FCV Learning Demonstration: Factors Affecting Fuel Cell Degradation

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Fuel Cell Vehicle Learning Demonstration

Objectives

- Validate H_2 FC Vehicles and Infrastructure in Parallel
- Identify Current Status and Evolution of the Technology
  - Assess Progress Toward Technology Readiness
  - Provide Feedback to H_2 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

Photo: NREL

Learning Demonstration Partners

CHRYSLER

bp

Ford

bp

GM

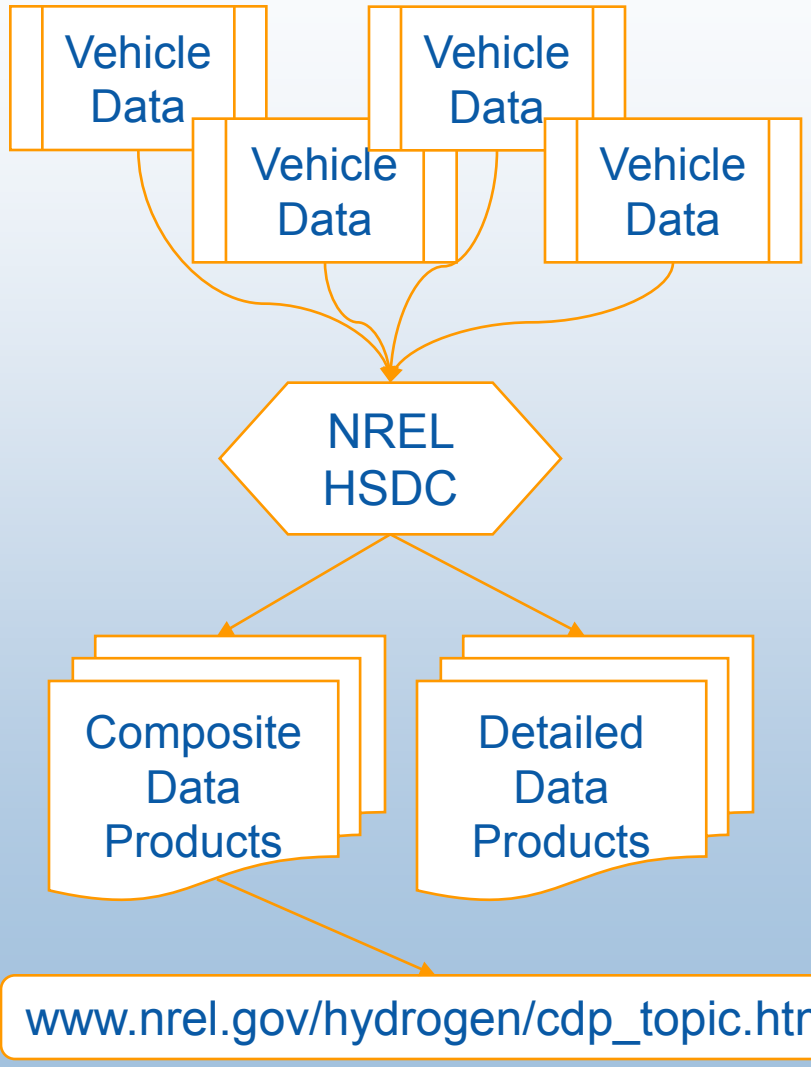
Chevron

HYUNDAI

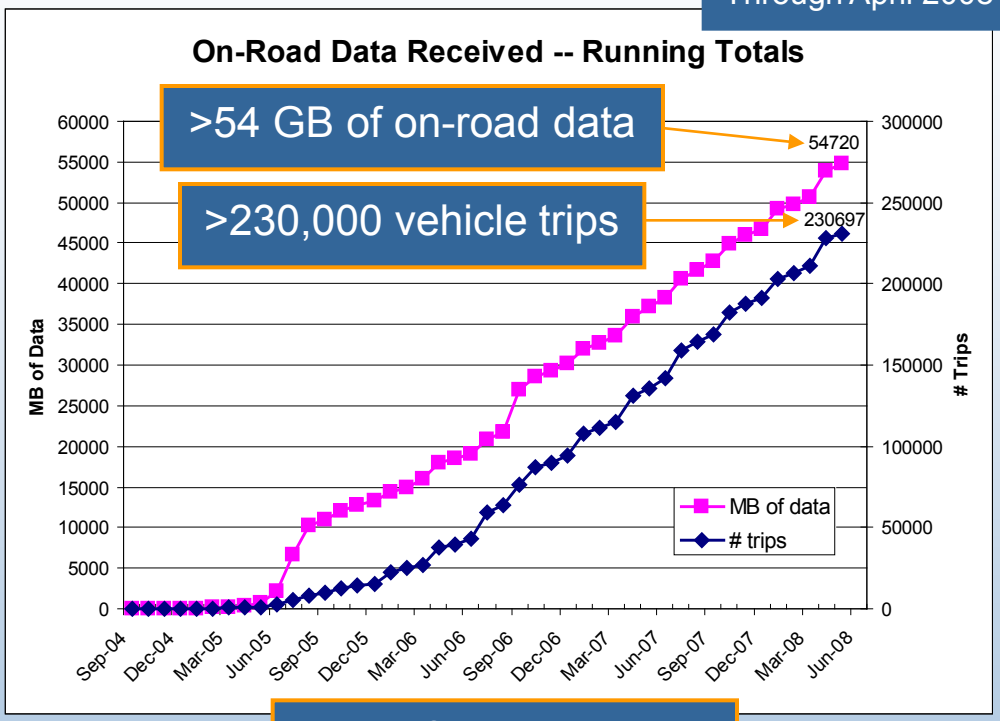
KIA

UTC Power
A United Technologies Company

FCV Learning Demonstration Data Collection



Through April 2008



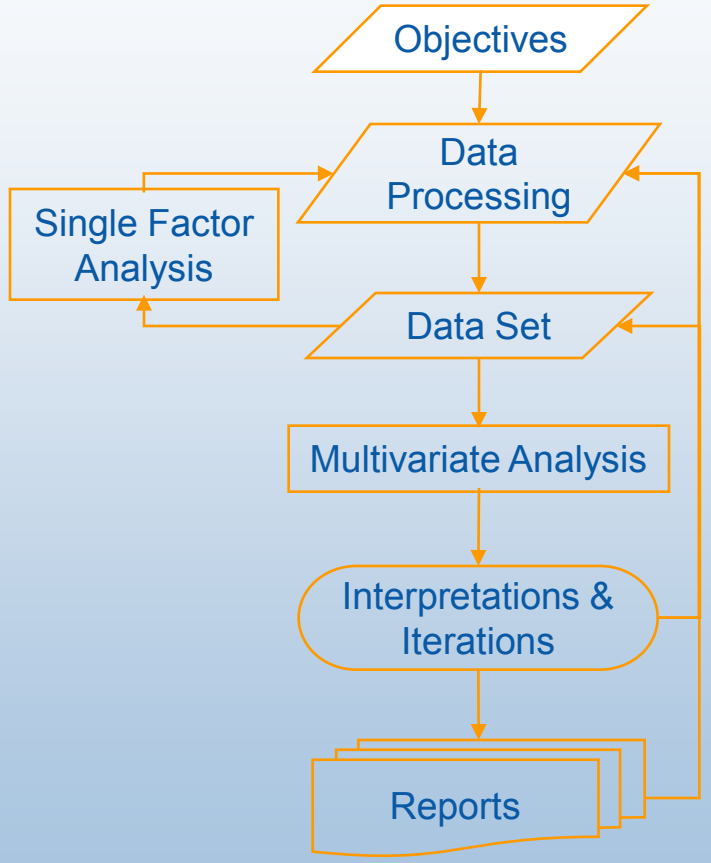
3 yrs of data analyzed
2 yrs of data to gather

Note: data not specifically controlled for a FC degradation study.

FC Degradation Analysis

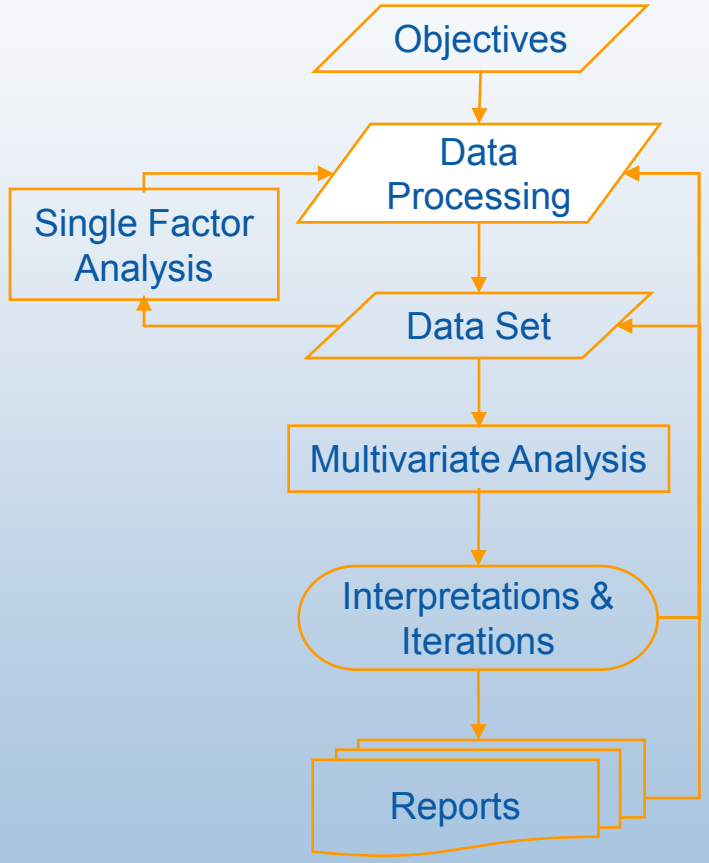
- Develop a fuel cell degradation study
- Utilize FCV Learning Demonstration real world data (driving and fueling) for study and identification of any relationships to fuel cell degradation
- Address lack of full scale, fuel cell degradation analyses/experiments
- Investigate reasons for differing fuel cell decay rates within a fleet
- Collaboration with project partners
- Reporting of any dominant factors affecting fuel cell degradation

Key metric in the FCV Learning Demonstration



Data Processing

- FC operation trip filters
- Sample (FC) filter
- Gen I available data (may vary between project partners)
- Scaled & mean-centered data
- Data through December 2007
- Observation: FC Decay Rate
  - Voltage decay estimate
  - Low, average, or high decay rate classification



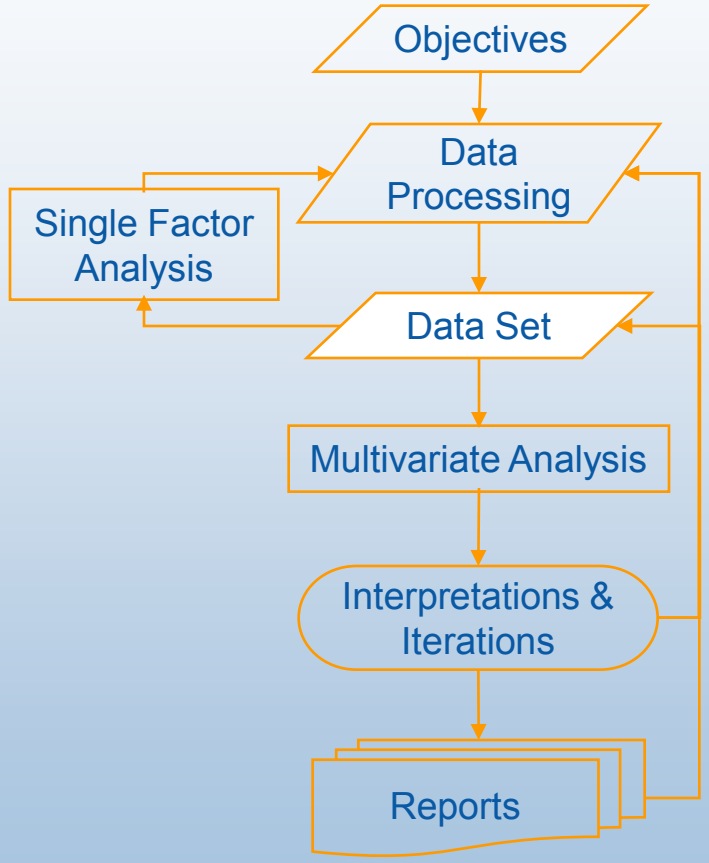
Data Set

Sample	Decay Rate	Variables			
Stack1	DR1	Data(1,1)	Data(1,2)	…	Data(1,75)
Stack2	DR2	Data(2,1)	Data(2,2)	…	Data(2,75)
.	.	.	.		.
.	.	.	.		.
.	.	.	.		.
.	.	.	.		.
Stack31	DR31	Data(31,1)	Data(31,2)	…	Data(31,75)

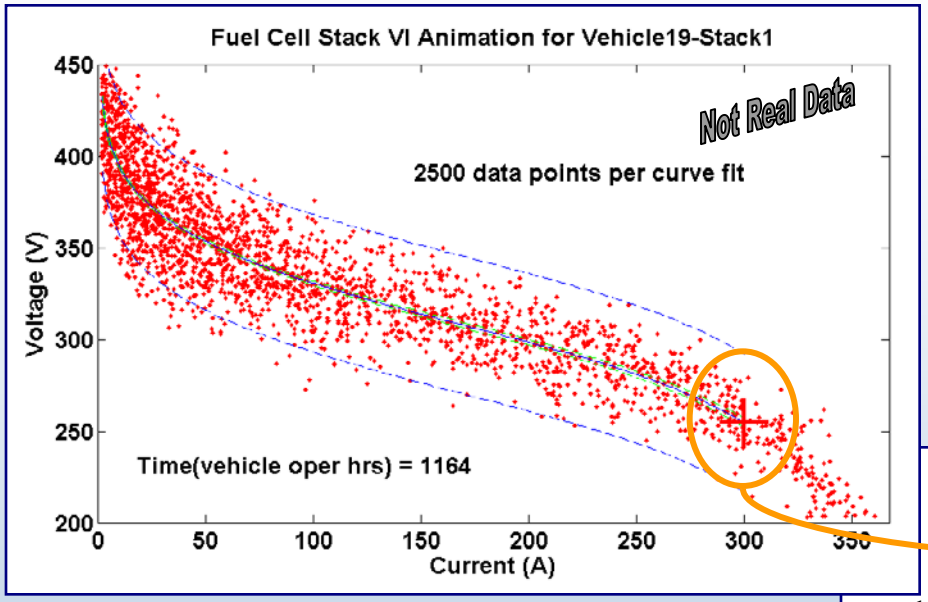
Select available variables that may have a relationship to known or expected degradation mechanisms

Variable Categories

FC Voltage & Current
Install Date
Starts/hr
Idle Time
Time Between Trips
Trip Length
Ambient Trip Temperature
Speed
Successful FC starts
Fill Data
Location

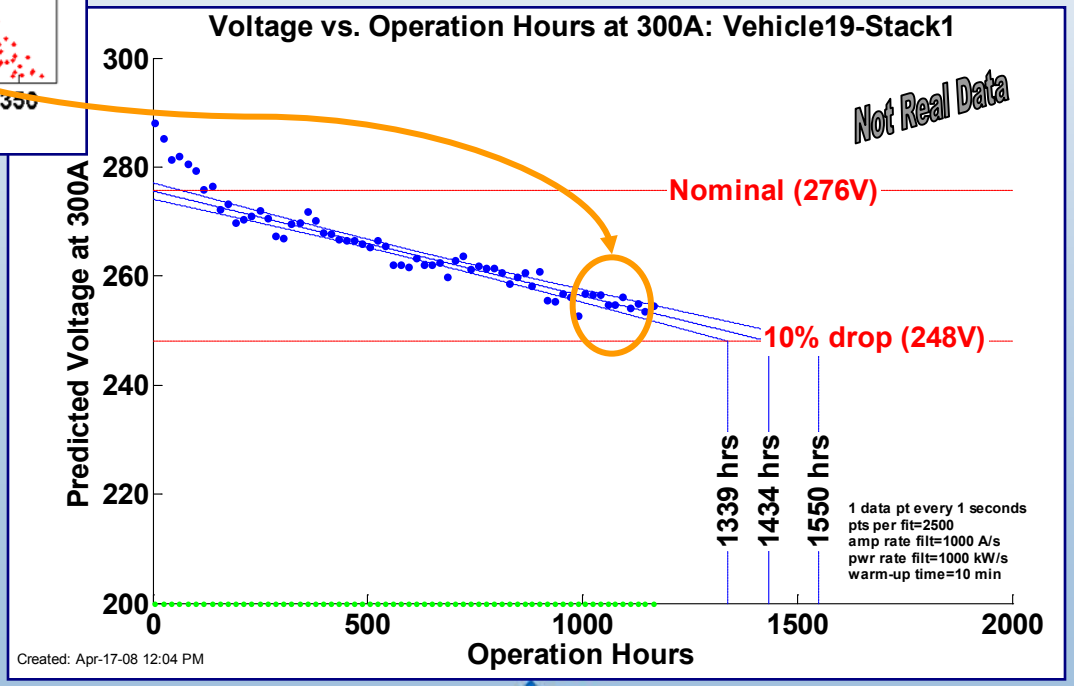


FC Stack Voltage Degradation Projection



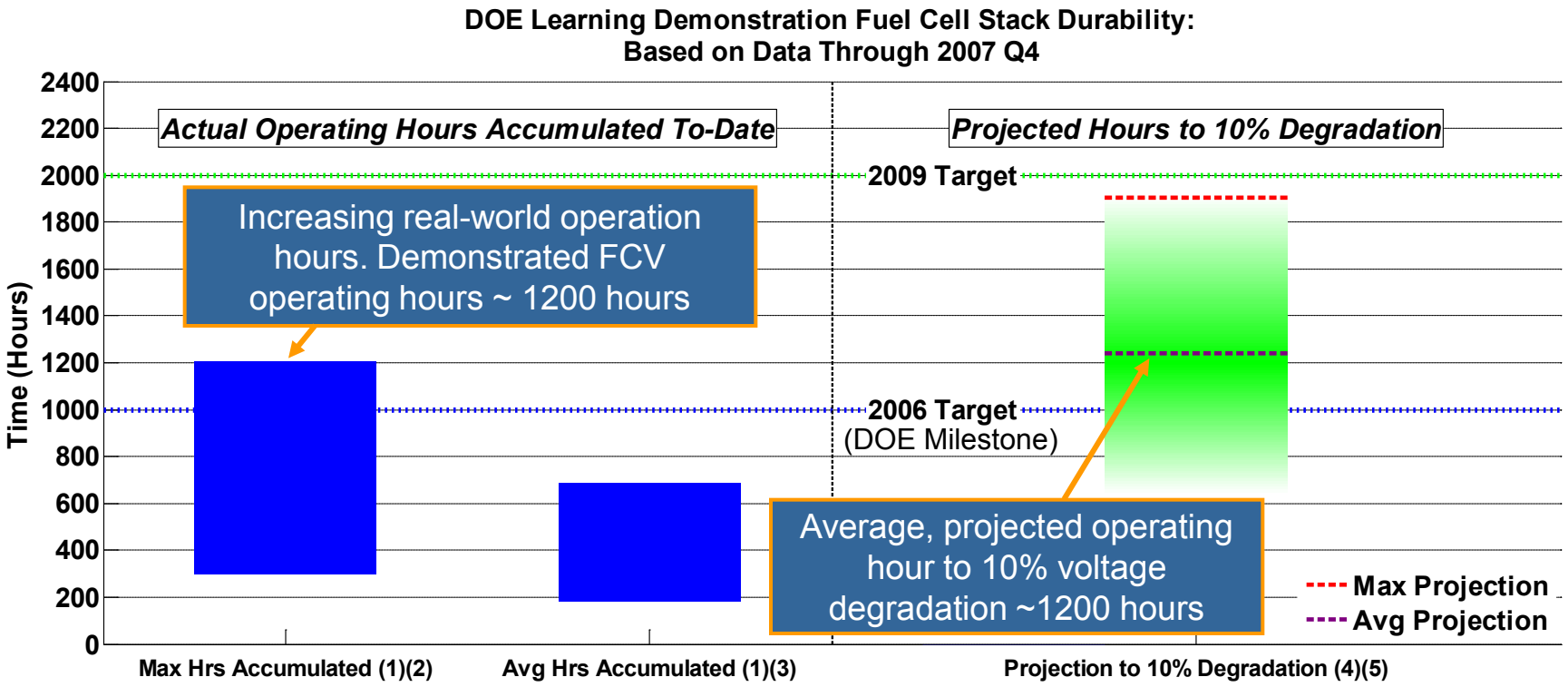
Note: a 10% decay in operating voltage is a DOE **benchmark**, ***not*** an indication of fuel cell end-of-life.

Decay rate =
slope of fit line



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

FC Stack Durability



(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.

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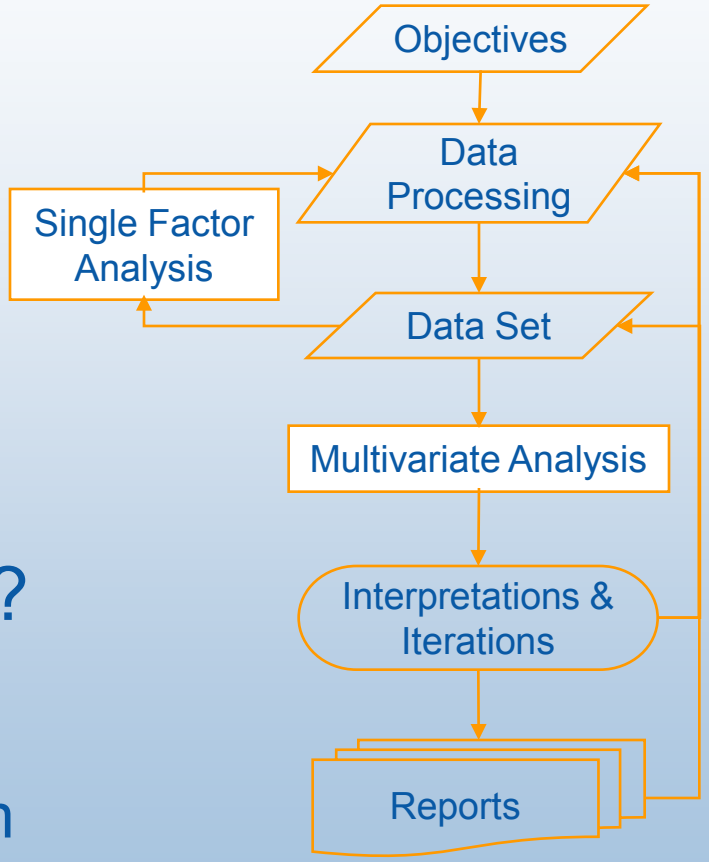
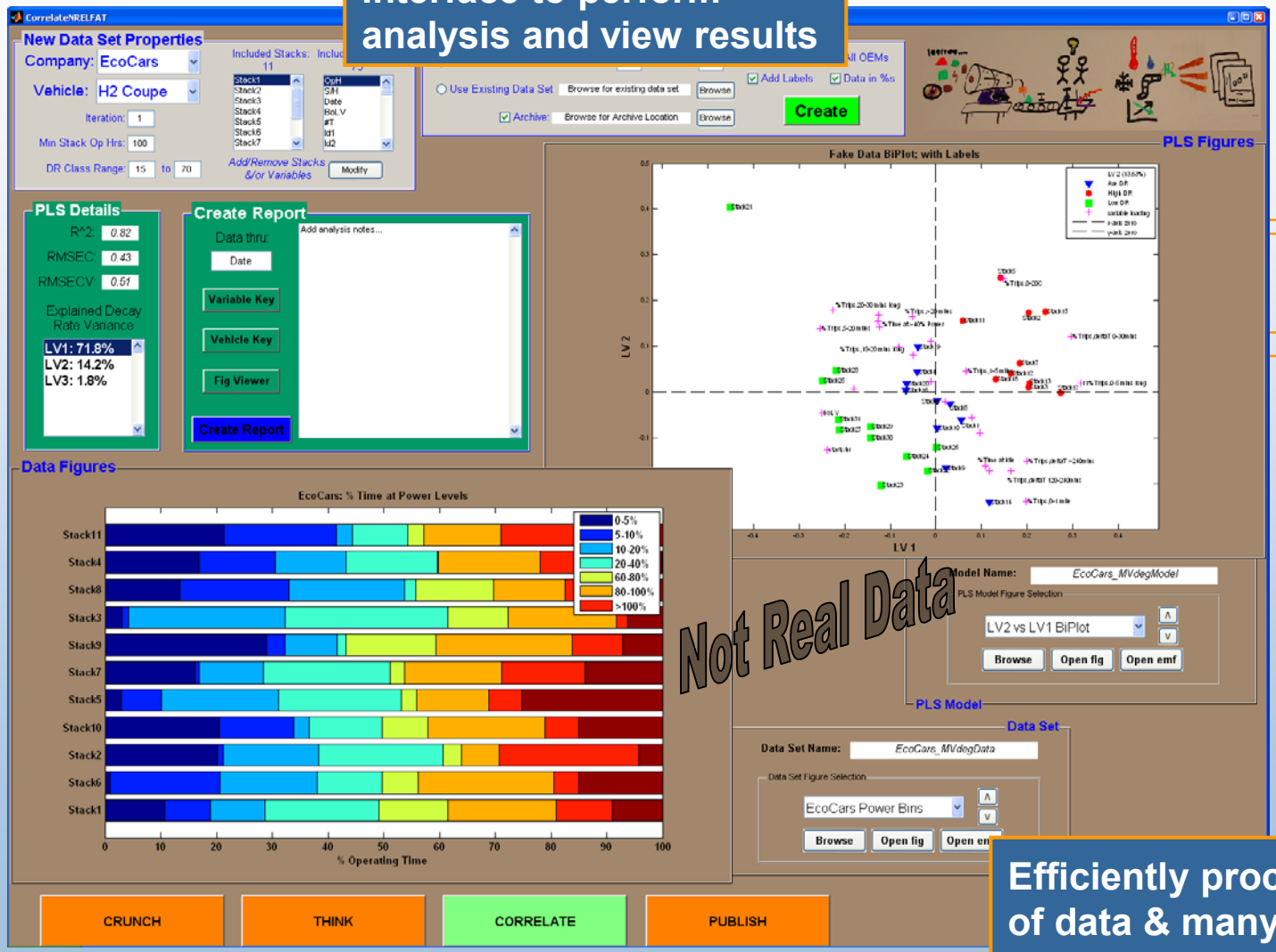
FC Degradation Multivariate Analysis

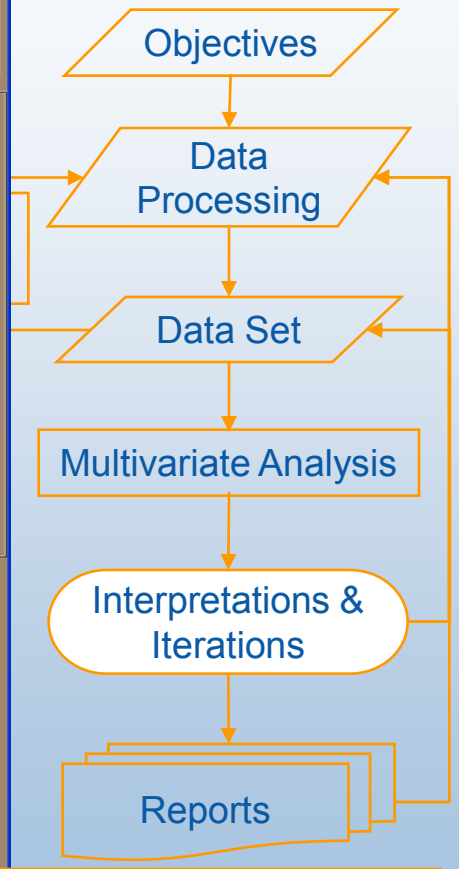
- Why multivariate analysis?
  - Dominant, single factors were not apparent in Single Factor analysis
  - Large data set
  - Data not collected in a controlled manor for a degradation study
  - Interrelated &/or redundant data variables (reduction of factors)
  - Likely a combination of factors
- Why Partial Least Squares (PLS)?
  - Linear regression model focused on FC decay rate
  - Model designed to explain maximum variance in decay rate



Correlate Interface

Interface to perform analysis and view results

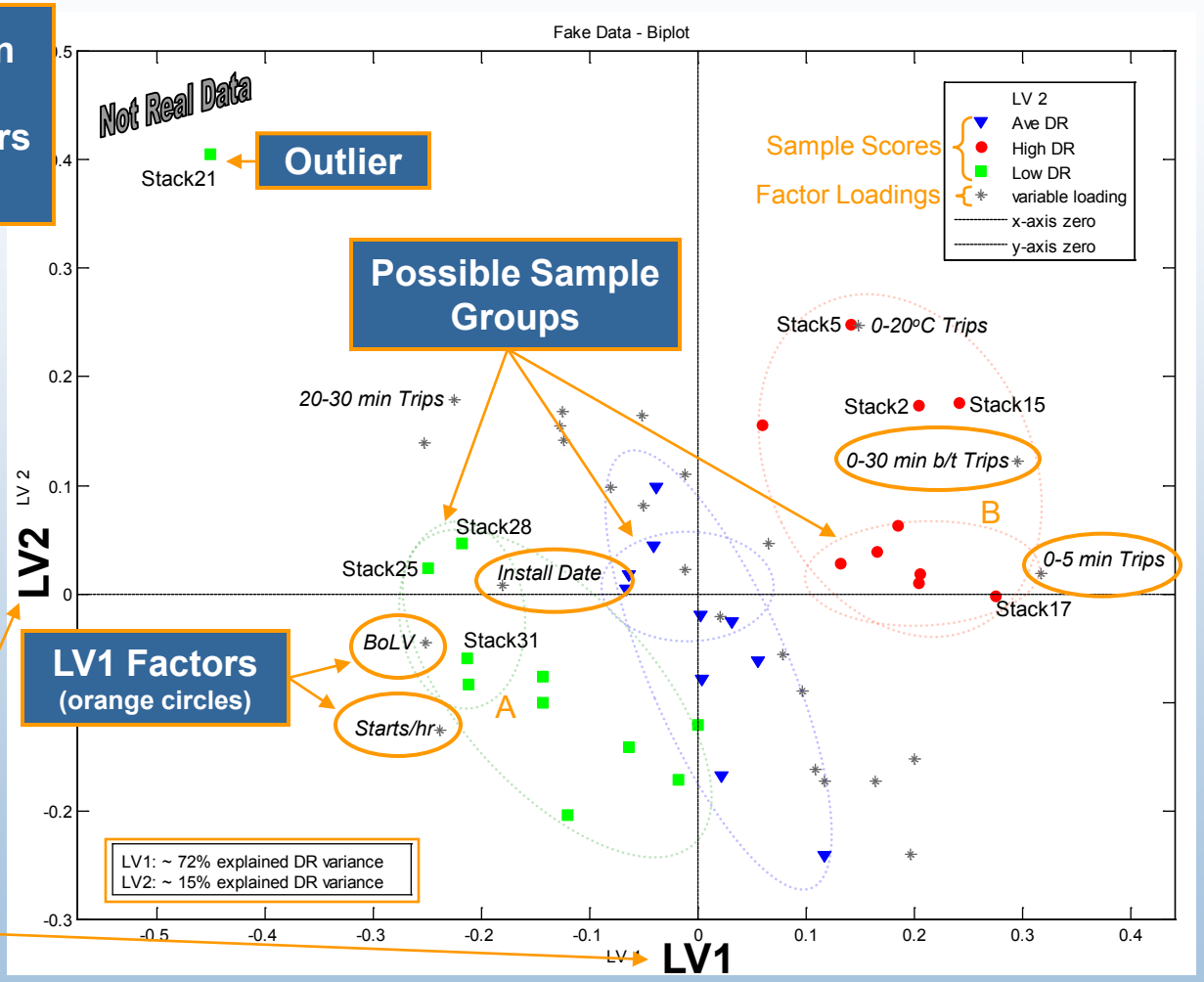




Efficiently process large amounts of data & many analysis iterations

What are the Correlations?
BiPlot Example

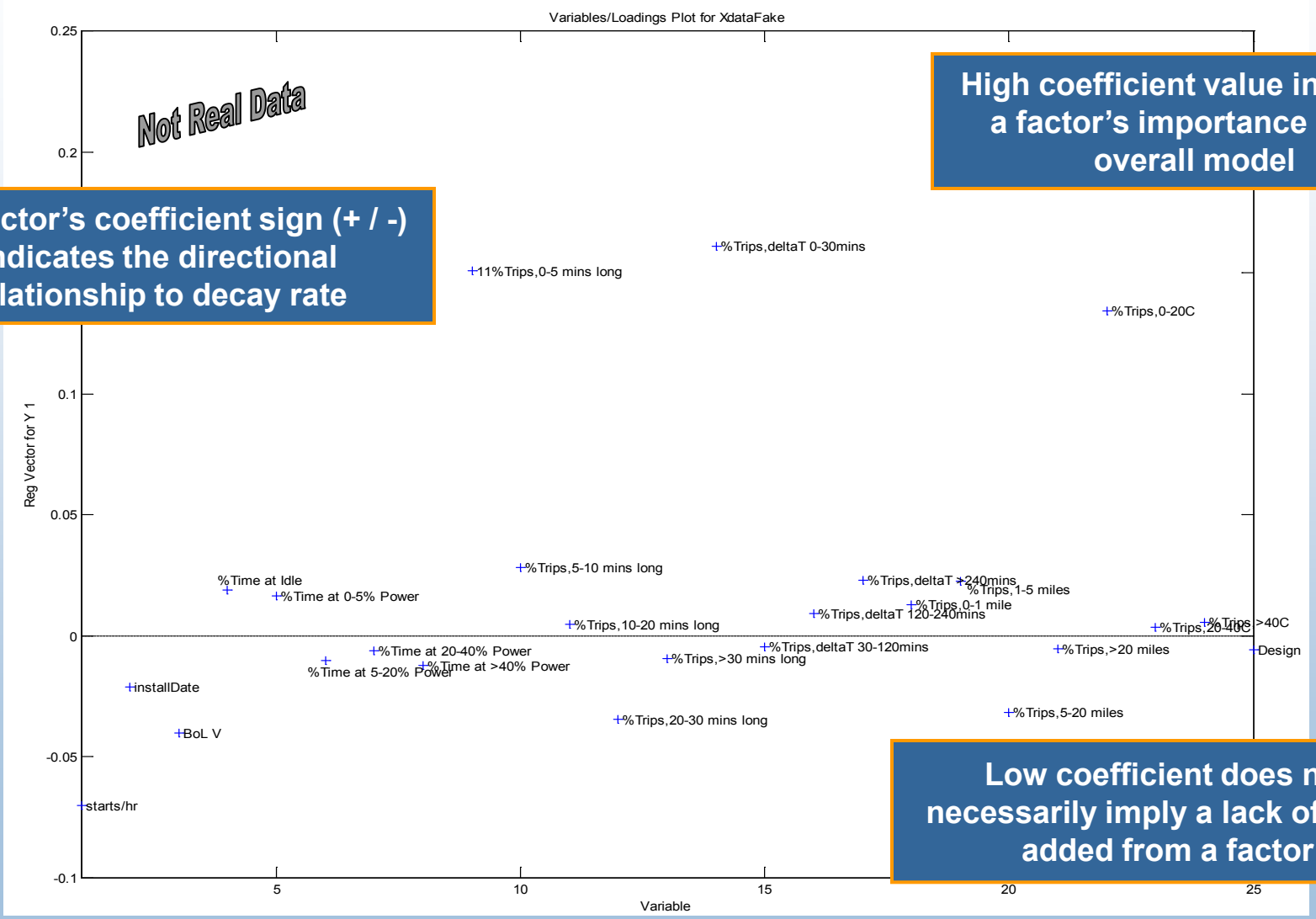
Goal: find tendencies within the decay rate groups that translate to decay rate factors and the factors' affects



Latent Variables: Combination of input factors that describe decay rate variance

Note: the data depicted here helps illustrate the process for the Learning Demonstration (LD) analyses. Ultimately, the goal is to identify factors of decay rate and what the affect is (positive or negative). In order to do this, tendencies within the low, average, and high decay rate classification need to apparent. The actual data is more scattered than the example shown here, thus making it more difficult to identify patterns, especially in the LD fleet analysis.

What Factors are Important to the Model?
Regression Vector Example

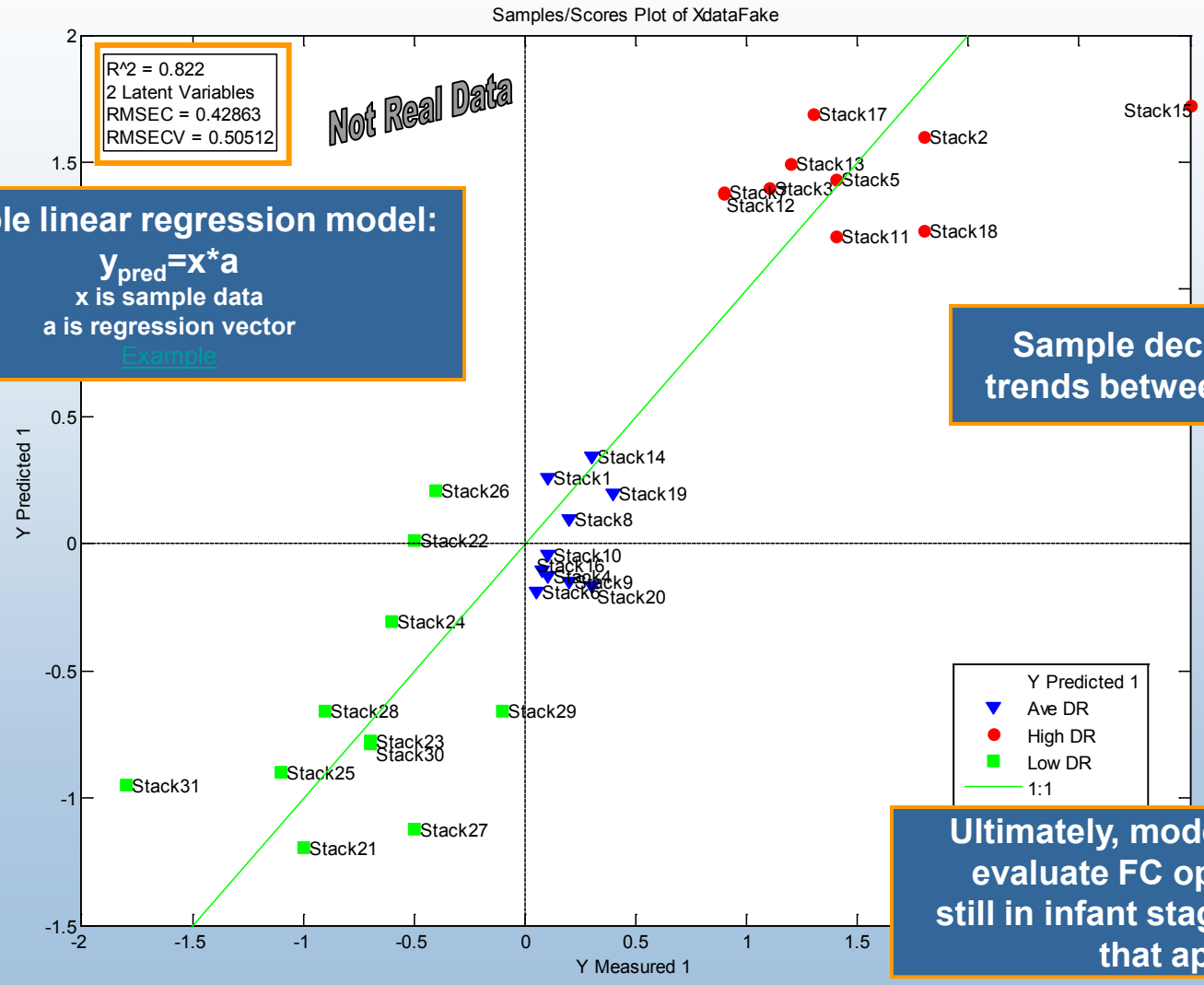


High coefficient value indicates a factor's importance in the overall model

The factor's coefficient sign (+ / -) indicates the directional relationship to decay rate

Low coefficient does not necessarily imply a lack of value added from a factor

How Good is the Model?
Predicted vs. Measured Example



Multiple linear regression model:

$y_{pred}=x*a$

x is sample data

a is regression vector

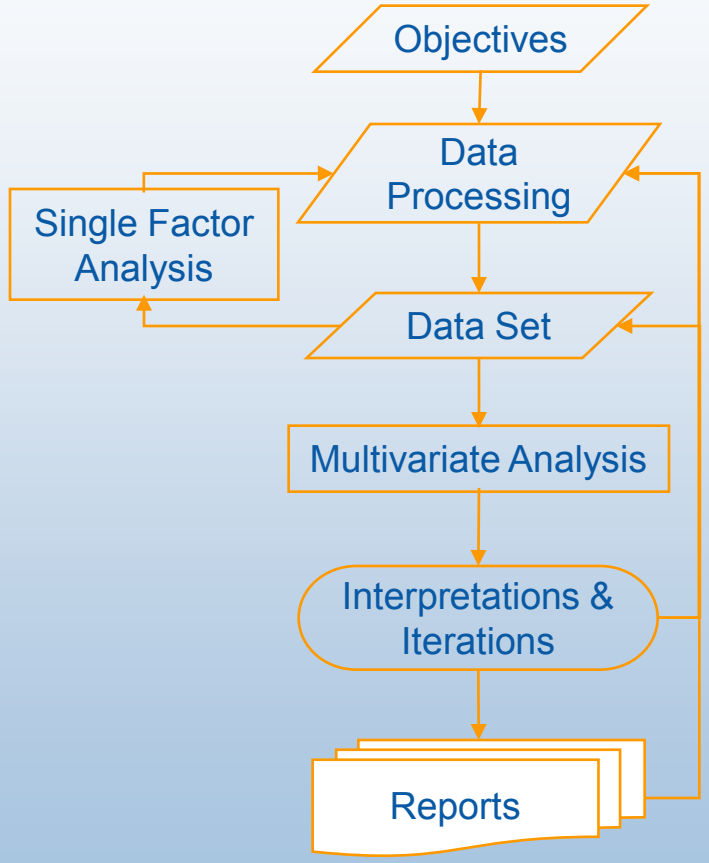
Example

Sample decay rate prediction & trends between decay rate classes

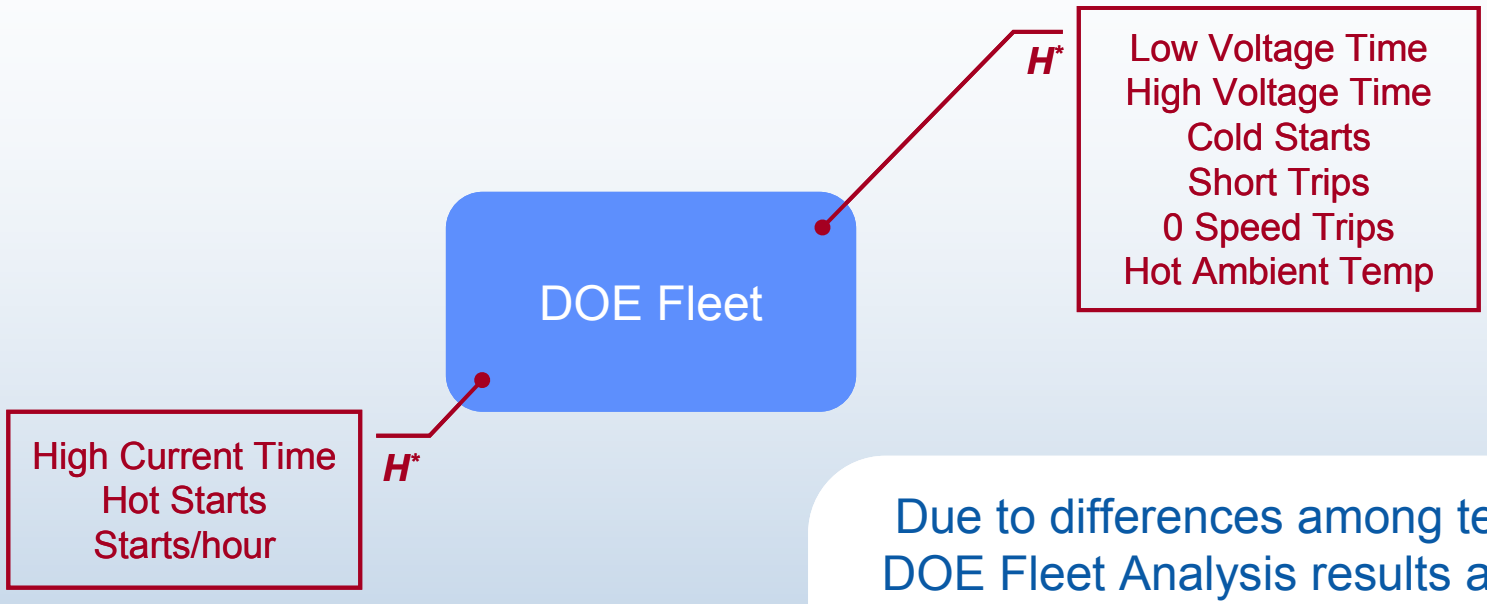
Ultimately, model could be used to evaluate FC operation changes; still in infant stage and not ready for that application.

Multivariate Analysis Results

- Public reporting through bi-annual composite data products and conferences
- Detailed reporting with project partners
- Collaboration with project partners is key



PLS Results - Learning Demonstration Degradation Factor Summary



Due to differences among teams, the DOE Fleet Analysis results are spread out and concrete conclusions are difficult to draw.

Individual team analyses (CDP#49) focused on patterns within a fleet.

1) On-going fuel cell degradation study using Partial Least Squares (PLS) regression model for combined Learning Demonstration Fleet.
2) DOE Fleet model has a low percentage of explained decay rate variance.

H*: Factor group associated with high decay rate fuel cell stacks
L**: Factor group associated with low decay rate fuel cell stacks

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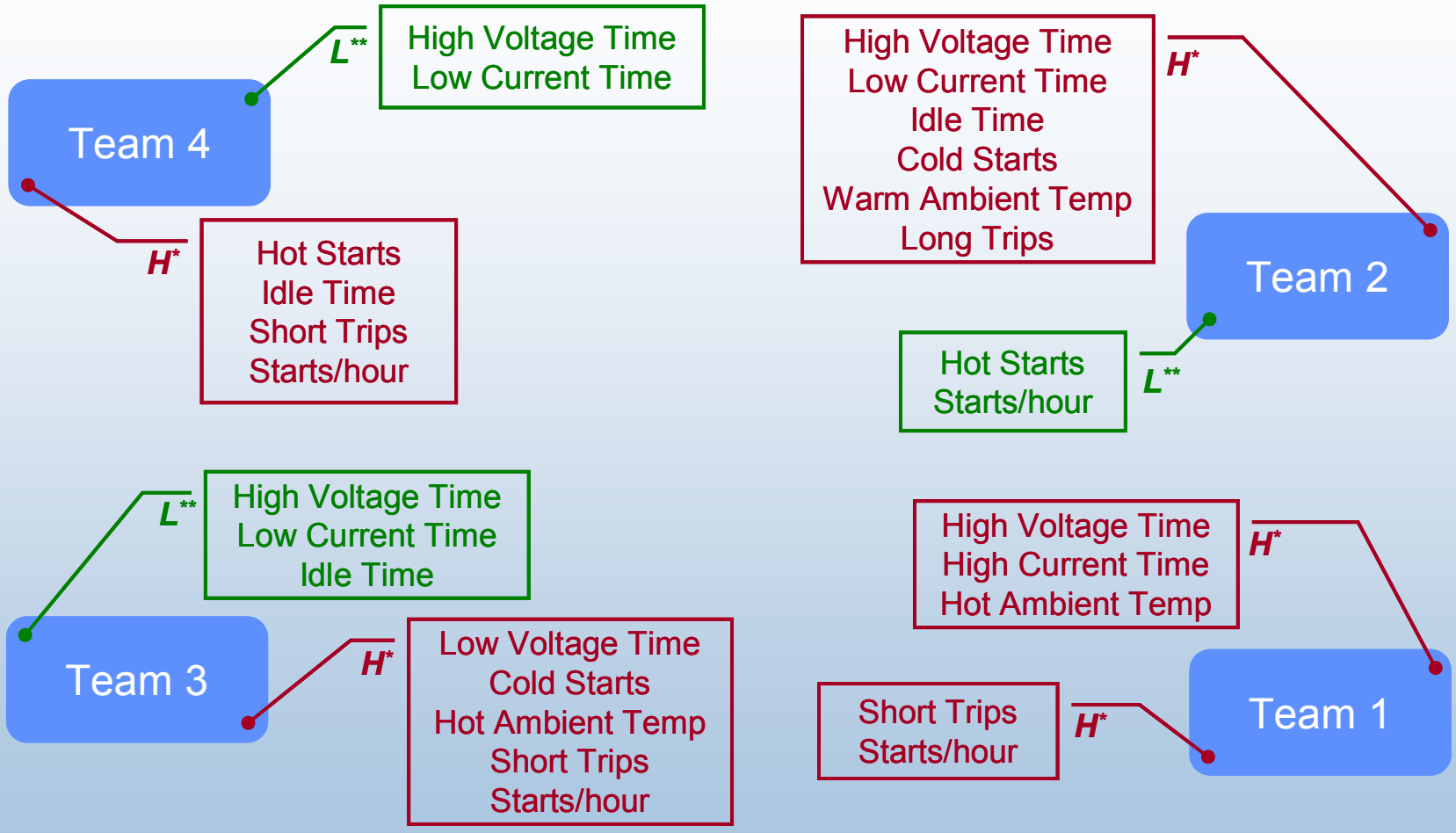
PLS Results – Identification of Factors Contributing to FC Degradation per Team



1) On-going fuel cell degradation study using Partial Least Squares (PLS) regression model for each team.
2) Teams' PLS models have a high percentage of explained decay rate variance, but the models are not robust and results are scattered.

H*: Factor group associated with high decay rate fuel cell stacks
L**: Factor group associated with low decay rate fuel cell stacks

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Summary

- FCV on-road data (92 vehicles)
- Different look than a lab study of degradation
- Analysis Learning
  - Decay rate classifications
  - Analysis iterations & adjustments to input factors & included samples
  - 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 have high R^2 values, but are not robust
  - Identification of trends difficult because of scattered sample data
  - Use DOE Fleet level analysis to compare difference between teams
- **Collaboration** with teams

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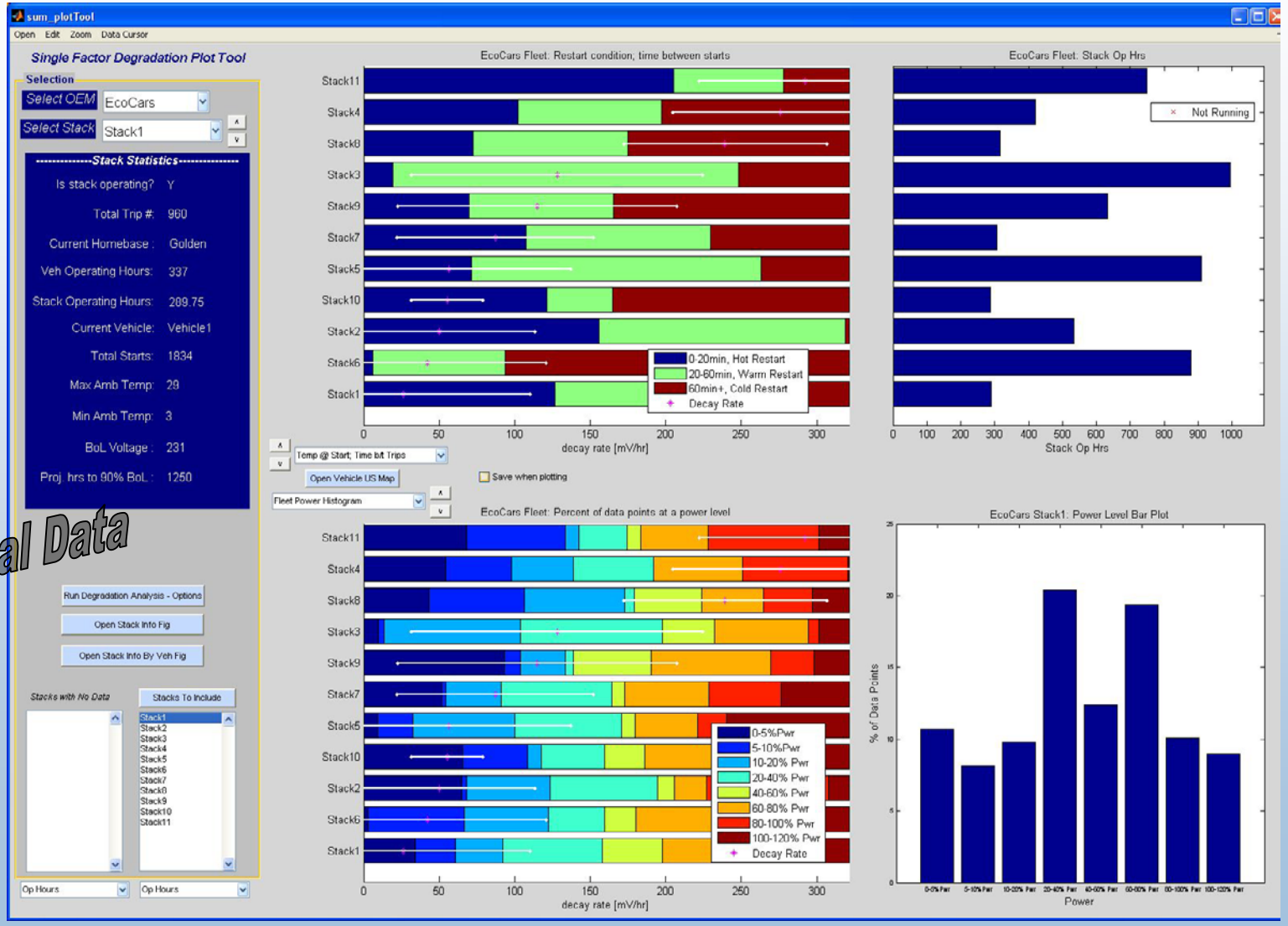
All public Learning Demo papers and presentations are available online at http://www.nrel.gov/hydrogen/proj_tech_validation.html

Single Factor GUI



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View the Learning Demonstration CDPs:

- By topic
- By date
- By CDP#

Composite Data Products by Topic

The public technical analysis results from DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project are generated in the form of composite data products (CDPs). The following CDPs, which are organized by topic, are offered in both PowerPoint and JPEG formats.

If these technical results are reproduced in your own documents or presentations, please provide appropriate reference to the U.S. Department of Energy's National Renewable Energy Laboratory.

Fuel Cell Stack Durability

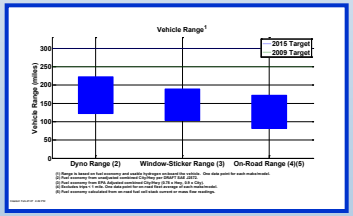
- Learning Demo Fuel Cell Stack Hours Accumulated, CDP #1A, 2/28/07 (PowerPoint 388 KB) (JPEG 89 KB)
- Projected Hours to 10% Stack Voltage Degradation, CDP #1B, 2/28/07 (PowerPoint 391 KB) (JPEG 155 KB)
- Fuel Cell Stack Hours Accumulated and Projected Hours to 10% Stack Voltage Degradation, CDP #1C, 2/28/07 (PowerPoint 392 KB) (JPEG 169 KB)

Fuel Cell Vehicle Range

- Fuel Cell Vehicle Range, CDP #2, 2/27/07 (PowerPoint 389 KB) (JPEG 121 KB)
- Effective Fuel Cell Vehicle Range, CDP #34, 2/26/07 (PowerPoint 389 KB) (JPEG 78 KB)
- Percentage of Theoretical Driving Range Between Refuelings, CDP #33, 2/26/07 (PowerPoint 392 KB) (JPEG 97 KB)

Fuel Cell Vehicle Fuel Economy and Stack Efficiency

- Fuel Cell Vehicle Fuel Economy, CDP #6, 2/27/07 (PowerPoint 388 KB) (JPEG 102 KB)
- Fuel Cell System Efficiency, CDP #8, 8/29/06 (PowerPoint 392 KB) (JPEG 97 KB)



Trusted sites

Equation Example

The model equation is:

$$y_{pred}=x*a+b,$$

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 -.3 …… .1 -.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
1		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'
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	1.9088
3	'Stack14'	'Ave DR'	0.3	0.9564	0.1621	-1.7865	1.1668	-0.3718	3.3533	-2.3877	-2.0153	1.5372	-0.5175	-0.946	-0.7902	-0.2794	0.6148	0.1669	0.6087	-0.0901
4	'Stack19'	'Ave DR'	0.4	-2.6699	1.8057	-0.0359	-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	1.1156	0.8852
6	'Stack16'	'Ave DR'	0.08	-1.8554	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	0.216	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	0.355	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	0.5559	-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	1.5551	-1.1299	-0.6303	-0.2813	3	-0.9433	1.3992	0.1117	0.8583	3	-0.6045	0.6944	-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	-0.8566	-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	-1.0083	0.333	0.9692	0.2446	3	-0.2315	0.7668	-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	0.9666	-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	-3.3098	-4.0173
23	'Stack22'	'Low DR'	-0.5	4	0.9	3.2	-1.1538	-1.3636	-1.3915	2.492	1.1191	2.2425	-0.0733	-1.6059	-2.0713	-0.8754	0.0138	-1.9133	0.5153	-0.2824
24	'Stack23'	'Low DR'	-0.7	8	1	3.3	0.1678	-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	-1.1478	-0.8106	-0.7513	1.065	1.0974	1.3586	-0.0588	-1.4506	-0.7715	-0.4371	0.8418	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	-0.4387	-1.2337	2.0068	2.2285	-1.2642	-1.3634	-0.8135	-2.0669	-1.9613
27	'Stack26'	'Low DR'	-0.4	4	0.9	3.3	2.3868	0.2159	-1.2385	-0.0499	0.5612	1.6762	0.0591	-1.2721	-1.3218	-0.8226	-0.8337	-1.27	0.1027	-0.0975
28	'Stack27'	'Low DR'	-0.5	8	0.8	3.4	1.0144	1.5754	-1.0684	-1.2042	-1.1699	-1.1214	-0.0688	0.0221	0.1769	1.4007	-1.0636	-0.029	-0.3601	0.1898
29	'Stack28'	'Low DR'	-0.9	6	1	3.2	-0.5118	-0.5713	0.2357	0.0855	0.9582	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	-1.4262	-0.4134	0.9107
31	'Stack30'	'Low DR'	-0.7	7	1	3.4	-0.9981	-1.4434	1.8432	0.8257	0.7211	-0.8587	2.3917	1.2358	0.6589	-0.7507	0.1136	0.6887	0.347	0.7259
32	'Stack31'	'Low DR'	-1.8	6	1	3.2	0.3995	0.8812	0.89	-1.1677	-1.2388	-1.176	-1.2937	0.1155	1.0806	1.4299	-0.1617	-0.4517	-0.1695	-0.4993