National Aeronautics and Space Administration

Application of Design of Experiments and Surrogate Modeling within the NASA Advanced Concepts Office, Earth-to-Orbit Design Process

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Outline

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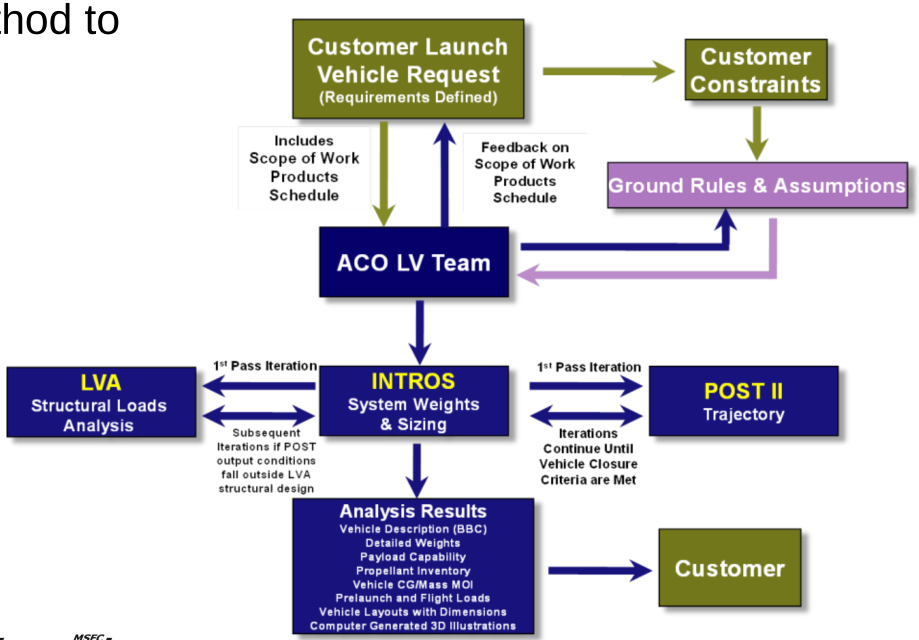
2. Current Design Process and Tools
3. Design Process Augmentation
4. Example Problem

Introduction

- Decisions made during early conceptual design can have a profound impact on life-cycle cost (LCC)
  - Widely accepted that nearly 80% of LCC is committed
  - Decisions made during early design must be well informed
- Advanced Concepts Office (ACO) at Marshall Space Flight Center aids in decision making for launch vehicles
  - Provides rapid turnaround pre-phase A and phase A studies
  - Provides customer with preliminary vehicle sizing information, vehicle feasibility, and expected performance

ACO Design Process and Tools

- ACO toolset consists of three primary tools for launch vehicle design
  - **INTegrated ROcket Sizing (INTROS):** Excel based tool utilizing MERs derived from historical vehicles to estimate system/sub-system masses
  - **Launch Vehicle Analysis (LVA):** Visual Basic tool for structural mass estimation using direct solution methods
  - **Program to Optimize Simulated Trajectories (POST):** Legacy code using direct shooting method to approximate the control function for an optimal trajectory



Design Process Augmentation

- Current design process is well suited for rapid turnaround trades that only require a handful of cases
- Analyst availability prohibitive for full design space exploration

Augmentation of current ACO process was desired in order to provide the customer with more information for decision making during early design

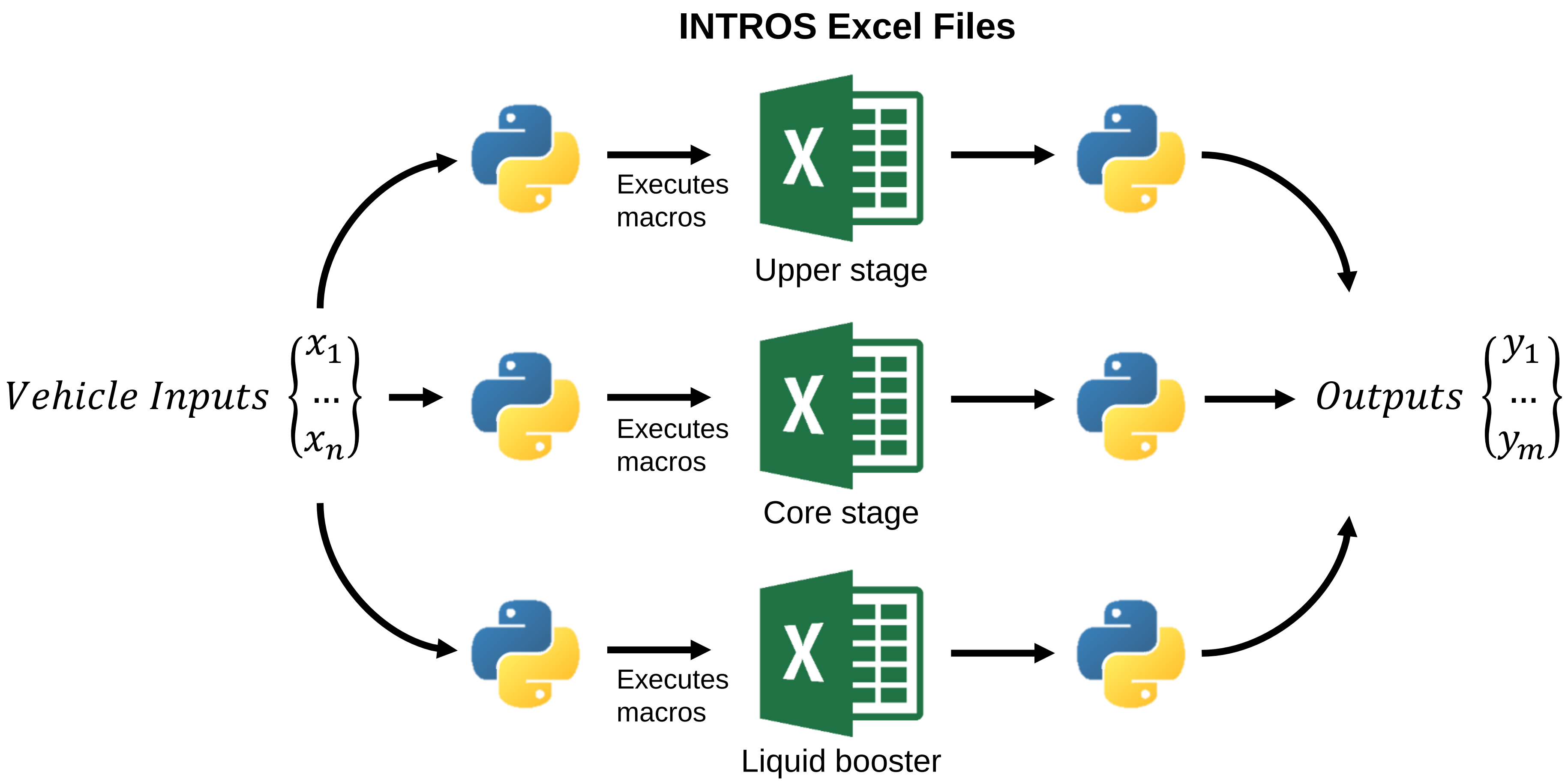
- Additional information includes:
  - Vehicle performance sensitivities
  - Broad vehicle architecture trades
  - Technology assessment

Providing such information requires large increase in case throughput!

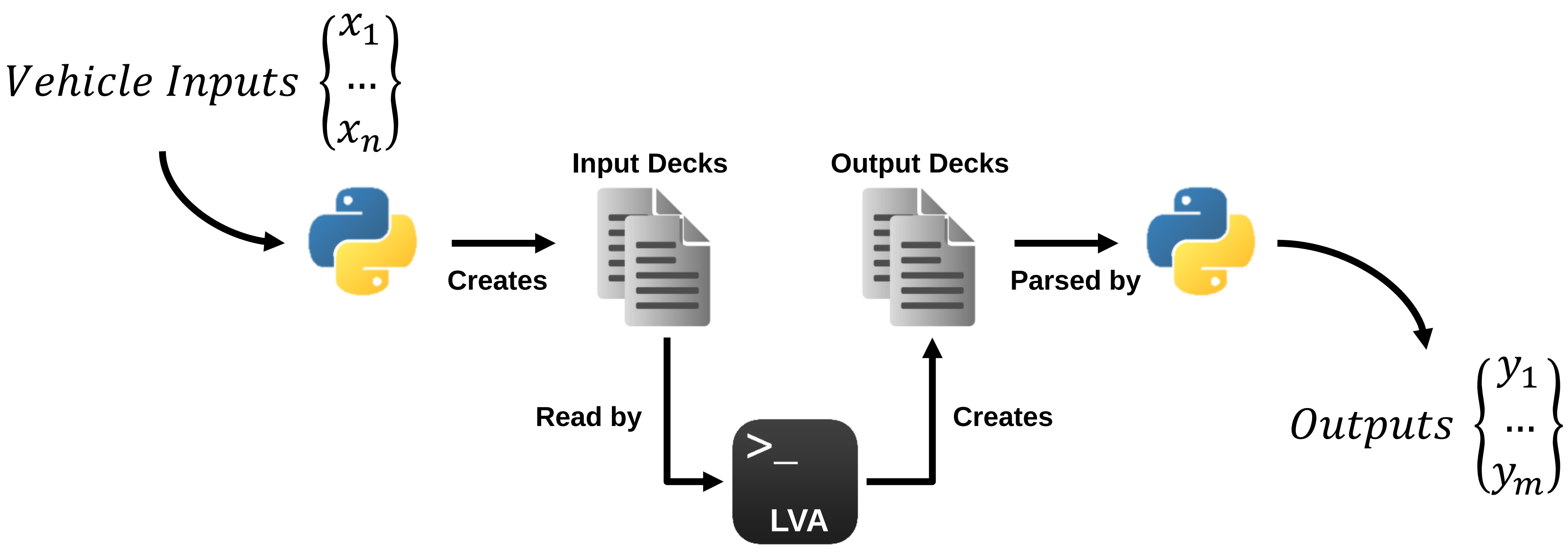
Design Process Augmentation

- Case throughput first improved via automation of design tools
  - All automation achieved using Python
  - INTROS and LVA integrated together
  - POST automated separately
- Tool automation ultimately enables execution of Design of Experiments (DOE) for the purpose of fitting surrogate models
- Surrogate models used to implement sensitivity analyses, trade space exploration, technology assessment, etc.

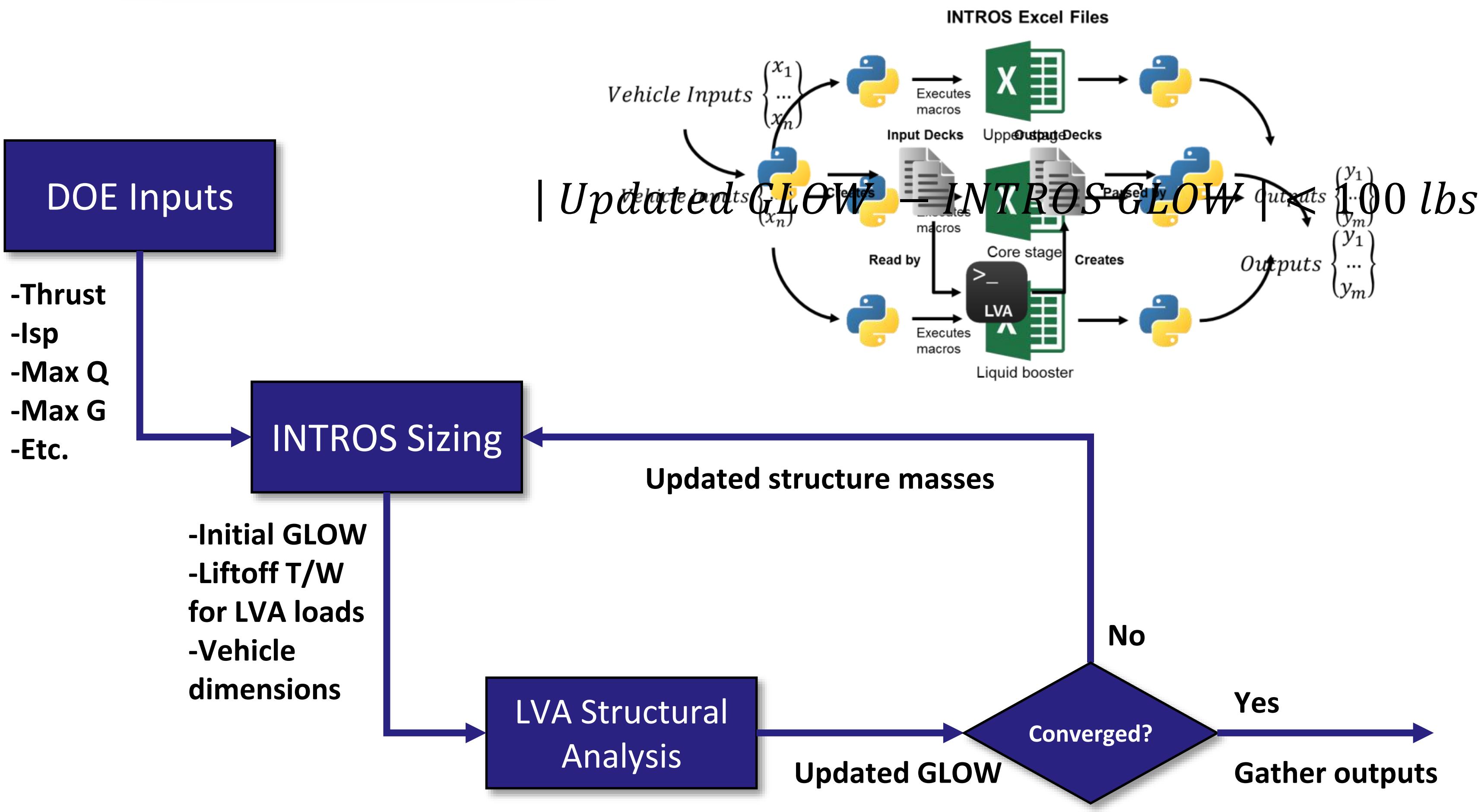
INTROS Automation



LVA Automation



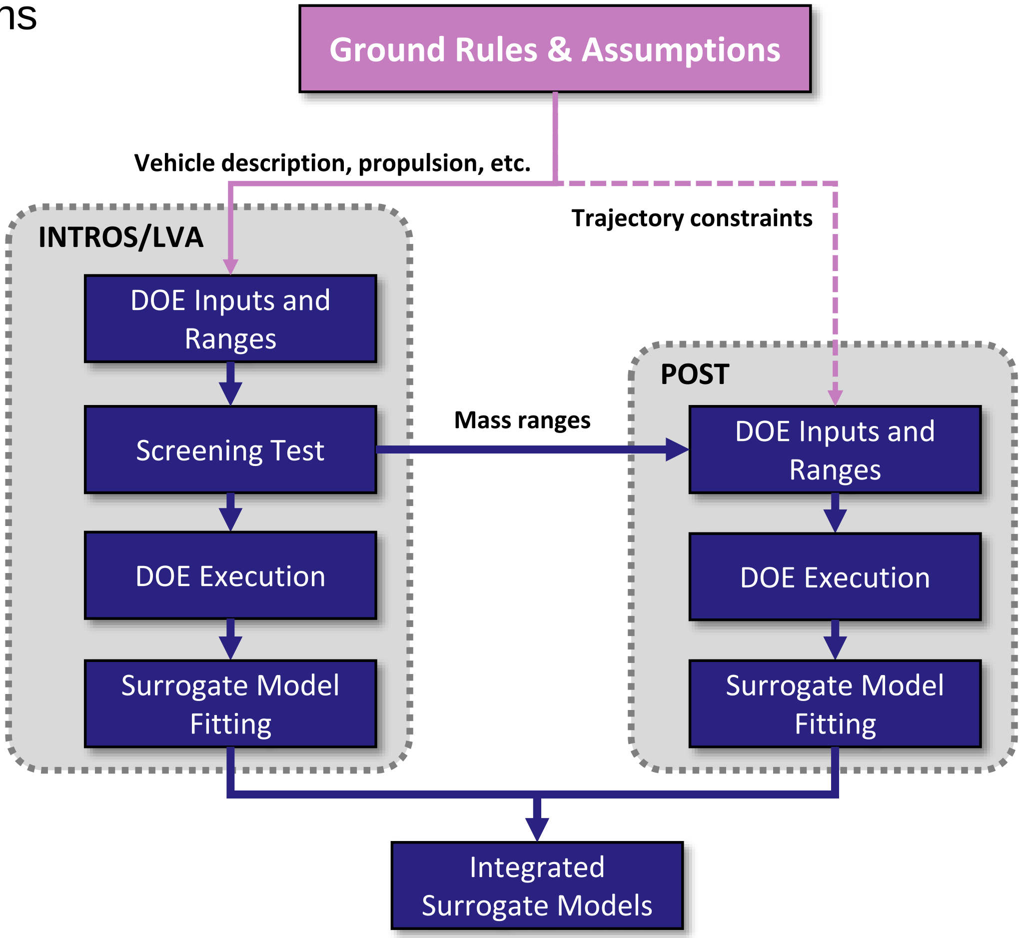
INTROS/LVA Integration



$$|\, Updated\ GLOW - INTROS\ GLOW \,| < 100\ lbs$$

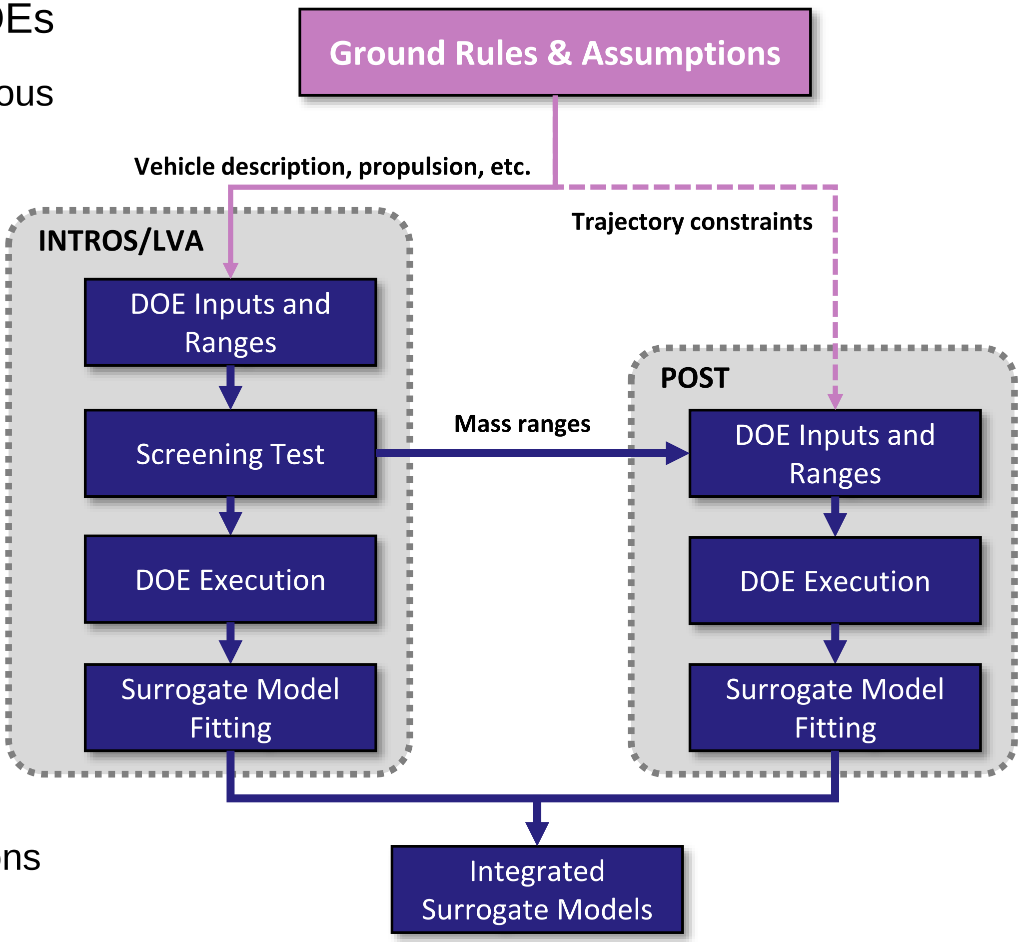
Automated Design Process

1. Develop ground rules and assumptions
   - Vehicle architecture
   - Customer requirements and constraints
   - Trades of interest
2. Develop INTROS/LVA DOE inputs and ranges
   - Identify desired DOE variables
   - Develop ranges to capture trades of interest
3. Run screening DOE to determine mass ranges for POST DOE
   - Matches INTROS/LVA mass output ranges with input ranges
   - Ensures proper integration of surrogate models



Automated Design Process

4. Execute INTROS/LVA and POST DOEs
   - Separation of tools allows for simultaneous execution
   - INTROS/LVA can complete 7,200 cases in 16 hours
   - POST can complete 2,500 cases in 2 hours
5. Fit surrogate models
   - Fit vehicle masses from INTROS/LVA
   - Fit payload mass delivered from POST
6. Integrate surrogate models
   - Connect surrogate models within JMP software
   - Perform analysis and create visualizations for delivery to customer



Example Problem: DOE

- Assume two-stage vehicle with solid boosters
- Trades will focus on design of upper stage
  - Propellant loading of the stage
  - Engine parameters
- Trades incorporated into INTROS/LVA DOE
- POST DOE includes vehicle masses from INTROS/LVA

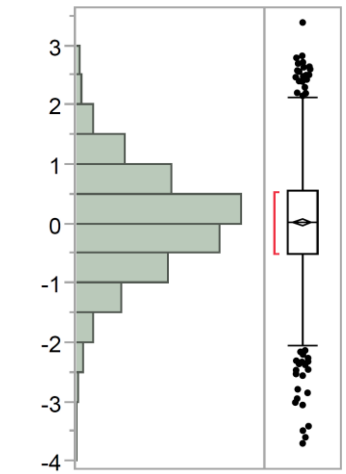
Variable	Range
Number of Engines	2, 3, 4, 5
Thrust per engine	20,000 – 65,000 lbf
Engine I_{sp}	440 – 470 sec.
OFR	5.4 – 6.0
LOX Tank cyl. length	3 – 12 ft
Max G	3 – 4
Max Q	540 – 700 psf

Variable	Range
Upper stage burnout mass	40,000 – 70,000 lbm
Upper stage prop. mass	205,000 – 375,000 lbm
Upper stage T/W	0.2 – 0.75
Upper stage I_{sp}	440 – 470 sec.
Upper stage total thrust	60,000 – 325,000 lbf
Core burnout mass	200,000 – 255,000 lbm
Destination (C_3)	-15 – 3 km^2/s^2
Max G	3 – 4
Max Q	540 – 700 psf

Example Problem: Surrogate Modeling

- Surrogate model fitting performed in JMP
  - Response surface equations (RSE)
  - Stepwise regression
- Goodness-of-fit testing
  - Residual-by-predicted and actual-by-predicted plots
  - R^2 and Root Mean Squared Error (RMSE)
  - Percent error distribution

$$R = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \beta_{ij} x_i x_j + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \varepsilon$$

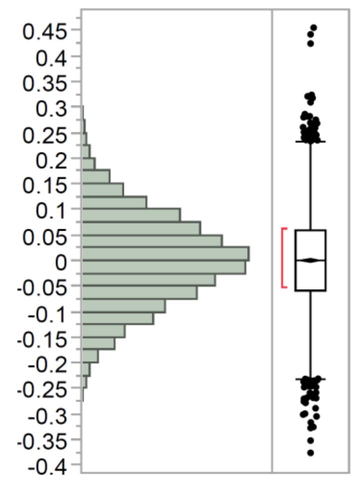


Quantiles

100.0%	maximum	3.38201
99.5%		2.63735
97.5%		1.85738
90.0%		1.11502
75.0%	quartile	0.53921
50.0%	median	0.02761
25.0%	quartile	-0.5159
10.0%		-1.1209
2.5%		-1.9034
0.5%		-3.0157
0.0%	minimum	-3.7073

Summary Statistics

Mean	0.008635
Std Dev	0.920398
Std Err Mean	0.0265034
Upper 95% Mean	0.0606329
Lower 95% Mean	-0.043363
N	1206



Quantiles

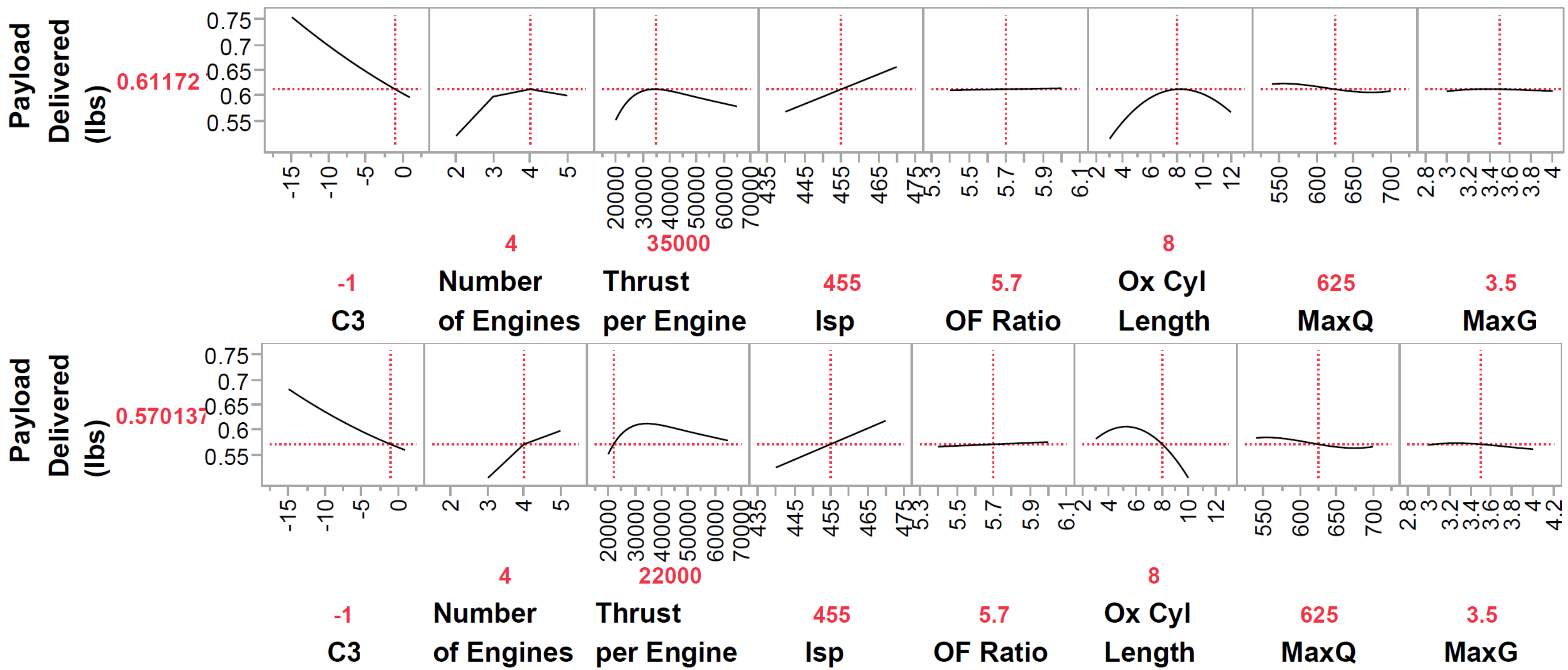
100.0%	maximum	0.45518
99.5%		0.24184
97.5%		0.17308
90.0%		0.10962
75.0%	quartile	0.05851
50.0%	median	0.00097
25.0%	quartile	-0.0575
10.0%		-0.1139
2.5%		-0.1743
0.5%		-0.2314
0.0%	minimum	-0.3766

Summary Statistics

Mean	0.0000742
Std Dev	0.0887955
Std Err Mean	0.0010465
Upper 95% Mean	0.0021256
Lower 95% Mean	-0.001977
N	7200

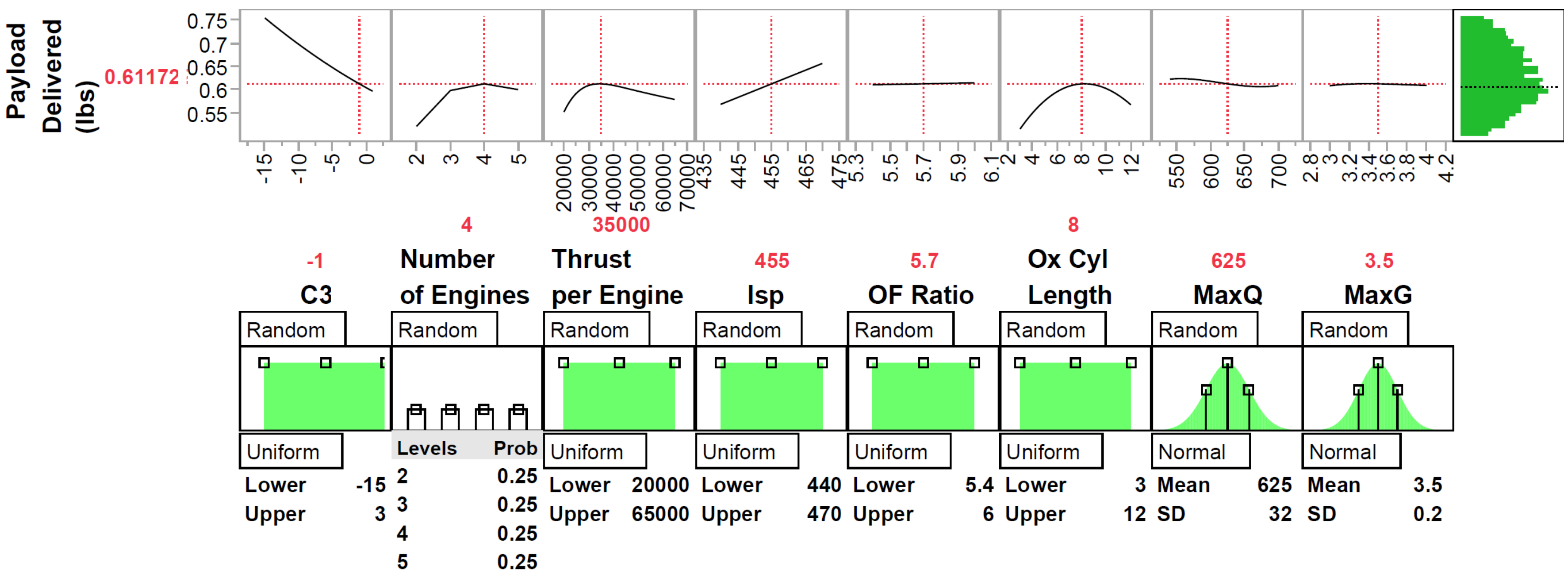
Results

- POST and INTROS/LVA surrogates are combined within JMP
- JMP “Profiler” is used as a standard visualization of the integrated surrogate models



Results

- Profiler also provides capability to perform Monte Carlo simulation, which can enable:
  - Inverse design
  - Probabilistic design
  - Risk assessment
  - Technology assessment



Conclusions

- ACO launch vehicle design process successfully augmented
  - Automated design tools to improve case throughput
  - Integrated INTROS and LVA tools
  - Developed process for application of DOE and surrogate modeling to enable trade space exploration

Automated process can ultimately be used to provide customer with vast amount of information for use in decision making during early conceptual design

Questions?