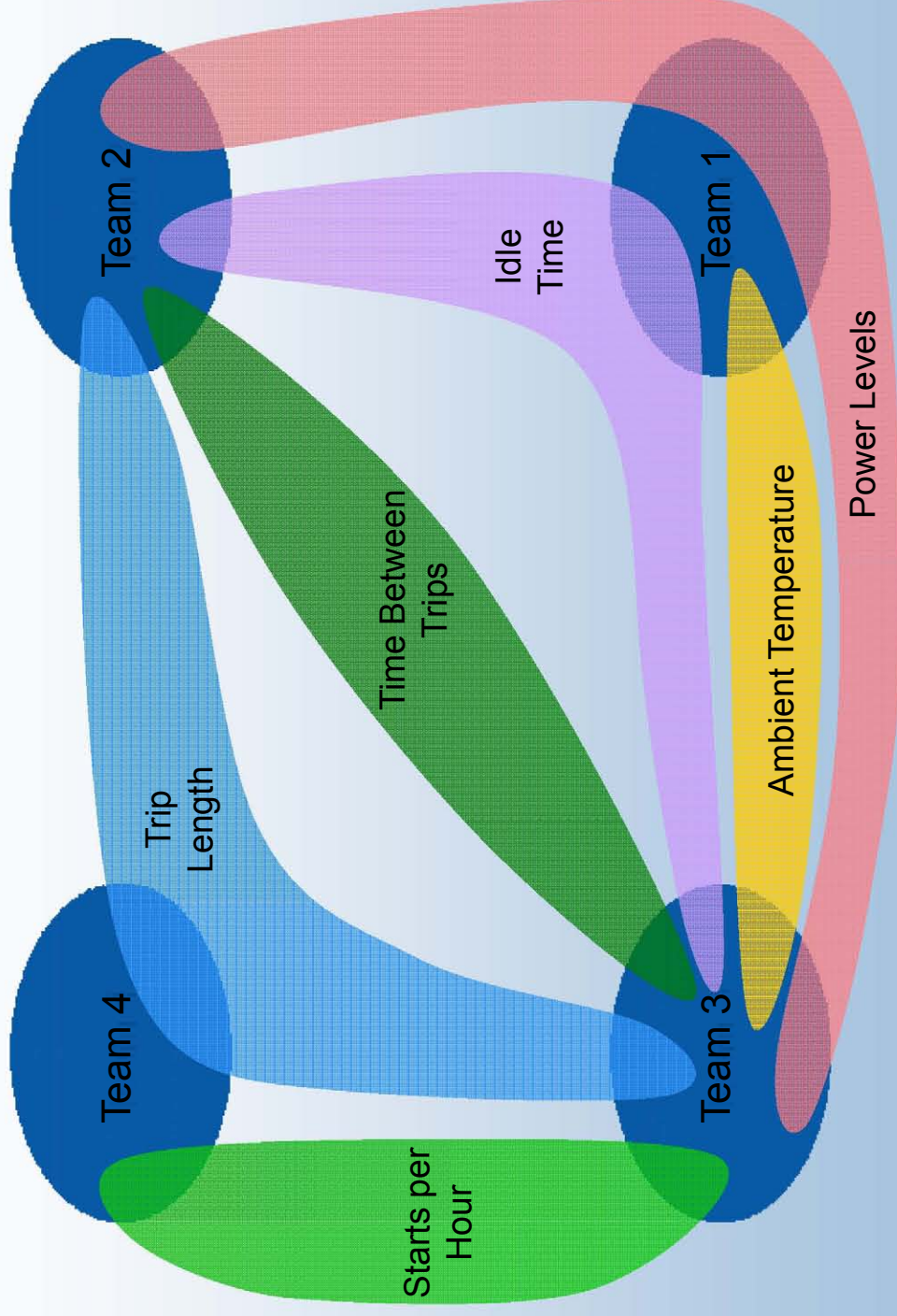
PLS Results - Learning Demonstration Degradation Factor Summary

<i>~29% Decay rate variance explained by a combination of the data variables below¹</i>	<i>Correlation to Decay Rate Data</i>
Starts per hour (+)	
Power levels (high & average) (+)	High decay rate ²
Trip length (-)	
Time between trips (+)	
<i>~10% Decay rate variance explained by a combination of the data variables below¹</i>	<i>Correlation to Decay Rate Data</i>
Idle time (+)	High decay rate ²
Power levels (low) (+)	

1. Findings based on a Learning Demonstration Fleet, Partial Least Squares (PLS) regression model. Approximately 39% decay rate variance explained by the model.

2. As part of the variable combination, a (+) indicates a directional relation to high decay rate and a (-) indicates an inverse relation.

PLS Results – Identification of Factors Contributing to FC Degradation per Team



1. Results are from partial least squares (PLS) regression analysis of each team's fleet of vehicles individually
2. First two collections of factors cover ~61%-76% of decay rate variance

Summary

- Gen I FCV on-road data (77 vehicles)
- Different look than a lab study of degradation
- Analysis Learning
 - Adjustment of input factors & included samples
 - Correlation and interpretations
 - Decay rate classifications
 - Analysis iterations & variations
 - Additional data
- Complex factor interactions affecting FC degradation
- Team level analysis vs. DOE Fleet level analysis
 - Team level analysis more valuable because of the variations between teams
 - Team level analyses high R^2 , but not robust
 - Identification of trends difficult because of scattered sample data
 - Use DOE Fleet level analysis to compare difference between teams
- **Collaboration** with teams

Contact Information

Jennifer Kurtz

National Renewable Energy Laboratory

jennifer_kurtz@nrel.gov

303-275-4061

Keith Wipke (Primary project contact)

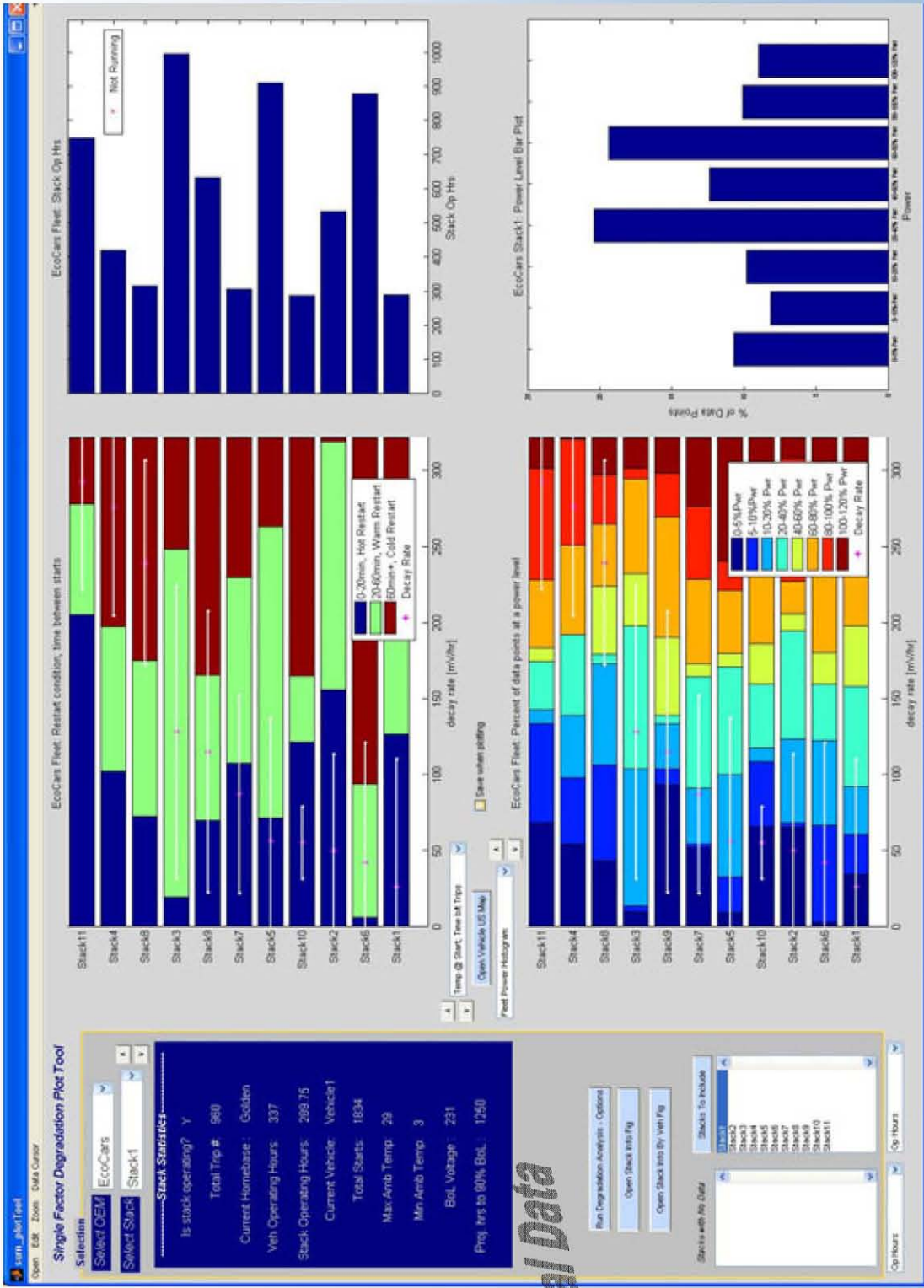
National Renewable Energy Laboratory

keith_wipke@nrel.gov

303-275-4451

All public Learning Demo papers and presentations are available online at
http://www.nrel.gov/hydrogen/proj_tech_validation.html

Single Factor GUI



Not Real Data



Equation Example

The model equation is:

$$y_{\text{pred}} = x \cdot a + b,$$

where a is the regression vector, x is a sample's data vector, y_{pred} is the predicted decay rate, and b is the intercept ($b=0$ for this model).

Because of the data processing (mean-centering and scaling) in the model, the x & y_{pred} value is processed and y_{pred} is reverted back into decay rate units for the prediction.

x =sample data, a vector that is 1 by factor #:

e.g. [50 300 .5 7 .2 1]

a = regression vector, a vector that is factor # by 1:

e.g. [.4 .1 -.31 -.1 .1]'

Simulated Data Set Snapshot

Scaled & mean-centered Simulated Data

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
		dr class	decay rate	'starts/hr'	'installDate'	'BoL_V'	'%Time at idle'	'%Time at 0-5% Power'	'%Time at 5-20% Power'	'%Time at 20-40% Power'	'%Time at >40% Power'	'11%Trips 0-5 mins long'	'%Trips 5-10 mins long'	'%Trips 10-20 mins long'	'%Trips 20-30 mins long'	'%Trips >30 mins long'	'%Trips,deltaT 0-30mins'	'%Trips,deltaT 30-120mins'	'%Trips,deltaT 120-240mins'	'%Trips,deltaT >240mins'
1																				
2	'Stack1'	'Ave DR'	0.1	-0.1224	-0.0433	-0.2671	0.9801	2.0946	-1.097	-1.3893	-0.4951	0.2587	-1.3046	0.9192	-0.284	0.0594	0.988	0.029	-0.9523	1.9068
3	'Stack14'	'Ave DR'	0.3	0.9564	0.1621	-1.7865	1.1688	-0.3718	3.3633	-2.3877	-2.0153	1.5372	-0.5175	-0.946	-0.7902	-0.2794	0.6148	0.1869	0.6087	-0.0901
4	'Stack19'	'Ave DR'	0.4	-2.6899	1.8057	-0.0369	-1.1829	-0.8934	-0.7473	2.4426	0.2698	-1.4345	-0.0127	-0.1324	1.241	1.1452	2.6778	1.8368	0.415	0.315
5	'Stack4'	'Ave DR'	0.1	-0.6632	0.796	-1.3993	-0.925	0.6467	-0.7417	0.1277	-0.0823	-1.2796	-0.2806	0.1573	1.1257	0.9811	0.2081	-2.1949	1.156	0.8852
6	'Stack16'	'Ave DR'	0.08	-1.8654	1.9325	1.9854	0.2644	0.1928	-0.6638	-0.1239	0.7469	0.0567	1.5482	0.552	-0.6348	-1.269	-1.1313	-0.2027	0.7208	-0.774
7	'Stack6'	'Ave DR'	0.05	-0.1575	-0.9132	-0.7291	0.2116	0.6075	-0.1523	0.5761	-1.2568	-0.5223	0.1478	1.3778	0.5948	-0.9698	-1.1713	-0.112	0.3438	0.2379
8	'Stack20'	'Ave DR'	0.3	0.3114	1.3161	0.4388	-0.3527	1.7141	-1.6304	-0.6724	0.2142	0.2595	-0.6156	0.365	0.466	-0.4677	0.8561	-0.3481	0.7648	-0.3795
9	'Stack8'	'Ave DR'	0.2	-0.0802	-1.5164	-0.5007	0.3233	0.7031	-0.3645	-0.2415	-0.3731	0.0027	0.9539	-0.6931	-0.4886	1.5929	0.3993	-2.0619	0.3436	0.7792
10	'Stack9'	'Ave DR'	0.2	2.272	-1.2803	-0.8049	0.9042	-0.1033	0.2058	0.2714	0.3721	0.8292	0.5067	-0.6316	-0.1037	-0.8406	0.8424	0.3043	0.0551	0.6103
11	'Stack10'	'Ave DR'	0.1	0.3512	-1.088	-0.4266	1.0646	-2.1375	1.2576	1.1686	0.5334	0.3913	0.9348	1.1198	-0.1601	-0.6294	0.2247	0.9886	-0.0973	-0.1242
12	'Stack7'	'High DR'	0.9	0.0434	-0.97	0.1327	0.0971	-0.2427	0.2325	0.5569	-0.446	3	0.1987	0.0147	0.2737	-0.4188	3	-1.0885	0.117	0.2037
13	'Stack12'	'High DR'	0.9	-1.0645	-1.1929	-1.1501	-0.0091	-1.6408	0.4643	1.702	0.3959	3.2	-1.7495	-0.3418	1.3338	0.2672	3.2	0.0573	0.0822	1.1605
14	'Stack13'	'High DR'	1.2	1.3481	-0.1176	1.4045	1.3163	0.3012	0.9483	-1.0956	0.8314	3.3	1.8198	-1.1097	-0.8793	-1.1554	3.3	0.3438	-0.2039	-0.0355
15	'Stack5'	'High DR'	1.4	-0.338	0.7697	-0.4182	0.3149	1.5651	-1.1299	-0.6303	-0.2813	3	0.9433	1.3992	0.1117	0.8583	3	-0.8045	0.8844	-0.1321
16	'Stack15'	'High DR'	3	-0.3652	-0.97	0.0042	0.3699	1.0604	-0.822	-0.8	0.2131	3.4	0.0037	0.3136	-0.9103	0.1576	3.4	-0.2978	0.3685	0.3322
17	'Stack2'	'High DR'	1.8	-0.1616	-0.97	0.0787	-0.498	0.4472	-0.0605	-0.1787	-0.4572	3.3	2.474	-0.8301	-0.3182	-0.049	3.3	0.2543	-0.8886	-0.2694
18	'Stack17'	'High DR'	1.3	0.0157	0.6867	-1.0452	-2.0373	-0.3112	1.0023	-0.1477	-0.7956	3.4	0.9652	-2.931	-2.0341	0.9453	3.4	1.5767	2.4232	0.3374
19	'Stack18'	'High DR'	1.8	0.4296	-0.3012	0.9709	0.8241	-1.0063	0.333	0.9692	0.2446	3	-0.2315	0.7688	-0.1687	-1.0141	3	-0.5258	-0.5702	0.0873
20	'Stack11'	'High DR'	1.4	0.6729	1.8538	1.3549	0.4893	-0.6673	-0.0349	0.9572	0.2396	3.2	-0.6295	1.9543	-0.1645	-0.6314	3.2	0.7293	-1.2537	0.0526
21	'Stack3'	'High DR'	1.1	1.6345	-0.0214	-0.2185	0.9655	-1.0085	0.6782	-0.1478	0.7591	3.1	1.3455	-0.6422	-1.3496	-1.2967	3.1	-0.503	-0.1216	0.1326
22	'Stack21'	'Low DR'	-1	5	0.8	3	-3.0161	-0.9376	-1.0309	-0.956	3.7897	-3.0329	-0.836	-0.6717	3.1392	3.0144	-1.6469	2.2609	-3.3060	-4.0173
23	'Stack22'	'Low DR'	-0.5	4	0.9	3.2	-1.1530	-1.3536	-1.3915	2.492	1.1191	2.2425	-0.0733	-1.6059	-2.0713	-0.8754	0.0130	-1.9133	0.5153	-0.2024
24	'Stack23'	'Low DR'	-0.7	8	1	3.3	0.1670	-0.2314	-1.0224	1.0162	0.1064	0.365	1.9118	-0.8217	-0.9249	-0.1906	-0.7116	0.1544	1.1529	-0.3456
25	'Stack24'	'Low DR'	-0.6	6	1	3	-1.1470	-0.8106	-0.7513	1.065	1.0974	1.3006	-0.0600	-1.4506	-0.7715	-0.4371	0.0410	2.4091	1.8478	1.2701
26	'Stack25'	'Low DR'	-1.1	5	1	3.4	-0.8019	0.1015	0.197	0.0506	-0.4357	-1.2337	2.0069	2.2285	-1.2642	-0.4371	-1.3634	-0.8135	-2.0669	-1.9613
27	'Stack26'	'Low DR'	-0.4	4	0.9	3.3	2.3060	0.2159	-1.2385	-0.0499	0.5612	1.6762	0.0591	-1.2721	-1.3210	-0.8226	-0.0337	-1.27	0.1027	-0.0975
28	'Stack27'	'Low DR'	-0.5	8	0.8	3.4	1.0144	1.5754	-1.0694	-1.2042	-1.1699	-1.1214	-0.0600	0.0221	0.1769	1.4007	-1.0636	-0.029	-0.3601	0.1690
29	'Stack28'	'Low DR'	-0.9	6	1	3.2	-0.5110	-0.5713	0.2357	0.0055	0.9502	0.039	-0.7643	0.392	1.1355	-0.5296	-1.1349	0.6159	-1.1922	-1.6271
30	'Stack29'	'Low DR'	-0.1	8	0.8	3.1	1.4142	2.194	-1.4426	-1.5923	-1.7649	-0.9529	0.73	-0.4633	-0.295	1.4613	0.6977	-1.2652	-0.4134	0.9107
31	'Stack30'	'Low DR'	-0.7	7	1	3.4	-0.9901	-1.4434	1.8432	0.0257	0.7211	-0.0507	2.3917	1.2358	0.6589	-0.7507	0.1136	0.6007	0.347	0.7259
32	'Stack31'	'Low DR'	-1.8	6	1	3.2	0.3995	0.8812	0.89	-1.1677	-1.2308	-1.176	-1.2937	0.1155	1.0006	1.4299	-0.1617	-0.4517	-0.1695	-0.4993