A Methodology to Assess the Capability of Engine Designs to Meet Closed-loop Performance and Operability Requirements

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Outline

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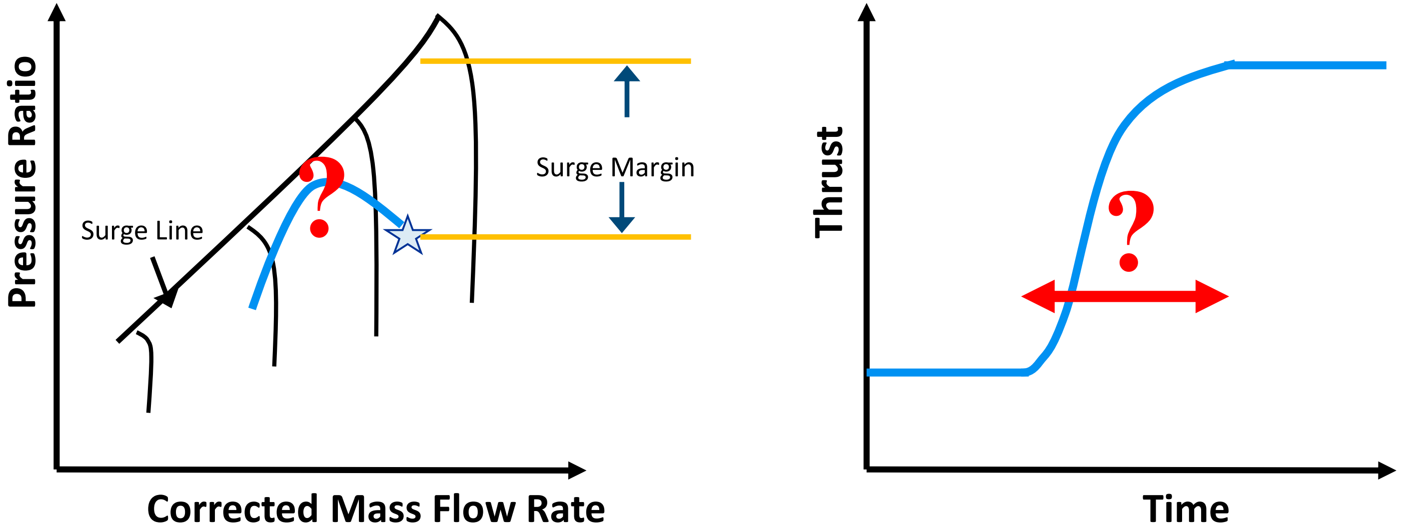
- Overview of methodology
  - Control design and data collection
  - Finding the limiting design point
- Application and evaluation
  - Test engine models
  - Application
  - Evaluation of the methodology
  - Metrics for Comparison
- Summary

Introduction

- Current engine design constraints are based on steady-state data and assumptions at “worst-case” operating conditions.
- Approach considered here uses dynamic performance to better understand engine and controller margins during transient operation



Introduction

- Control design considers **trade-off** between *performance* (time-response) and *operability* (surge margins)
  - Time response is the time required to transition from idle to 95% max thrust for step-change (requirement < 5 seconds)
  - **Faster engine response** necessarily requires operating **closer to surge line**
  - Must balance trade-off through controller design specifications
  - Trade-off further affected by **deterioration** as engine ages.

Motivation

- Closed-loop system should provide some guaranteed performance level throughout engine life cycle
  - Need a way to characterize effect of engine aging on performance level
  - Consider cases of random aging, rather than an assumed trend based on average/typical engine (more general description of aging)
- Develop metrics for describing the design requirements to meet this performance level and for comparing engine models

Data Collection

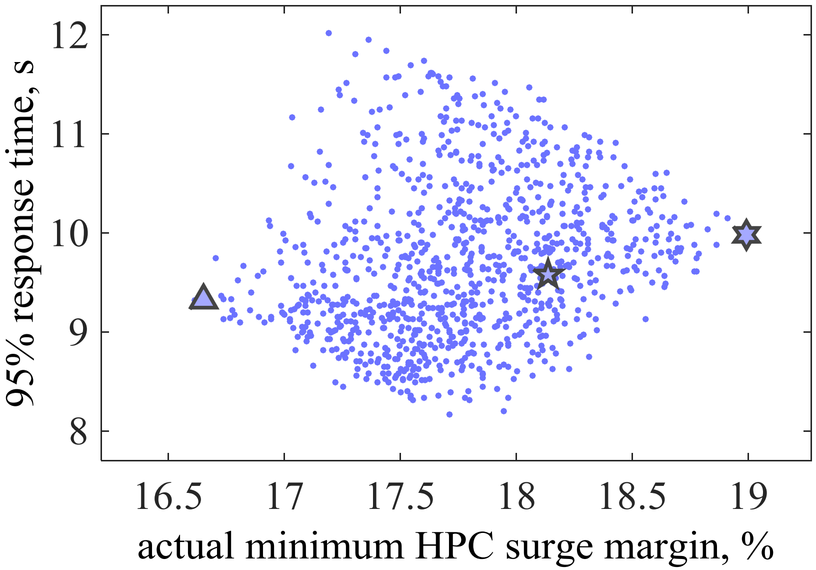
- Use the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA) to design controllers at set of design points for nominal engine
  - Provide an estimate of the closed-loop transient performance/capability of a conceptual engine design.
  - Capable of automatically tuning a controller for transient operation (subset of full controller).
  - Easily integrates with a users engine model in the MATLAB®/Simulink® Environment.

Data Collection

- TTECTrA controller contains **three main components**:
  - setpoint tracking controller
  - acceleration limiter
  - deceleration limiter
- Design point defined by specifications of each TTECTrA component
- In this effort:
  - Nominal engine is mid-life (design)
  - Setpoint tracking controller and deceleration limiter are the same for all controllers designed
  - Design point identified by minimum HPC SM for which acceleration schedule designed for, *minSMd*

Data Collection

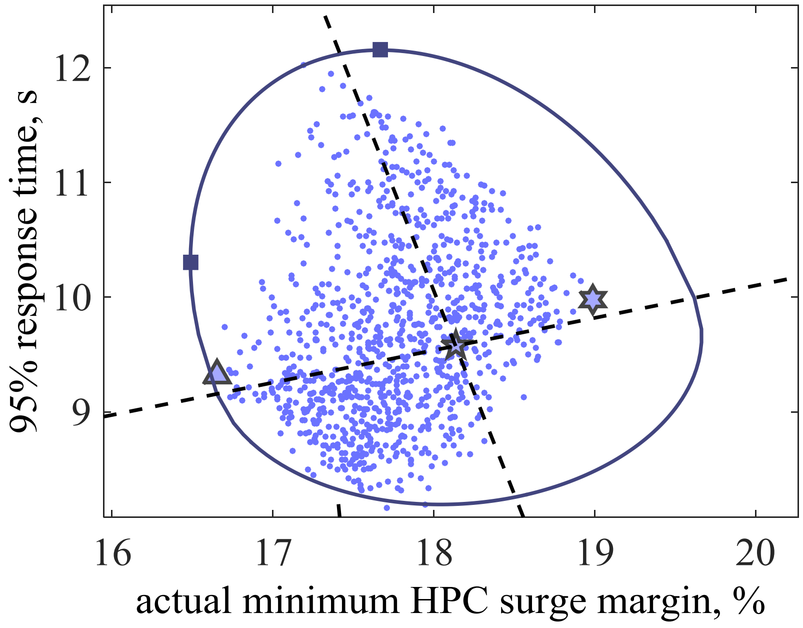
- Application of methodology requires an engine model that uses **health parameter** *h* to define engine age (deterioration)
  - h corresponds to efficiency and flow modifiers for each of the major turbo-machinery components
  - Each element of *h* is between 0 (new) and h_{eol} (end-of-life)
- Collect data from 2 sets of simulations
  - Known (anticipated) life conditions
    - New, mid-life, end-of-life
  - Randomly aged engines
    - independently, uniformly sample each element of h from 0 to h_{eol}



Defining Elliptical Boundaries on Performance Level

- Fit the Monte Carlo data at each trial design point into an ellipse
  - Length and rotation of ellipse x-axis based on new, mid-life, and end-of-life
  - Length of top- and bottom-half ellipse y-axes based on rest of Monte Carlo data

- Relate design point (*minSMd*) to performance level (*minSMa* and *tr*)
- Relate performance level to ellipse parameters
- Least squares approach to determine coefficients

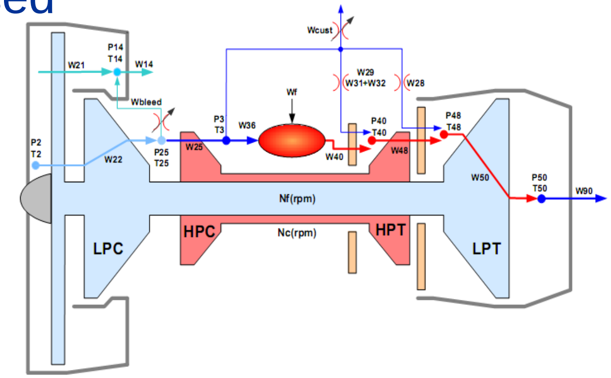


Finding the Limiting Design Points

- Implement binary search procedure to estimate limiting design point meeting either minimum HPC surge margin or maximum response time limit.
  - Utilize curve fits and defined relationships to find design limit which meets either requirement.
    - Based on fixed number of design points and Monte Carlo simulations to evaluate each design point.
    - Reduces the total number of design points and simulations to evaluate engine design.

Description of Engine Models

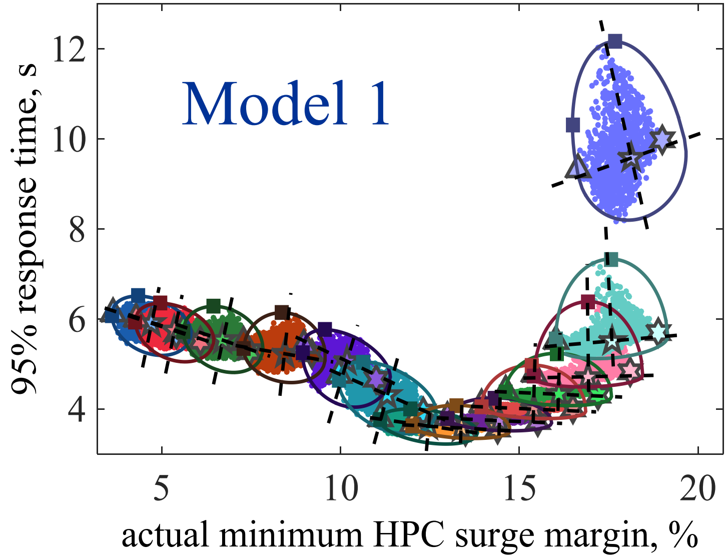
- Three variations of the Commercial Modular Aero-Propulsion System Simulation, 40k (C-MAPSS40)
  1. Unmodified C-MAPSS40k
  2. Inertia Modified
     - Turbine and compressor efficiency increased
     - HPC and HPT flow decreased
     - Shaft speed scalar increased
     - Shaft inertias modified
  3. Flow Modified
     - HPC and HPT flow rate scalars decreased

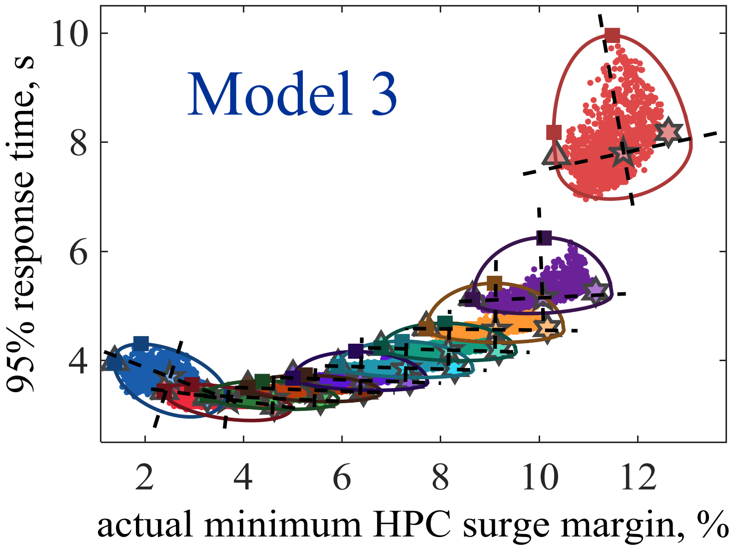


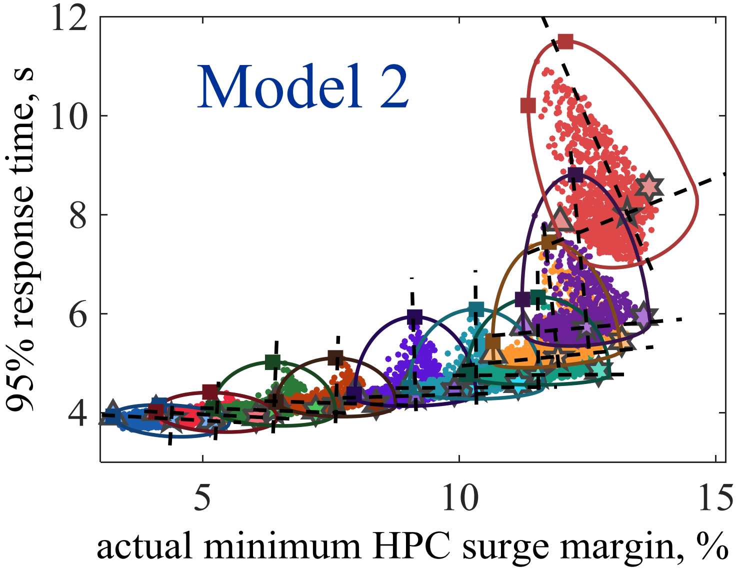
Control Design Objectives

- Setpoint controller: 1.5 Hz, 45 degrees phase margin
- Deceleration Schedule: 15% LPC surge margin
- Acceleration Schedule: impacted by each design
  - Model 1: 5% to 18% minimum HPC surge margin
  - Model 2: 4% to 13% minimum HPC surge margin
  - Model 3: 2% to 11% minimum HPC surge margin
- At each trial design point, 1003 simulations
  - New, mid-life, and end-of-life
  - 1000 engines with randomly-sample health parameter vectors

Application to Models





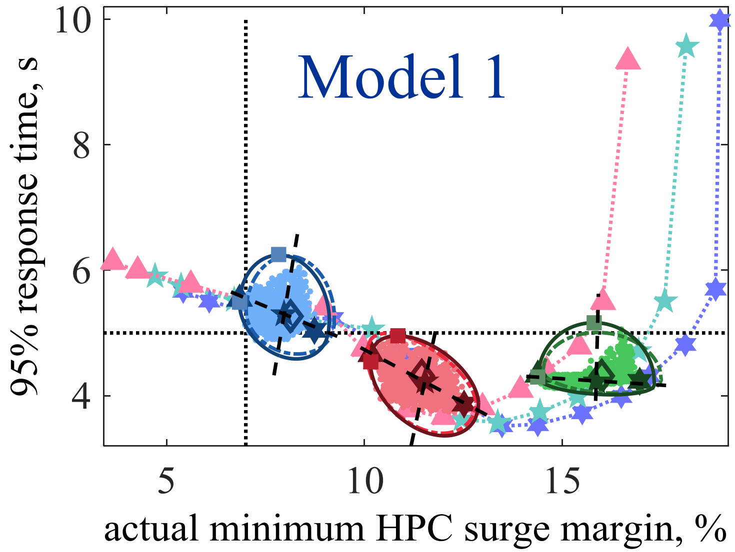


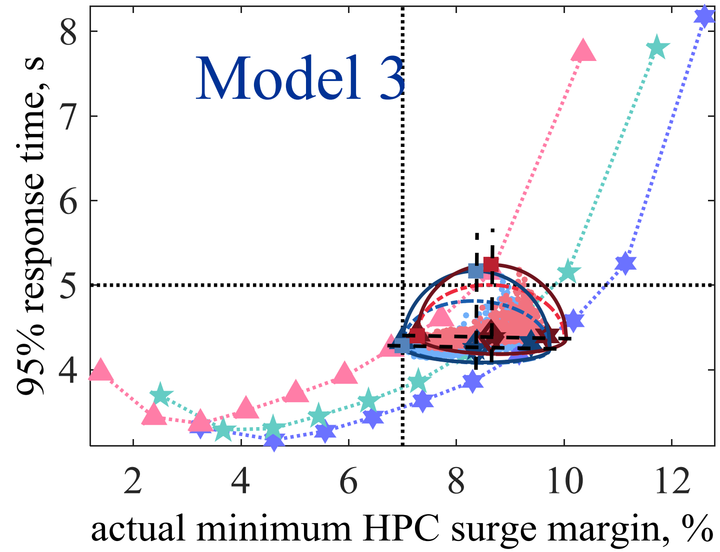
Applications to Model

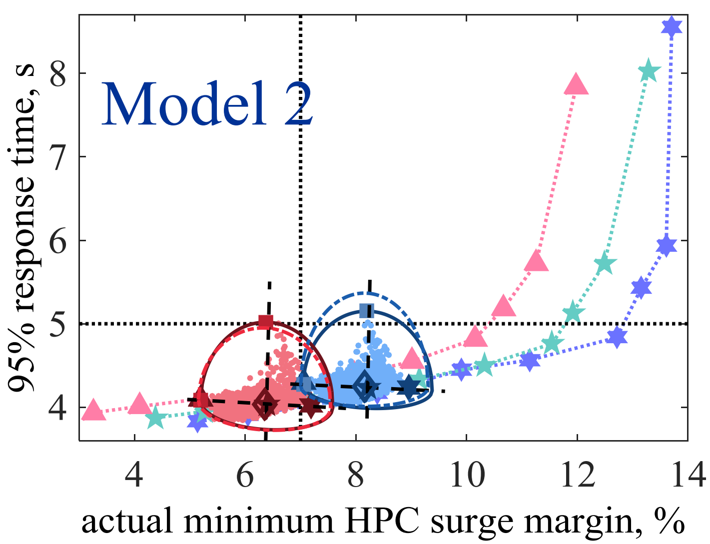
	Objective	Predicted Limit	minSMd(%)
Model 1	minSMa=7%	7.003	7.80
	tr=5s	4.99	10.06
	tr=5s	5.01	14.78
Model 2	minSMa=7%	7.001	7.36
	tr=5s	4.95	4.95
Model 3	minSMa=7%	7.00	8.23
	tr=5s	5.003	8.52

- Shape of model 1 results in two limiting design points which meet 5 second objective
- 99+% of points captured by ellipses for each mode
- Binary search algorithm able to find limiting design within 7 iterations (highly efficient)

Evaluation of the Methodology

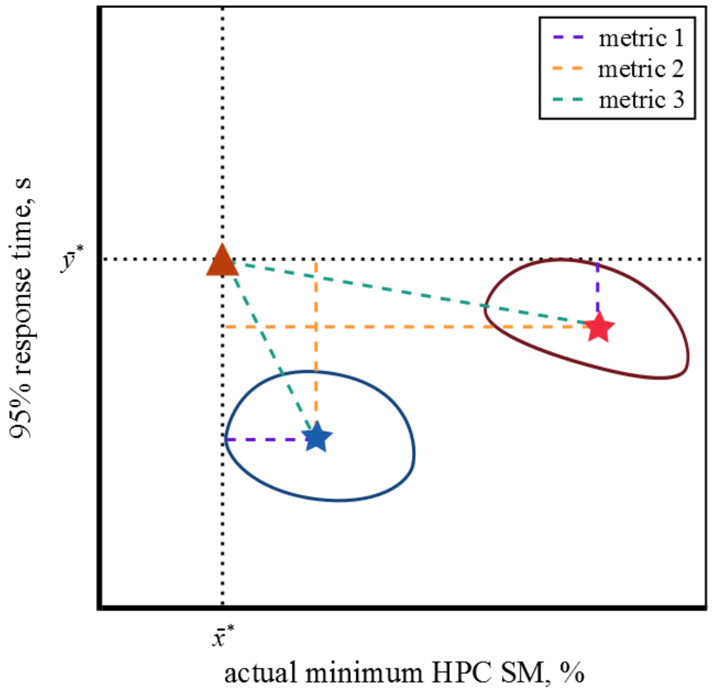






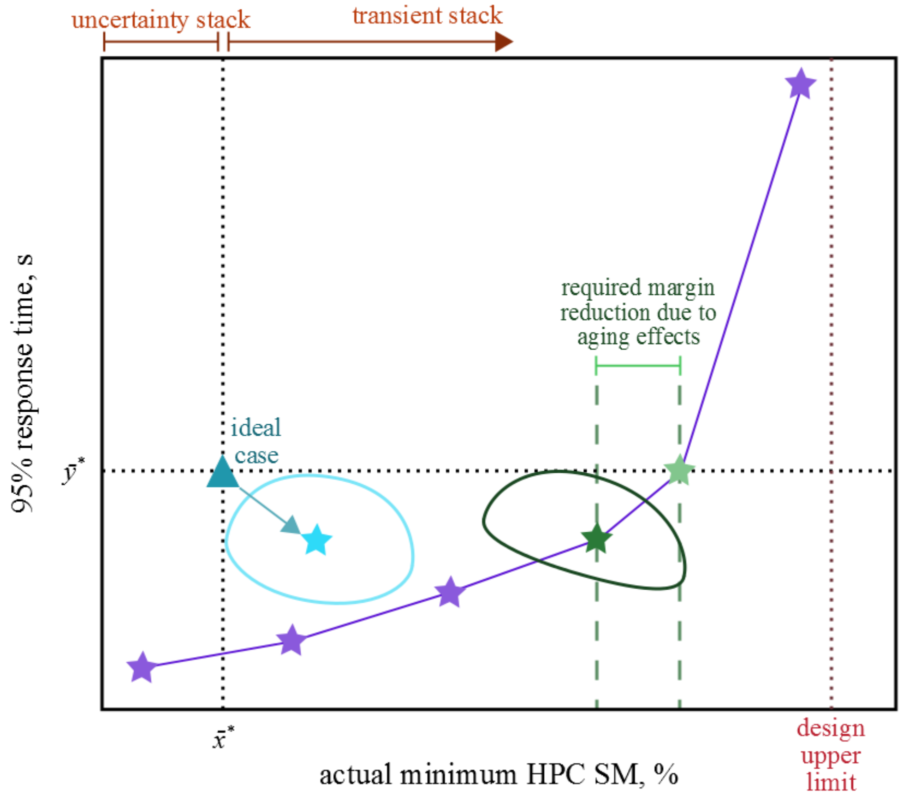
Metrics for Comparison

- Three metrics defined to help compare models through performance-operability trade-off and robustness due to aging
  1. Distance from nominal to limit for which controller was designed
  2. Distance from nominal to limit for which it was not designed
  3. Distance from nominal to intersection of two limits



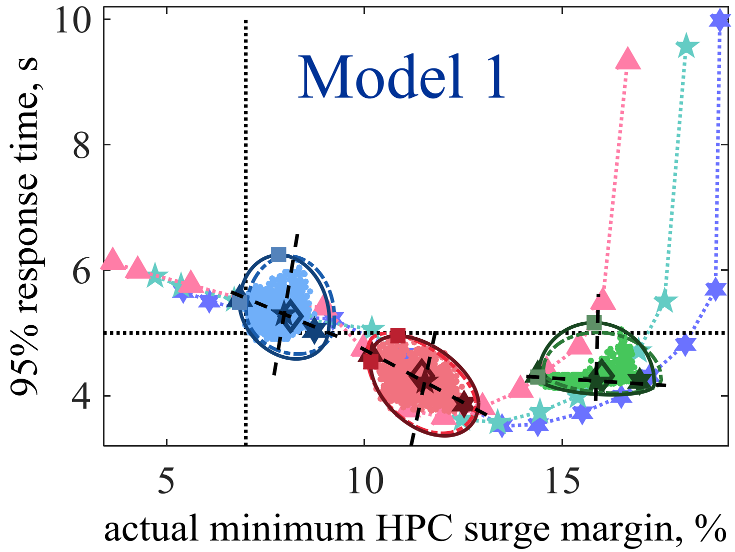
Potential Impact on Design

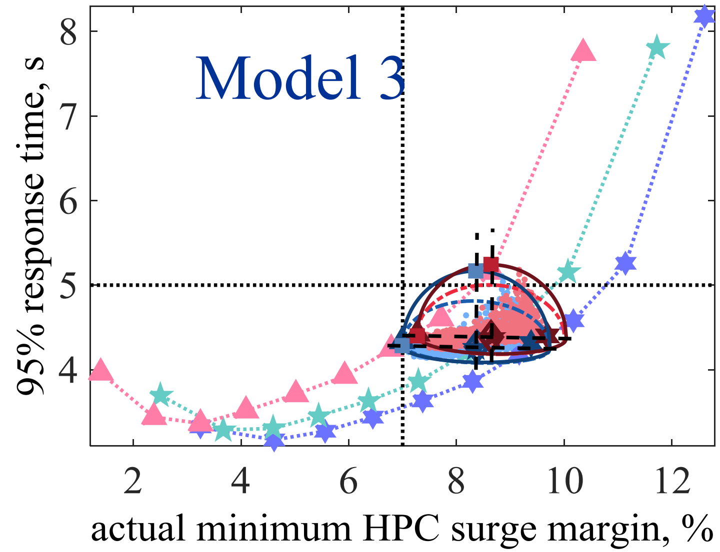
- minimum HPC SM value (x-limit) is the uncertainty stack
- Fixed performance time (<5 seconds)
- Operating point
  - very long throttle movement
  - Large 95% response time and actual minimum surge margin near constraint

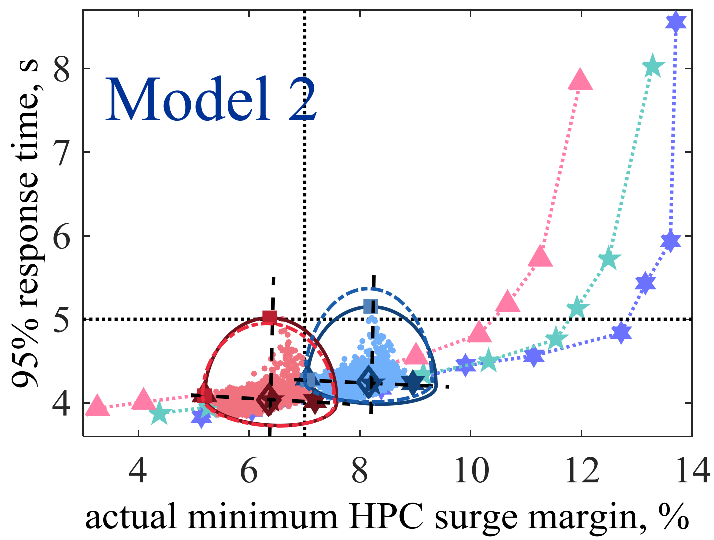


- Transient stack is surge margin between constraint and limit.
- Faster response correlates to unnecessary transient margin.
- **With ellipse, better define point near ideal operating point!**

Impact on Design







Summary

- An approach for estimating design points to bound controllers at which specific performance limit is not exceeded throughout engine life-cycle was proposed
  - Data collected from randomly aged engine at a set of trial design points
  - Determined parameters of ellipse bounding each data set and construct curve fit relating these parameters to the design point and nominal performance level
  - Employed binary search to determine limiting design points
  - Evaluate design to determine if there is additional margin that is unnecessary.

Thank you!

Any Questions?