A Parametric Geometry Computational Fluid Dynamics (CFD) Study Utilizing Design of Experiments (DOE)
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Outline

- Introduction
- Experimental Design Development
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Introduction

- NASA's Explorations Systems Mission Directorate (ESMD) is tasked with designing and developing the system of vehicles to fulfill the new space architecture
  - The first vehicle in the architecture is the Ares I Crew Launch Vehicle (CLV), which will be used to launch astronauts to low earth orbit.

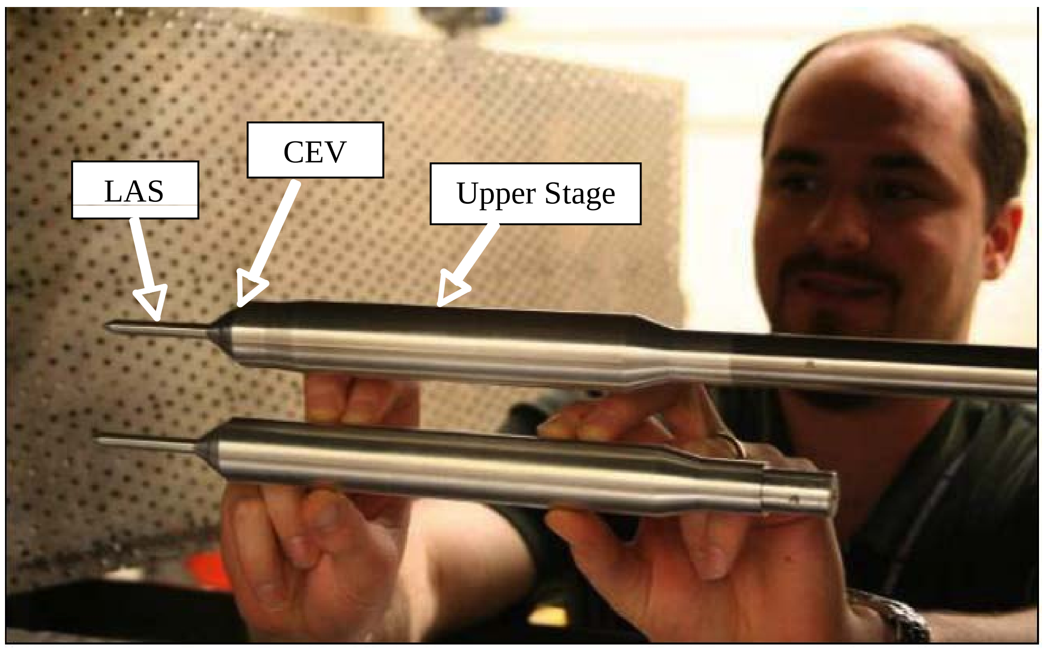


Figure 1. 0.548%-scale DAC-0 Wind Tunnel Model

LAS: Launch Abort System

CEV: Crew Exploration Vehicle

Introduction (cont'd)

- The Aerodynamics Panel is one organization element within the Ares I CLV program
  - responsible for assuring that the aerodynamic design satisfies the Ares I CLV requirements
  - Accomplishes this through combination of wind tunnel experiments and CFD analysis
  - One of the objectives of the CFD analysis is to provide a rapid assessment of possible outer mold line (OML) design changes.
- Preliminary wind tunnel testing of this configuration revealed potential aerodynamic improvement during the ascent phase of the LAS
- Therefore, a study was undertaken to understand this potential improvement using CFD and wind tunnel testing
  - The first phase of the study is with CFD
- The Aero Team identified a possible set of 1,566 combinations to study
  - Requested to utilize a DOE approach to efficiently answer the study questions and objectives

Experimental Design Development

- Utilized a "Design Guide Sheet" to gather appropriate information required to design an effective experiment (information obtained from subject matter experts (SME) in CFD, experimental aerodynamics and the CLV team)
  1. Objectives: *unbiased, specific and measurable and consequences/risks of results*
     - Using CFD, identify the important (and unimportant) LAS parameters (factors) that influence the integrated drag (response)
     - Quantify the relative magnitude of the factor effects and rank-order them in terms of their contribution to the integrated drag
     - Consequences: Guide future wind tunnel testing and CFD
     - Risks: A poorly designed experiment could cause inefficient use of CFD resources, too many or not enough wind tunnel experiments to answer the research questions, and ultimately poor drag performance of the vehicle in flight.
  2. Relevant Background: *previous data that may impact the design*
     - Previous wind tunnel results indicated LAS caused significant drag impact

Reference: Coleman, D.E. and Montgomery, D.C. (1993), "A Systematic Approach to Planning for a Designed Industrial Experiment," (with Discussion), Technometrics, Vol. 35, pp. 1-27.

Experimental Design Development

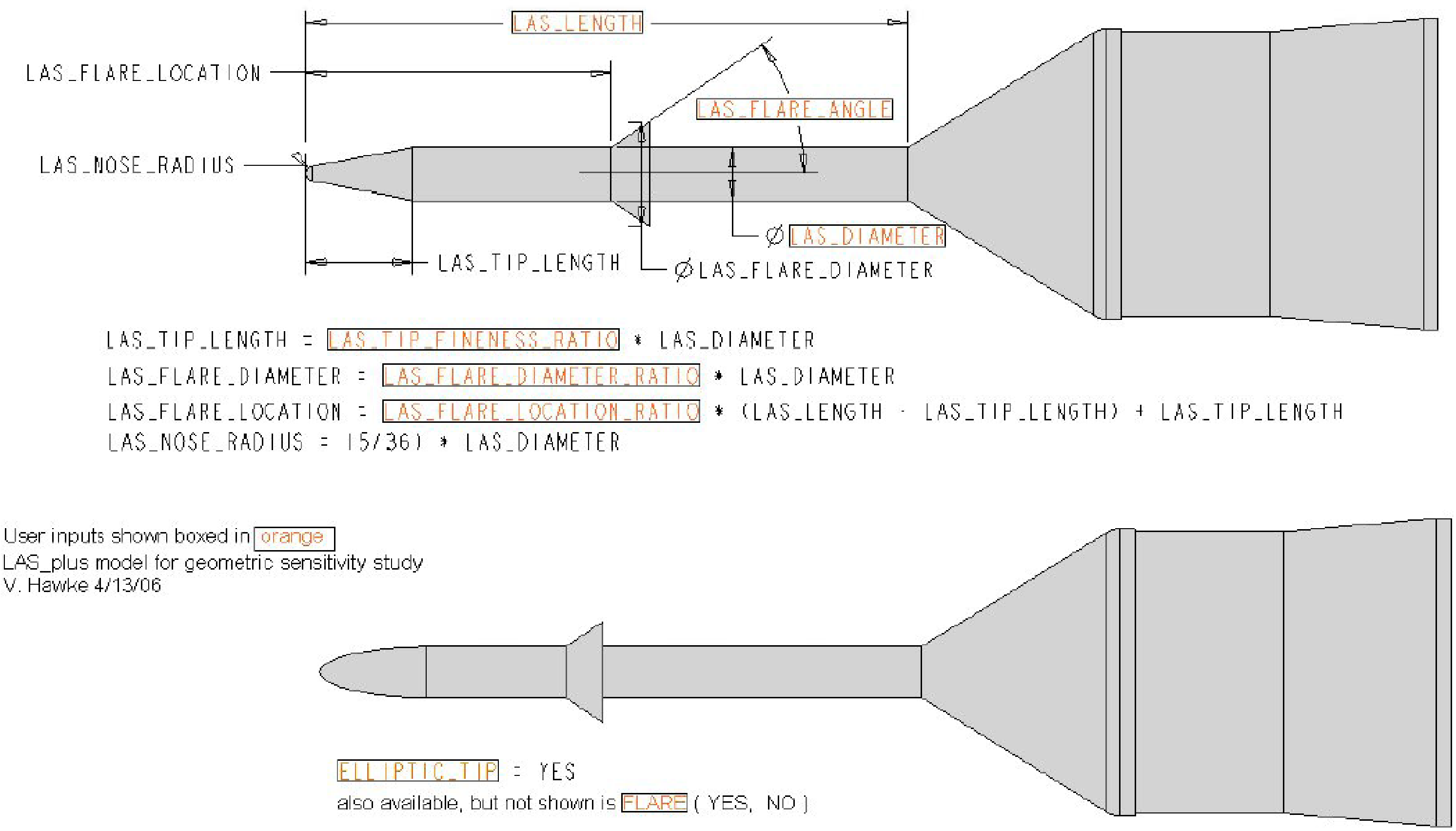
3. Response Variables, Measure of Performance: *Identify response variables, variables that are indicators of the performance of the system under investigation, and the methods of measuring them.*

Variable (abbrev.)	**Units**	**Range Low**	**Range High**	**Precision (source)**	**Priority (1 high)**	**Type (c, d)**	**Source**
Int_Drag (Integrated Drag)				computational, deterministic	1	continuous	CFD combined with trajectory

- Integrated Drag Coefficient: weighted sum of coefficients from 10 different pre-defined Mach numbers (0.7, 0.9, 0.95, 1.05, 1.1, 1.3, 1.46, 1.96, 2.74, and 4.0) based on dynamic pressure and time

Experimental Design Development

4. Factors, Control Variables: *measurable, controllable, and thought to be influential*



Experimental Design Development

Label	Factor (abbrev.)	Units	Range Low	Range High	Type	Restrictions
A	TowerLen (Tower Length)	inches	326	490	Continuous	
B	TowerDia (Tower Diameter)	inches	26	46	Continuous	
C	TipFineRatio (Tip Finess Ratio)	l/d ratio	0.5	2	Continuous	
D	FlareDiaRatio (Flare Diameter Ratio)	% of TowDia	1.5	2.5	Continuous	
E	FlareAngle	deg	25	45	Continuous	
F	FlareLoc (Flare Location)	ht/TowLen	0.4	0.8	Continuous	
G	TipShape		ellipse	sphere/cone	categorical	2 levels

Experimental Design Development

5. Factors to be held constant: *factors that are controllable, and whose effects are not of interest in this experiment*

Factor (abbrev.)	Units	Range Low	Range High	Comments
Re				Flight Reynolds number will be used in this investigation. Two other levels reflecting wind tunnel testing may be considered as a follow-up.
CFD code				A single CFD code (Overflow) will be used by the effort.
Axes-Sym Geometry				The CFD model will be axes-sym (angle-of-attack = 0 degrees)

6. Nuisance Factors: *factors are not controlled and are not of primary interest*

Factor (abbrev.)	Units	Range Low	Range High	Comments
CFD solution error				Numerical error in the CFD solutions has been considered negligible and will not be estimated. No replicates will be performed.

Experimental Design Development

7. Interactions: *Any prior knowledge of the effect of one factor being dependent on the level of another is important to ensuring it is captured in the design*
    - None identified with prior testing/analysis
    - Important to capture if they exist

8. Restrictions: *Examples of restrictions are time, number of experimental units, hard-to-change (HTC) factors*
    - Minimize number of geometries due to time associated with generating new models

9. Design Preferences: *any particular preferences on the statistical design*
    - Two level designs with center points are desirable based on the objectives

10. Analysis and Presentation Techniques Preferred: *very important to ensure the results are conveyed in a manner consistent with the SME practices*
    - Rank ordering of factor effects, with their relative contributions
    - Identify factor combinations that provided the *best* (minimum) integrated drag

Experimental Design Development

11. Trial Runs: *Can or should trial runs be conducted? Usually recommended when little prior knowledge is available*
    - No trial runs recommended based on timeframe and previous experience with the CFD code

Experiment Designs

- **Response:** Integrated Drag over the range of Mach numbers (0.7 to 4.0)

- **No Flare Configuration, 4-Factors**
  - **Full Factorial**, all possible combinations at two-levels
  - **Full Resolution**, allows for the estimation of:
    - Main Effects, Two-, Three-, and Four-factor Interactions
  - **Orthogonal** in factorial portion (without center points)
    - allows for unique estimation of model parameters
  - **Curvature** is detected with center points
  - Total of 16 + 2 = **18 configurations**, analyzed 10 Mach numbers

$$2^4$$

- **Flared Configuration, 7-Factors**
  - **1/2 Fraction** of all possible factorial combinations
  - **Resolution VII**, allows for estimation of:
    - Main Effects, Two- and Three-Factor Interactions
  - **Orthogonal** design, **Curvature** detection
  - Total of 64 + 2 = **66 configurations**, analyzed 10 Mach numbers

$$2_{VII}^{7-1}$$

Experiment Designs

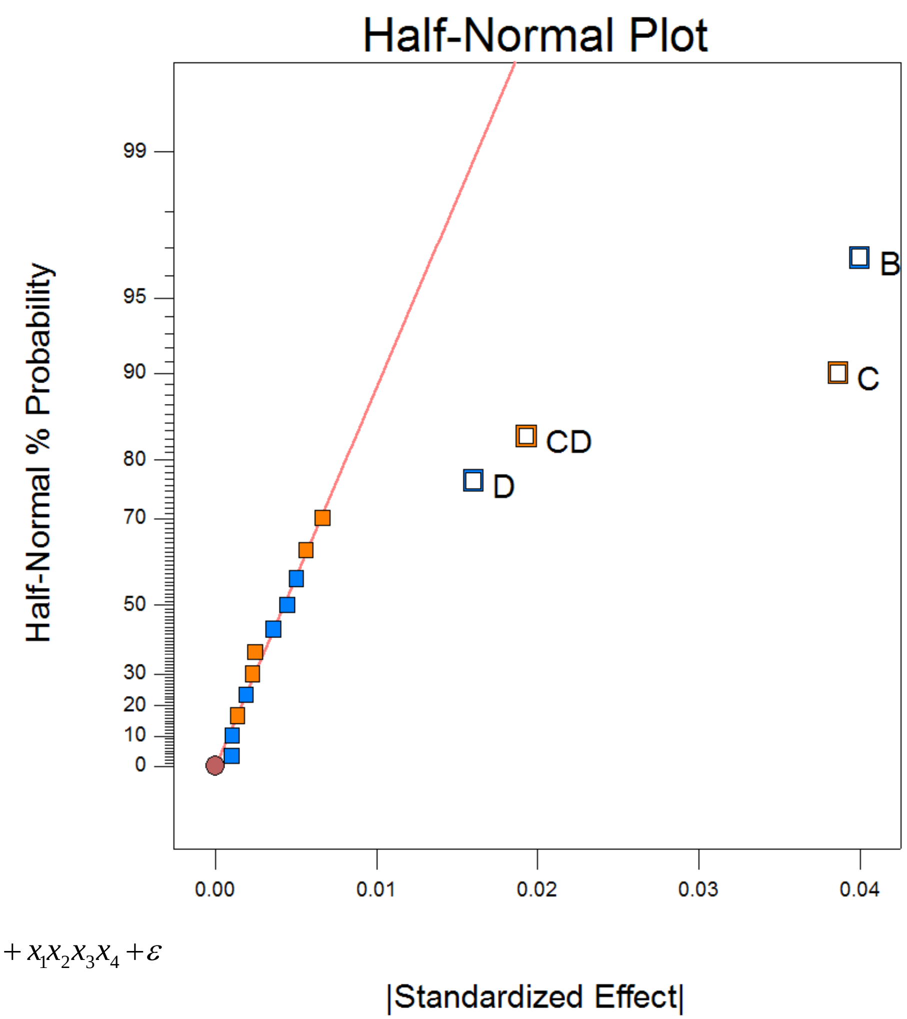
		Factor 1	Factor 2	Factor 3	Factor 4
Std	Point	A:TowerLen	B:TowerDia	C:TipFineRatio	D:TipShape
Order	Type	inches	inches	l/d ratio	
1	Fact	326	26	0.5	ellipse
2	Fact	490	26	0.5	ellipse
3	Fact	326	46	0.5	ellipse
4	Fact	490	46	0.5	ellipse
5	Fact	326	26	2	ellipse
6	Fact	490	26	2	ellipse
7	Fact	326	46	2	ellipse
8	Fact	490	46	2	ellipse
9	Fact	326	26	0.5	sphere/cone
10	Fact	490	26	0.5	sphere/cone
11	Fact	326	46	0.5	sphere/cone
12	Fact	490	46	0.5	sphere/cone
13	Fact	326	26	2	sphere/cone
14	Fact	490	26	2	sphere/cone
15	Fact	326	46	2	sphere/cone
16	Fact	490	46	2	sphere/cone
17	Center	408	36	1.25	ellipse
18	Center	408	36	1.25	sphere/cone

Four-Factor Experiment Design without Flare

Mathematical Model Building

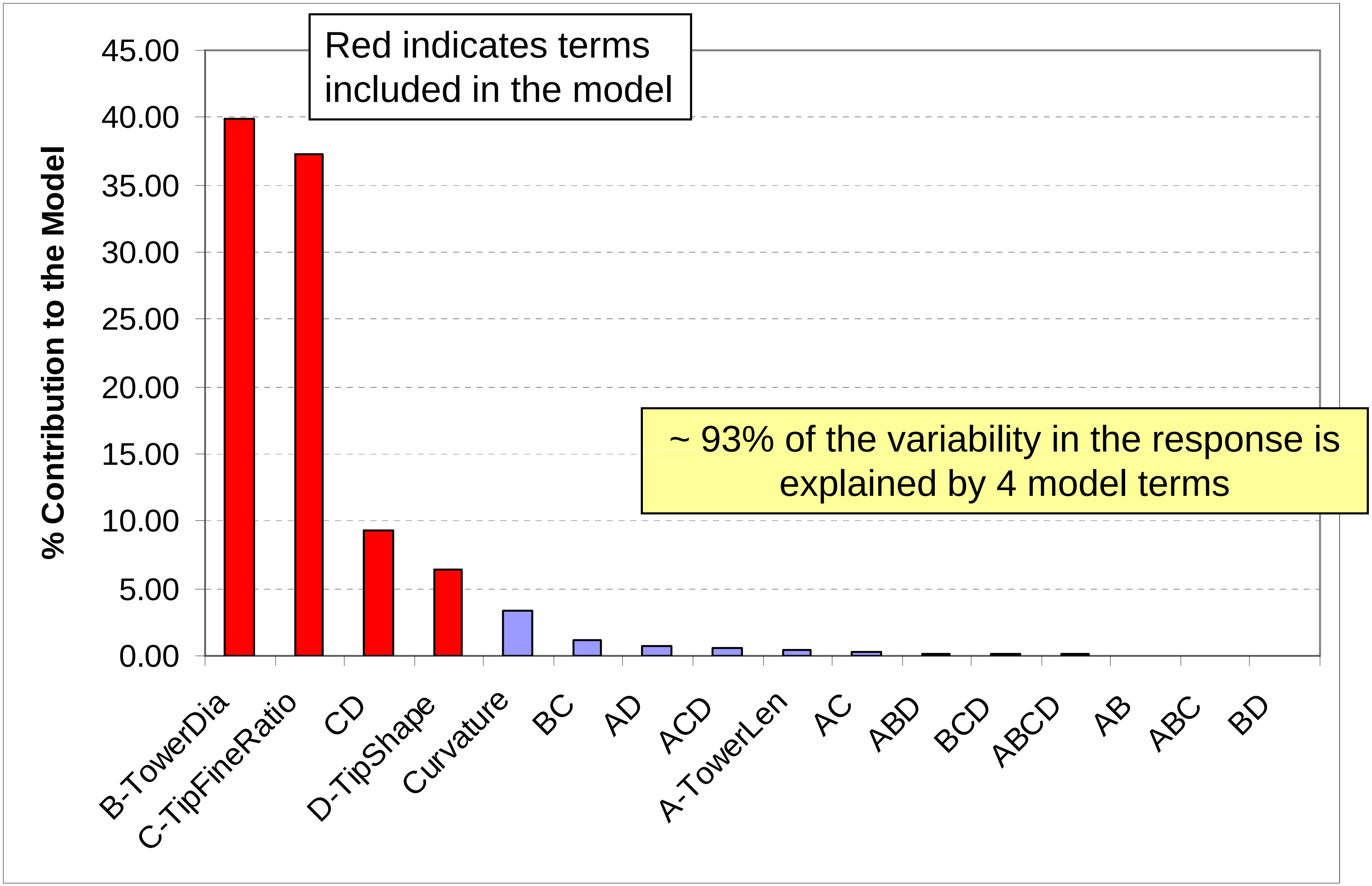
- Partition the total variability in the response (integrated drag) into components that can be uniquely attributed to specific factors and factor combinations

A: TowerLen
B: TowerDia
C: TipFineRatio
D: TipShape
■ Positive Effects
■ Negative Effects



$$y = \beta + \sum_{i=1}^{p} \beta_i x_i + \sum_{i=1}^{p-1} \sum_{j=i+1}^{p} \beta_{ij} x_i x_j + \sum_{i=1}^{p-2} \sum_{j=i+1}^{p-1} \sum_{k=j+1}^{p} \beta_{ijk} x_i x_j x_k + x_1 x_2 x_3 x_4 + \varepsilon$$

Pareto Plot - % Contribution to the Model



Model Graphs - B: Tower Diameter

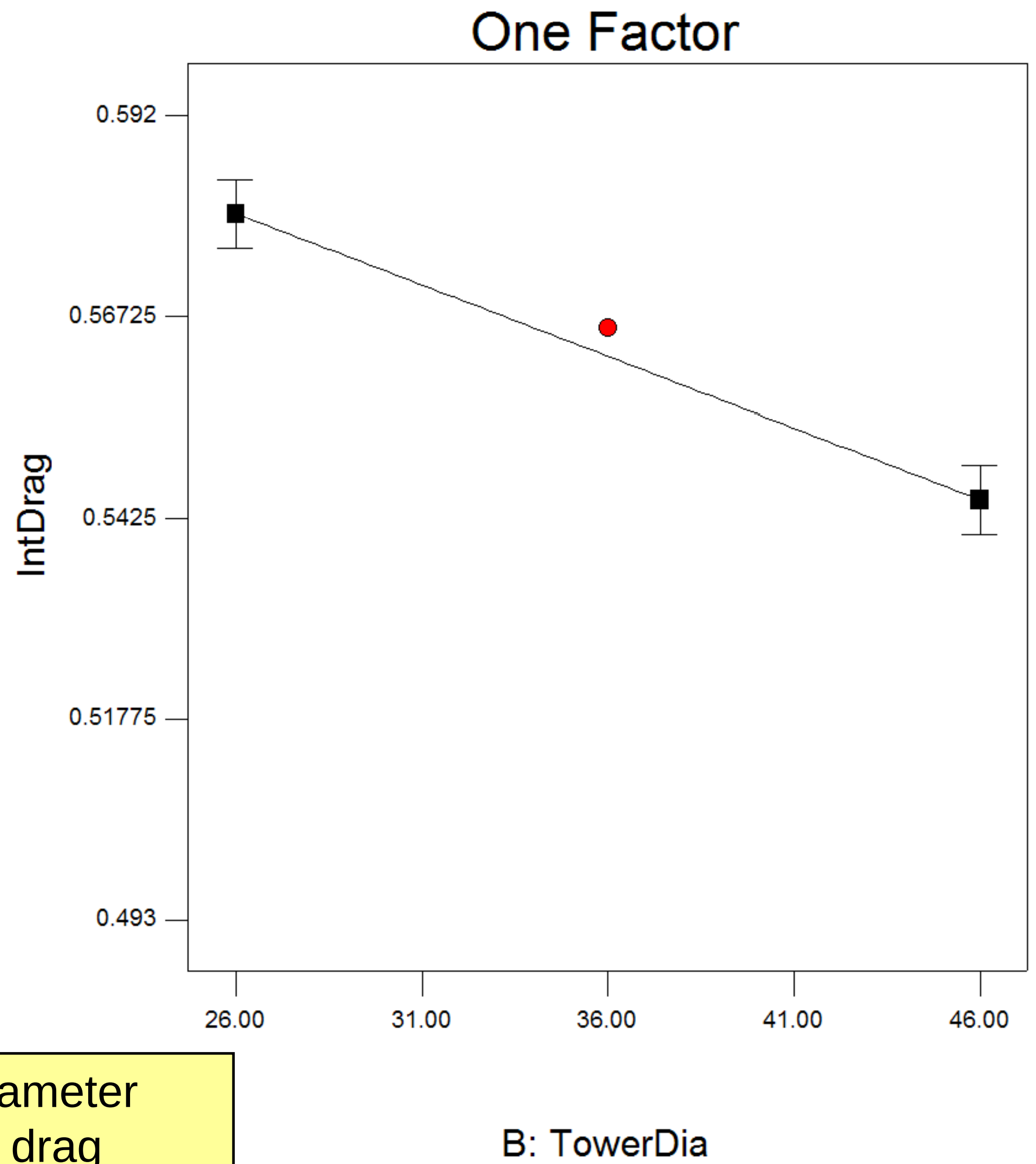
Design-Expert® Software

IntDrag

● Design Points

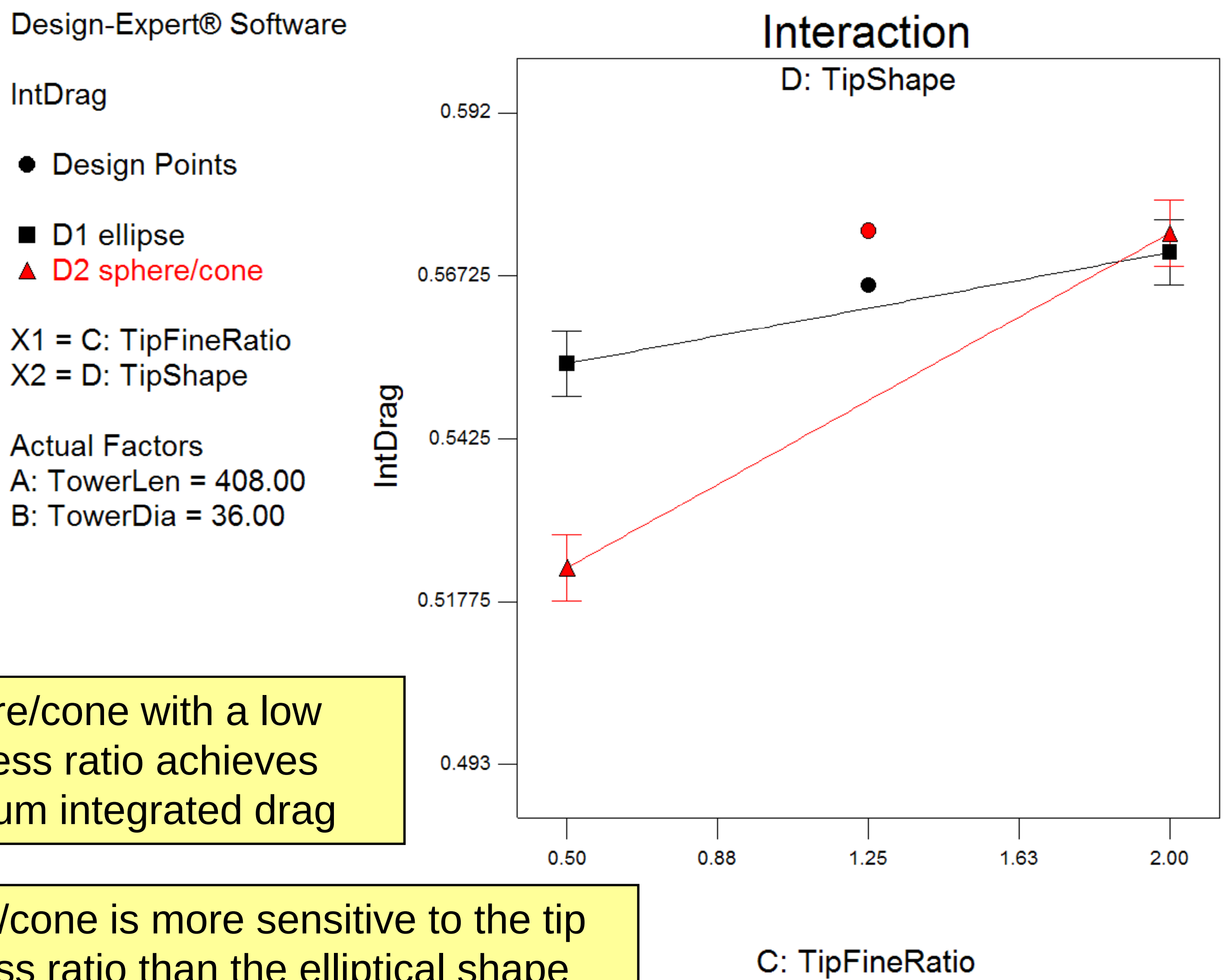
X1 = B: TowerDia

Actual Factors
A: TowerLen = 408.00
C: TipFineRatio = 1.25
D: TipShape = ellipse



Increasing the tower diameter decreases integrated drag

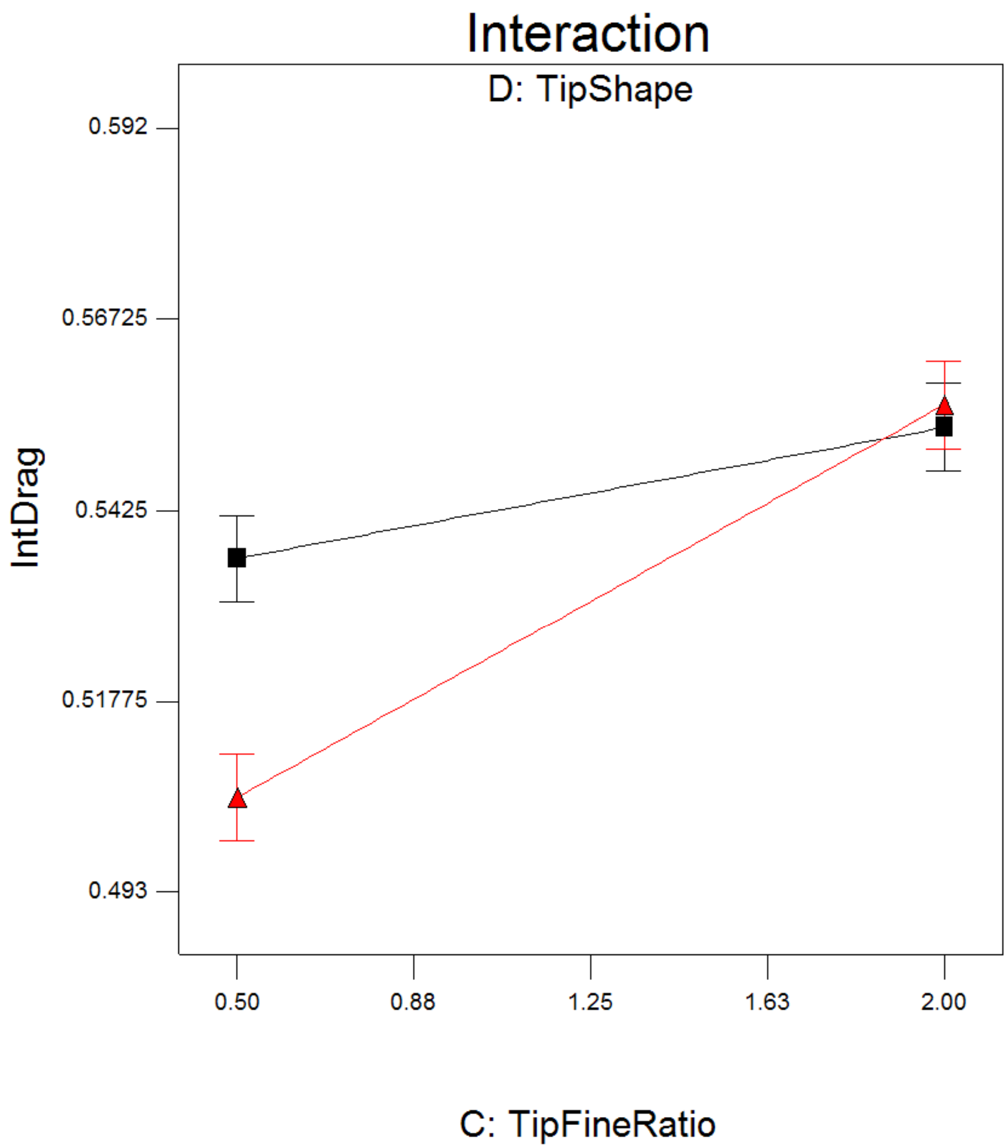
Tip Fineness Ratio (C) x Tip Shape (D)



Sphere/cone with a low fineness ratio achieves minimum integrated drag

Sphere/cone is more sensitive to the tip fineness ratio than the elliptical shape

Minimum Integrated Drag



Minimum Int. Drag = 0.494

B: Tower Dia. = 46 (wide)

C: Tip Fineness Ratio = 0.5 (blunt)

D: Tip Shape = sphere/cone

A: Tower Len. - not significant

Summary of No-Flare Configuration

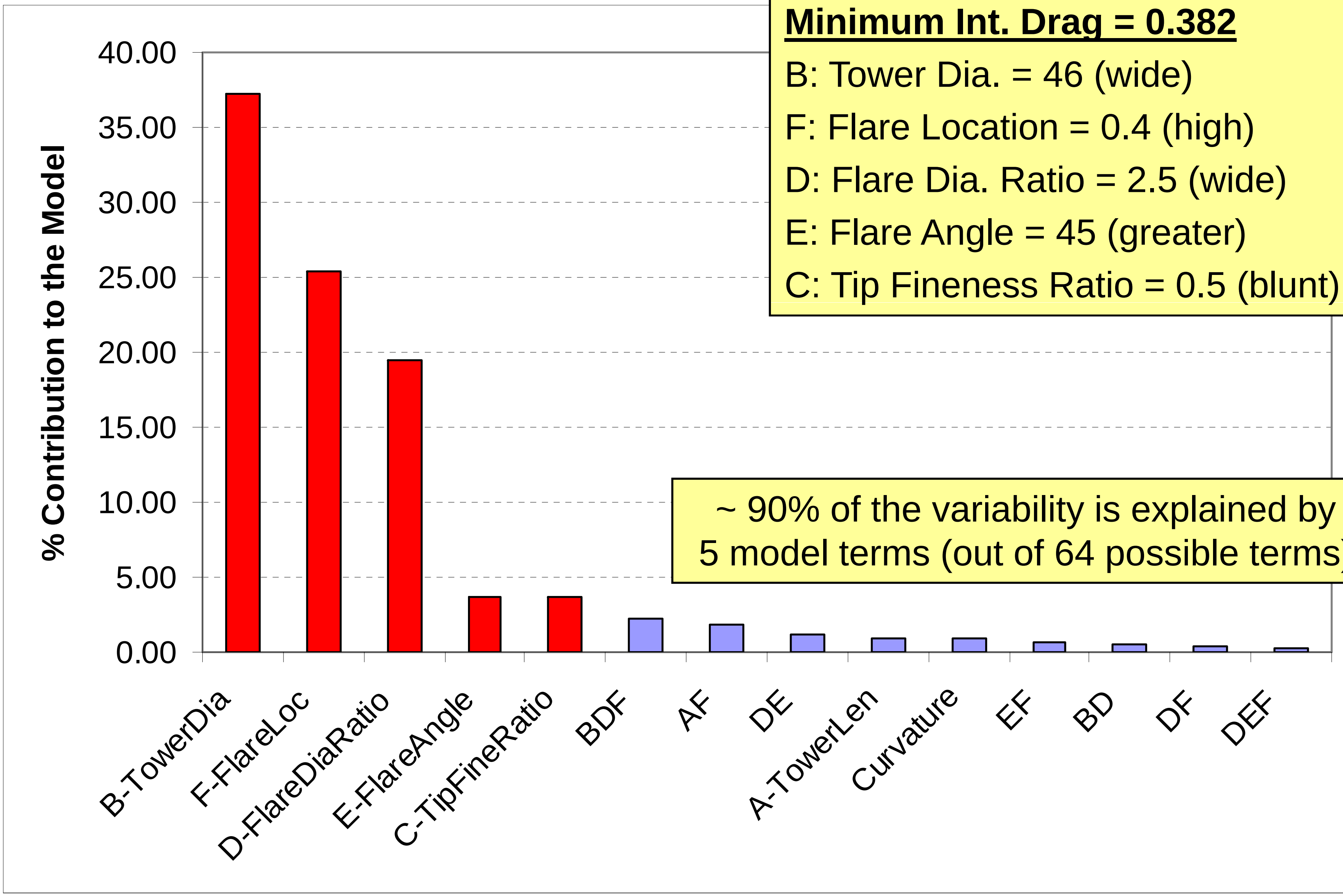
- Rank ordering: Tower Diameter (B), Fineness Ratio (C), Tip Shape (D)
  - Tower length (A) has a small contribution to integrated drag
  - Interaction provides additional insights - the effect of the fineness ratio depends on the setting of tip shape
- First-Order Approximate Model

$$IntDrag = 0.560 - 0.018B + 0.017C - 0.007D + .009CD$$

where the factors are in coded units (-1, +1)

  - Changing Tower Diameter from low (26) to high (46) results in
    2*0.018 = 0.036 decrease in integrated drag
- Curvature was detected
  - higher-order prediction model is required
  - **predictive capability of this first-order model is limited** in the interior of the design space

Flared Configuration Summary



Minimum Int. Drag = 0.382

B: Tower Dia. = 46 (wide)

F: Flare Location = 0.4 (high)

D: Flare Dia. Ratio = 2.5 (wide)

E: Flare Angle = 45 (greater)

C: Tip Fineness Ratio = 0.5 (blunt)

~ 90% of the variability is explained by 5 model terms (out of 64 possible terms)

Summary

- Design of Experiments (DOE) was applied to the LAS geometric parameter study to efficiently identify and rank primary contributors to integrated drag over the vehicles ascent trajectory in an order of magnitude fewer CFD configurations thereby reducing computational resources and solution time

- SME's were able to gain a better understanding on the underlying flow-physics of different geometric parameter configurations through the identification of interaction effects.
  - An interaction effect, which describes how the effect of one factor changes with respect to the levels of other factors, is often the key to product optimization
- A DOE approach emphasizes a sequential approach to learning through successive experimentation to continuously build on previous knowledge.
  - These studies represent a starting point for expanded experimental activities that will eventually cover the entire design space of the vehicle and flight trajectory

Ackowledgements

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