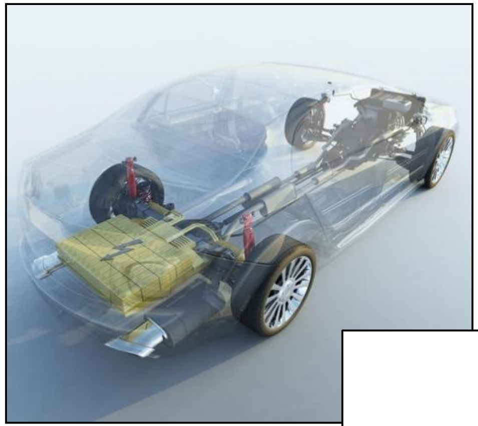
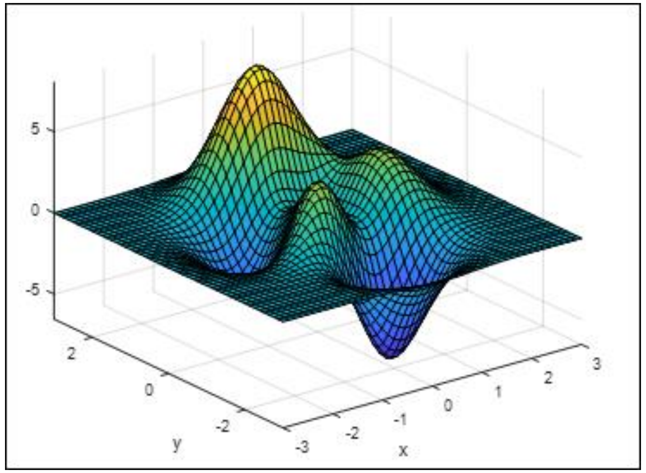
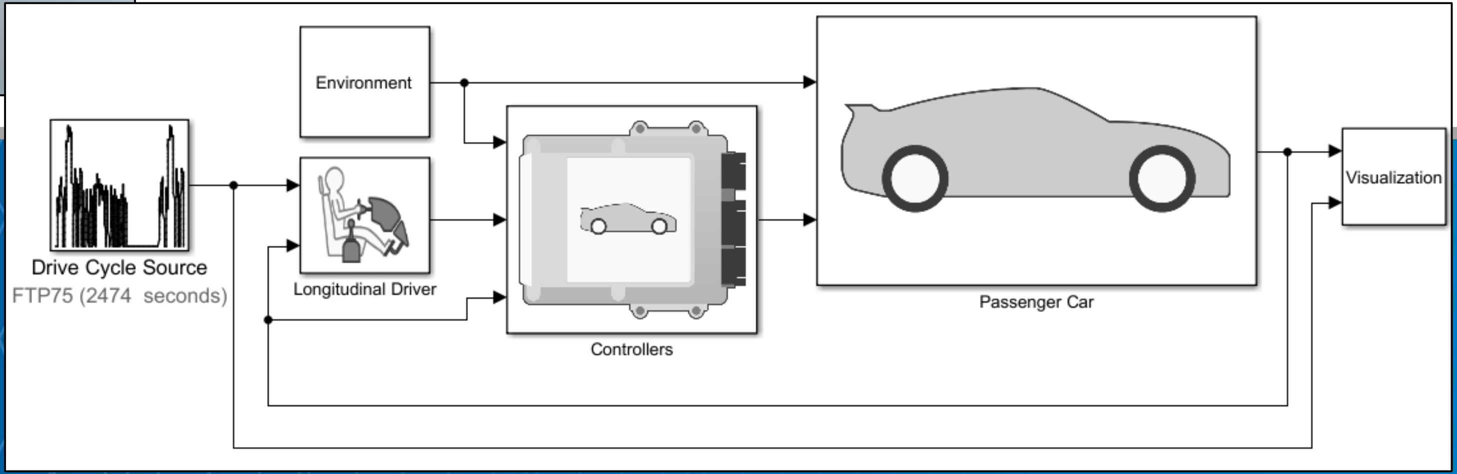
Objective Drivability Calibration

MathWorks Automotive Conference

April 30th, 2019







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MathWorks

Presenter

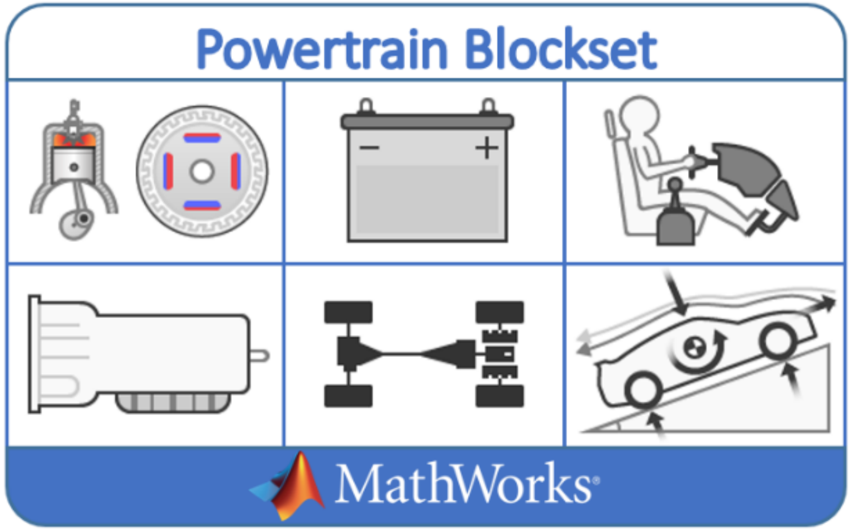
- Jason Rodgers
  - MathWorks Senior Application Engineer
    - Vehicle Dynamics Blockset
    - Powertrain Blockset
    - Model Based Calibration Toolbox
  - Previous experience at Toyota R&D
    - System Optimization and Control engineer
    - Optimizing powertrain design and controls subject to various constraints (cost, FE, drivability, etc.)
  - Education
    - BSME and MSME, University of Michigan
  - Areas of interest
    - Enabling Model-Based Design using physical modeling
    - Applying optimization techniques to modeling and control problems
    - Applying new technologies such as Deep Learning to Automotive problems

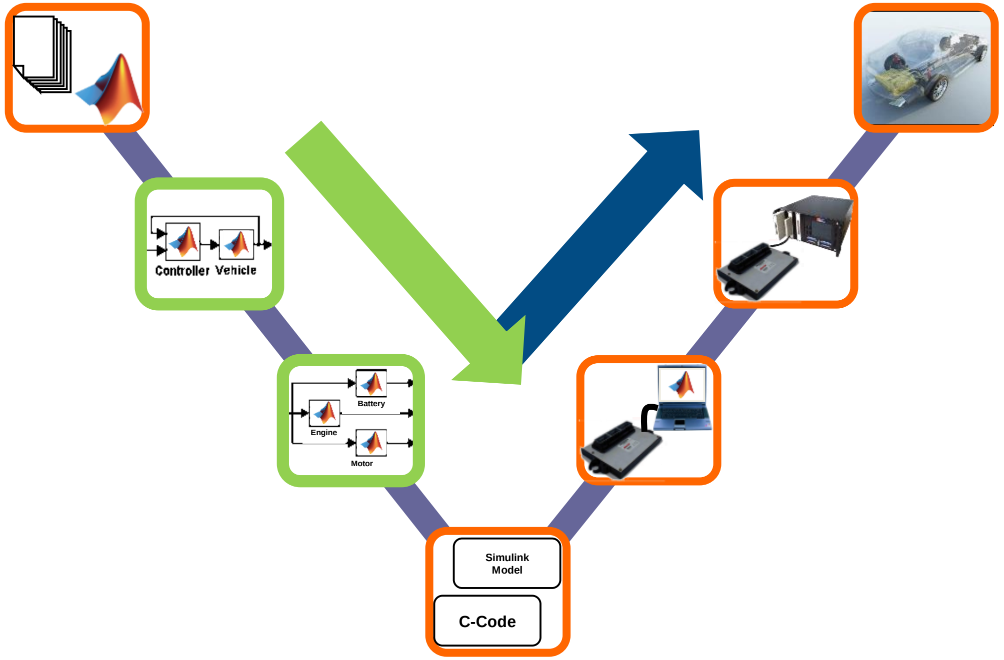
Key Takeaways

- Powertrain Blockset is capable of simulating low frequency drivability behavior

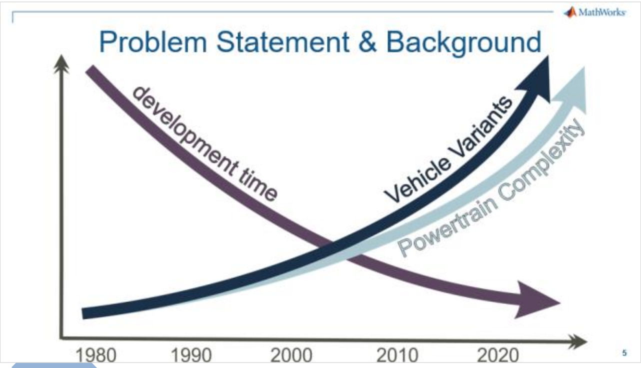
- Model re-use from early planning phase can be used to jumpstart calibration efforts

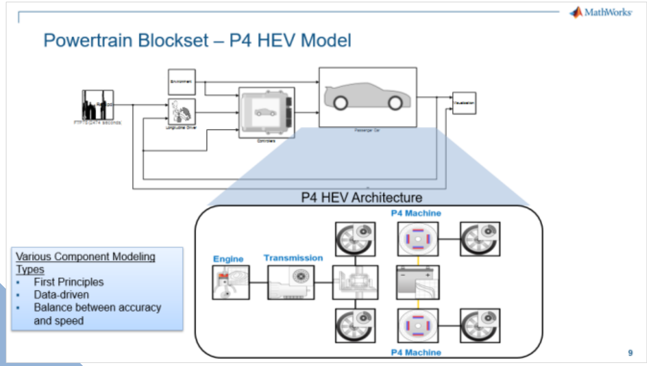
- Objective-based calibration can:
  - Improve calibration time
  - Account for performance trade-offs
  - Trace back to requirements
  - Objective and not subjective → repeatable



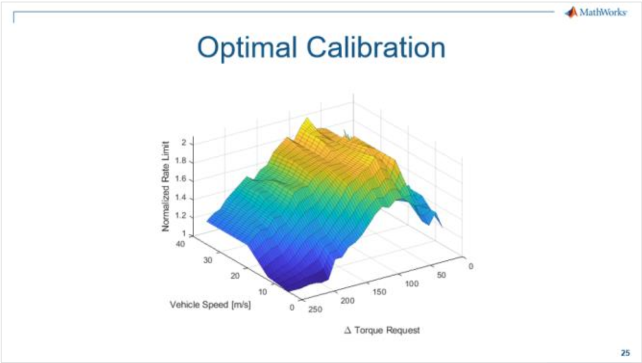


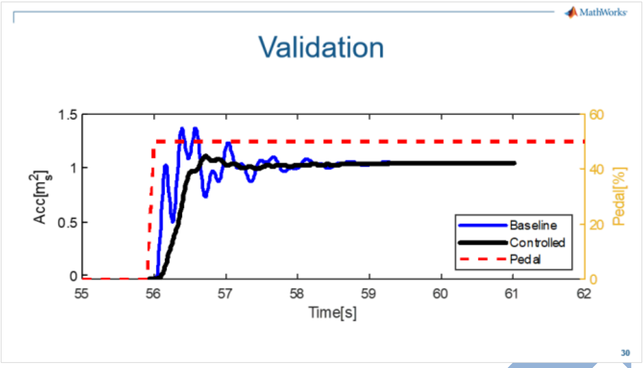
Agenda


Problem Statement & Background
development time
Vehicle Variants
Powertrain Complexity
1980
1990
2000
2010
2020

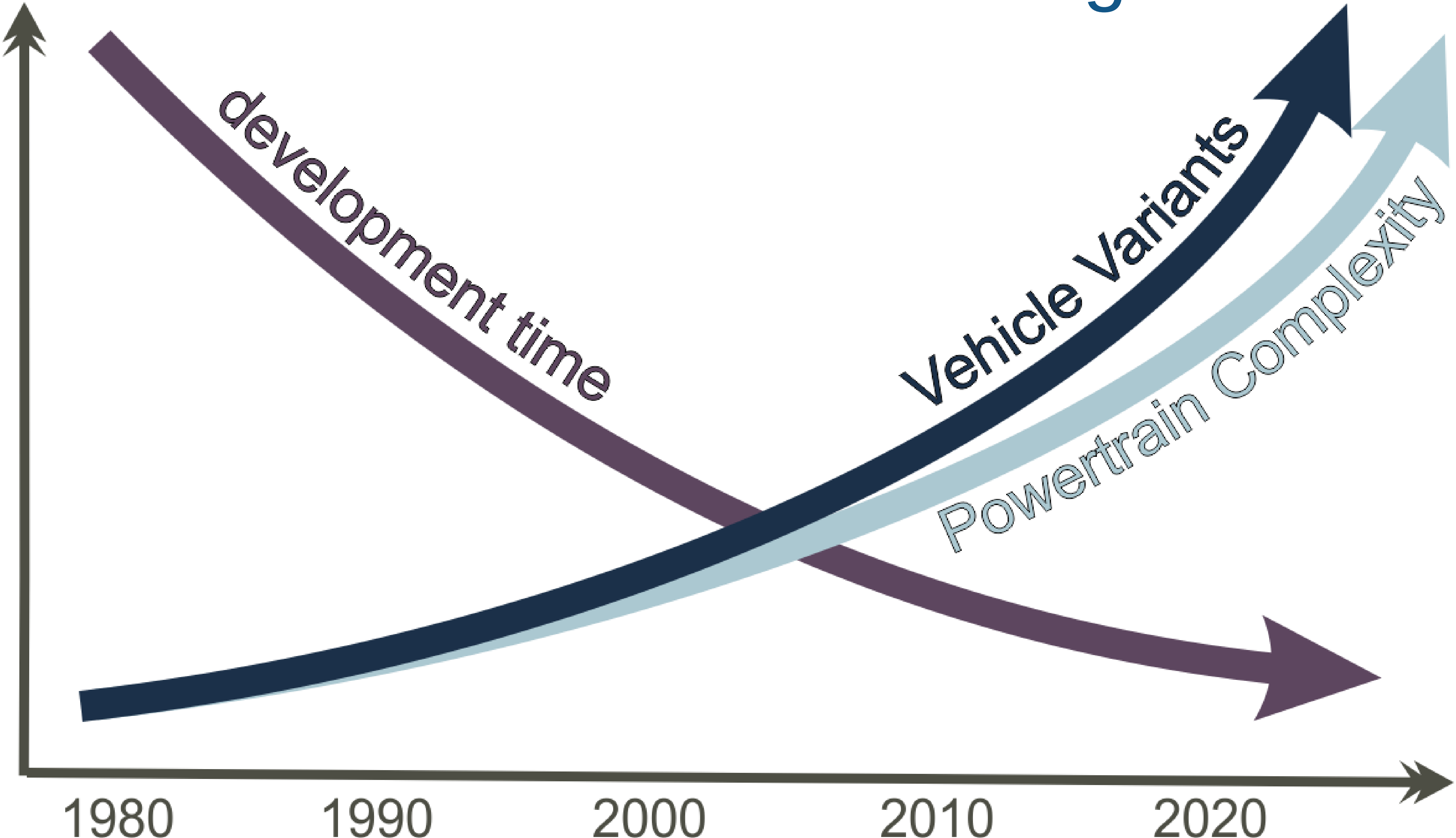

Powertrain Blockset – P4 HEV Model
P4 HEV Architecture
P4 Machine
Engine
Transmission
Various Component Modeling Types
First Principles
Data-driven
Balance between accuracy and speed


Defining an Objective Function
What are my goals?
What are my choices?
What restricts my choices?


Optimal Calibration
Normalized Rate Limit
Vehicle Speed [m/s]
Δ Torque Request

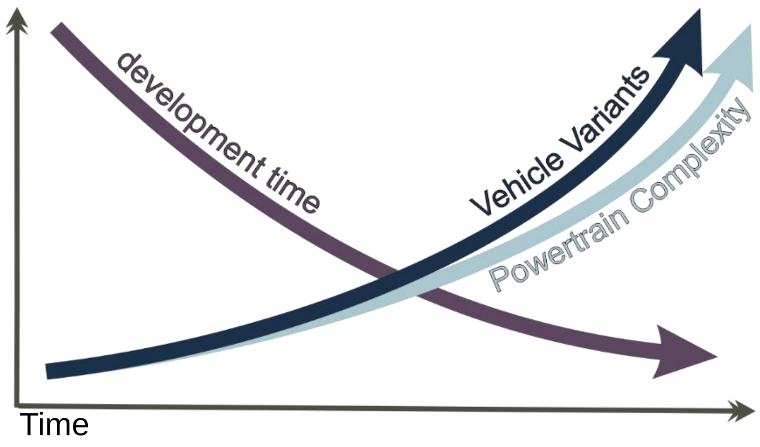

Validation
Acc[m/s²]
Pedal[%]
Time[s]
Baseline
Controlled
Pedal

Problem Statement & Background

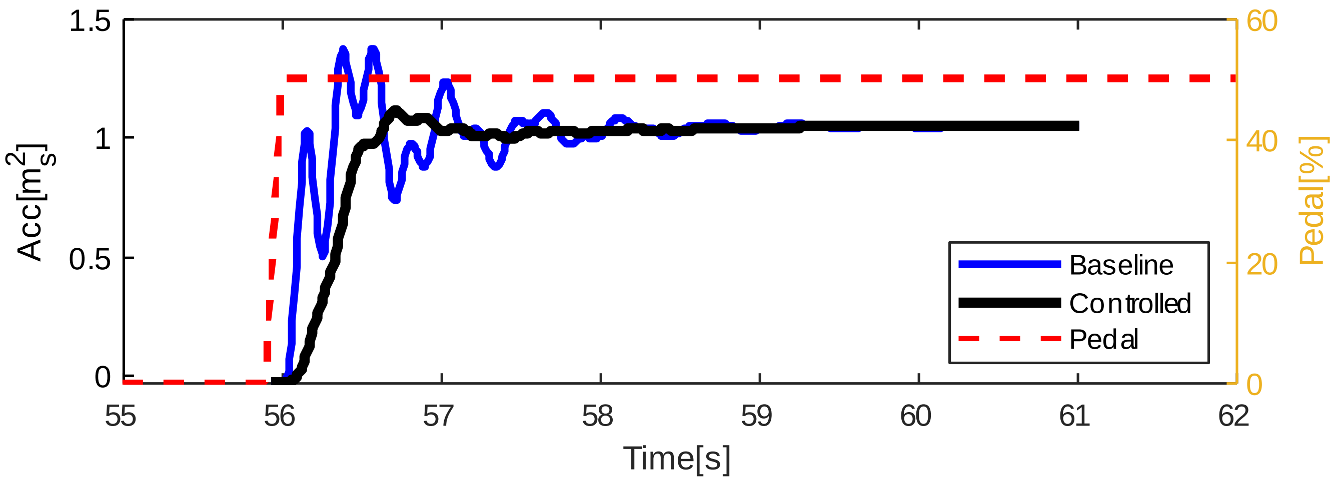


Problem Statement

- What is the problem?
  - ECU can have dramatic effect on drivability
  - Manual calibration is time sink
  - Ratings are defined by experienced but subjective drivers
  - Efficiency improvements are needed
    - Decreasing development time
    - Increasing powertrain complexity and number of variants



- How to solve the problem?
  - Use objective based approach to tune ECU calibration parameters
    I. Requirements driven
    II. Objective based - Repeatable
    III. Automated – Time savings
    IV. Optimal with respect to requirements



Background

What is drivability?

- Response characteristic of the vehicle to driver inputs under different driving conditions

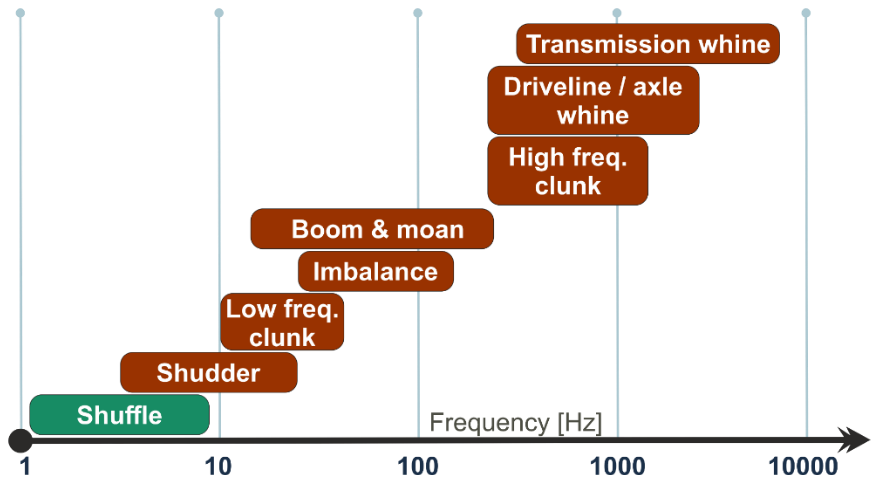
- Want the driver to be as comfortable as possible
  - Hesitation
  - Sluggish
  - Hard start
  - Noise/Oscillations

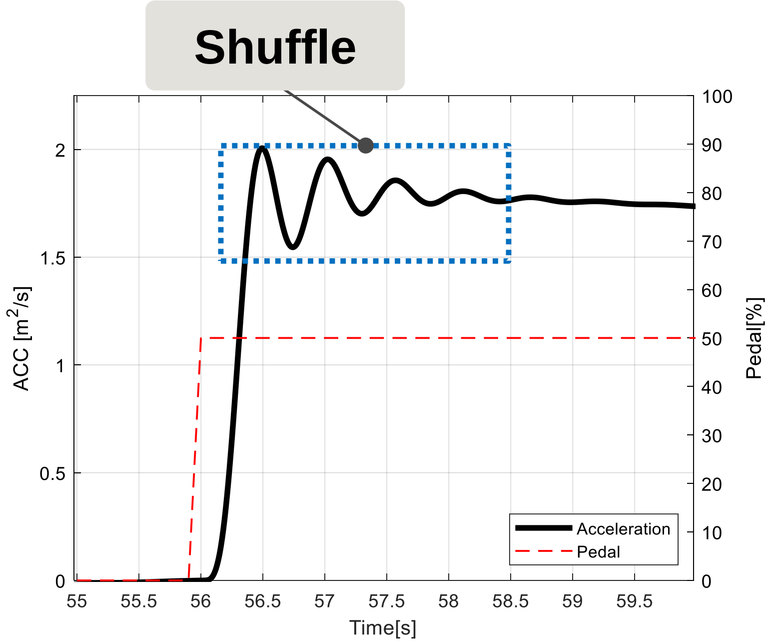
- Drivability is affected by many sources
  - Gear shifts
  - Engine Idle
  - Braking
  - Acceleration
  - Etc.

Background

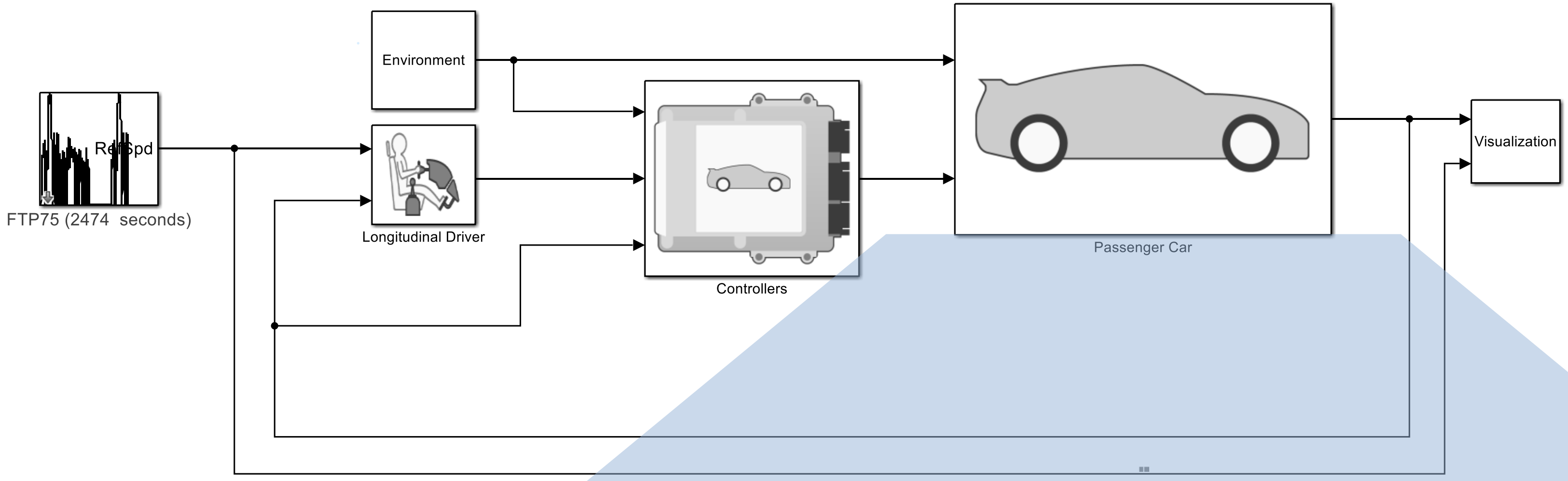
What are we focusing on?

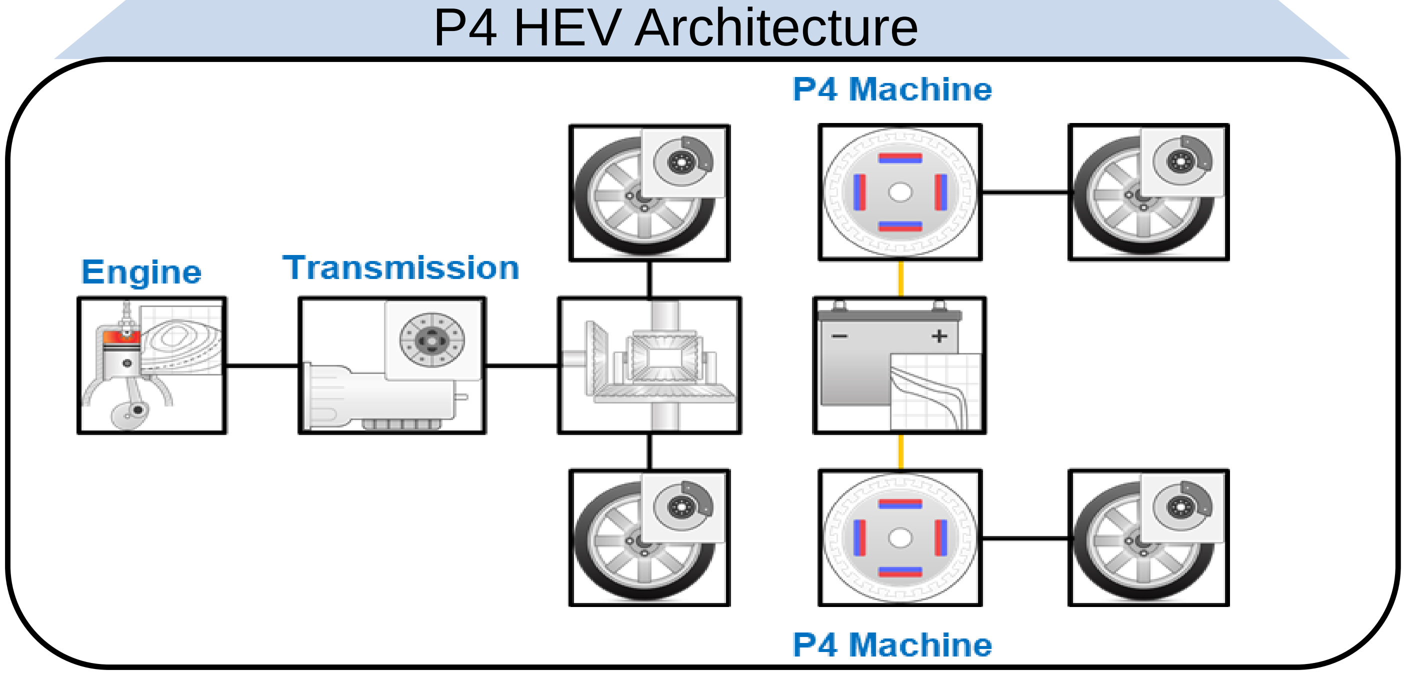
- Shuffle related to tip in
  - NVH longitudinal effect caused by sudden changes in the drive torque
  - Some room to optimize hardware but controller is more cost effective
  - 2-8 Hz depending on the gear
- Not considering shift shock, clunk, or higher order modes
- Acceleration is measured at CG
- No gear shift during tip in event





Powertrain Blockset – P4 HEV Model



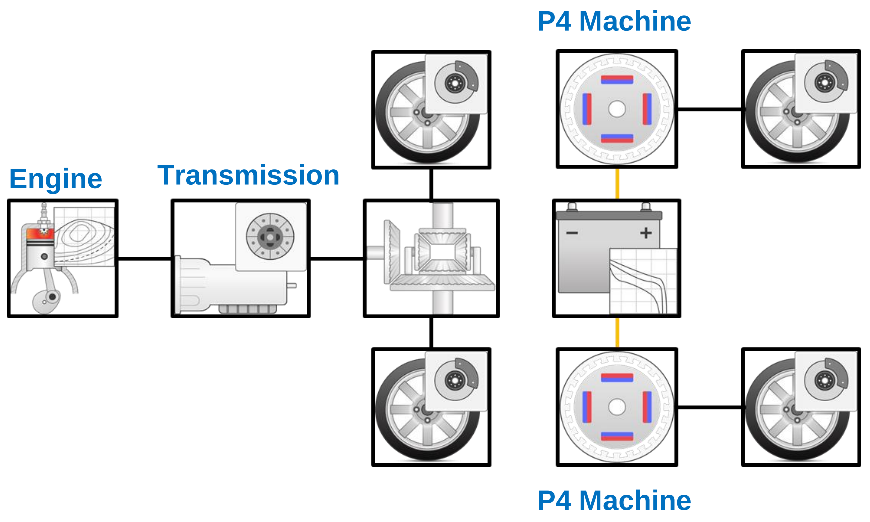


Various Component Modeling Types

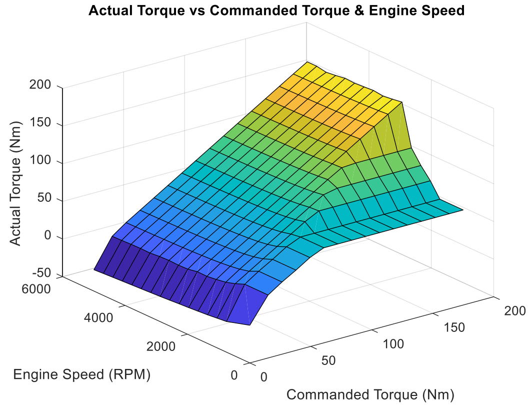
- First Principles
- Data-driven
- Balance between accuracy and speed

Powertrain Blockset – P4 HEV Model

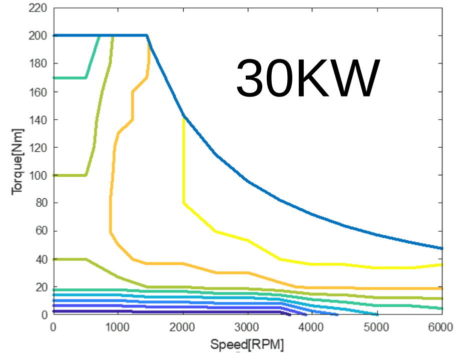
- P4 HEV Powertrain model
  - Started from reference application and modified for testing and added tip-in controller
  - Model fidelity is typical for Fuel Economy and acceleration studies
  - Model reuse
- Engine
  - 1.5L L4 95kW(126hp) @5500RPM
  - Map-Based Model
- 2 P4 30kW Motors
  - Map-Based Model
- 1.3 kWh Battery
  - Map-Based Model



Engine Map

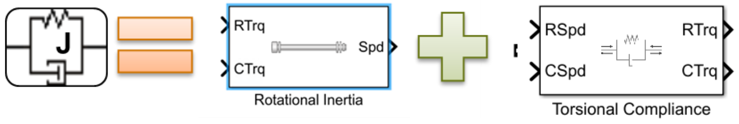


Motor Map

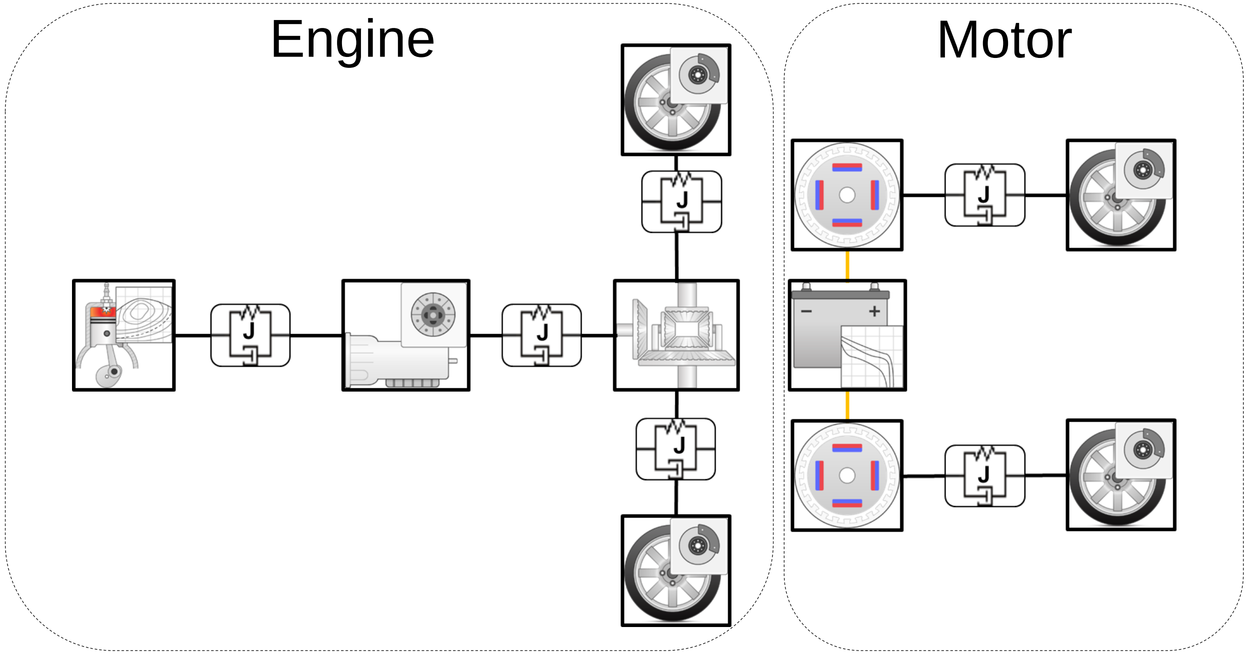


P4 Component Modeling

- Driveline oscillations are captured by rotational inertia and compliance blocks that exist in reference model



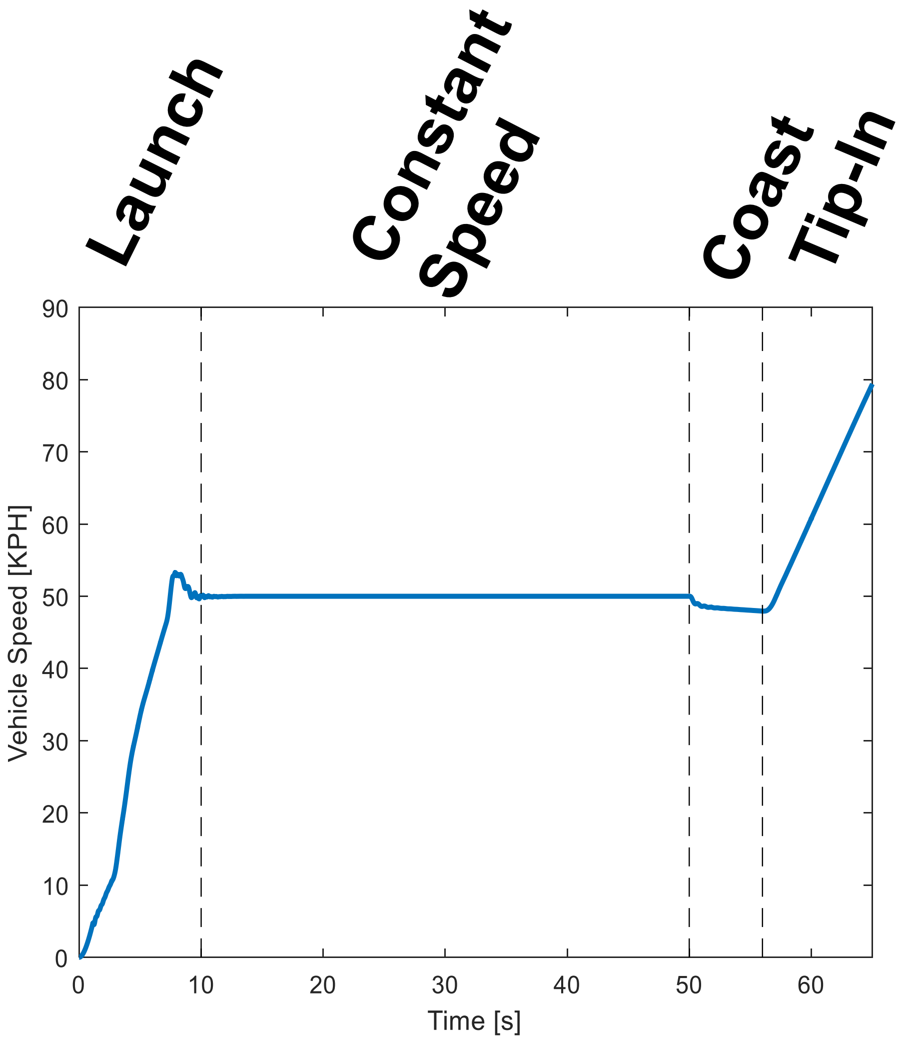
- Linear damping and stiffness
  - Openness of model allows for replacing with nonlinear components
- 2 Torque Paths
  - Engine
  - Motor



Driving Scenario

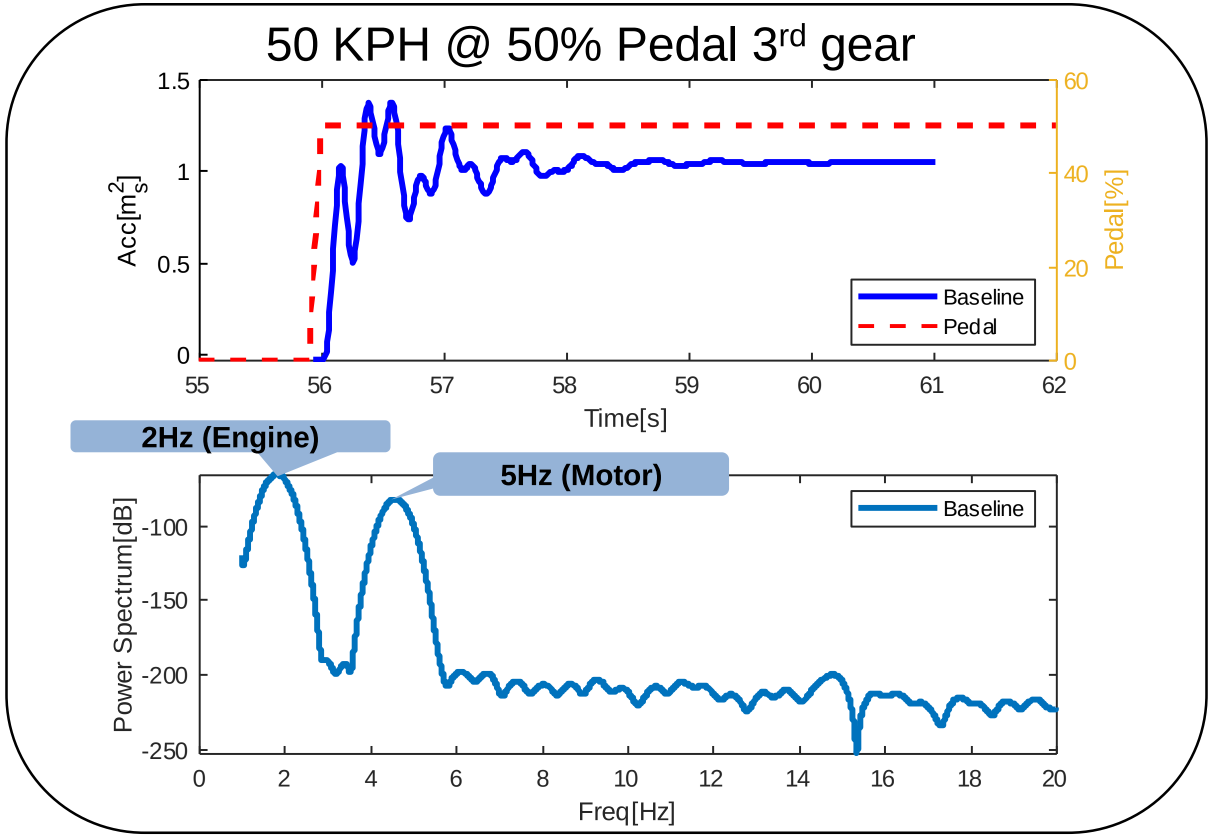
- What scenario are we using?

  1. Accelerate to Constant Speed
  2. Hold Speed and shift to desired gear. Allow transients to subside.
  3. Let off pedal
  4. Apply pedal step input



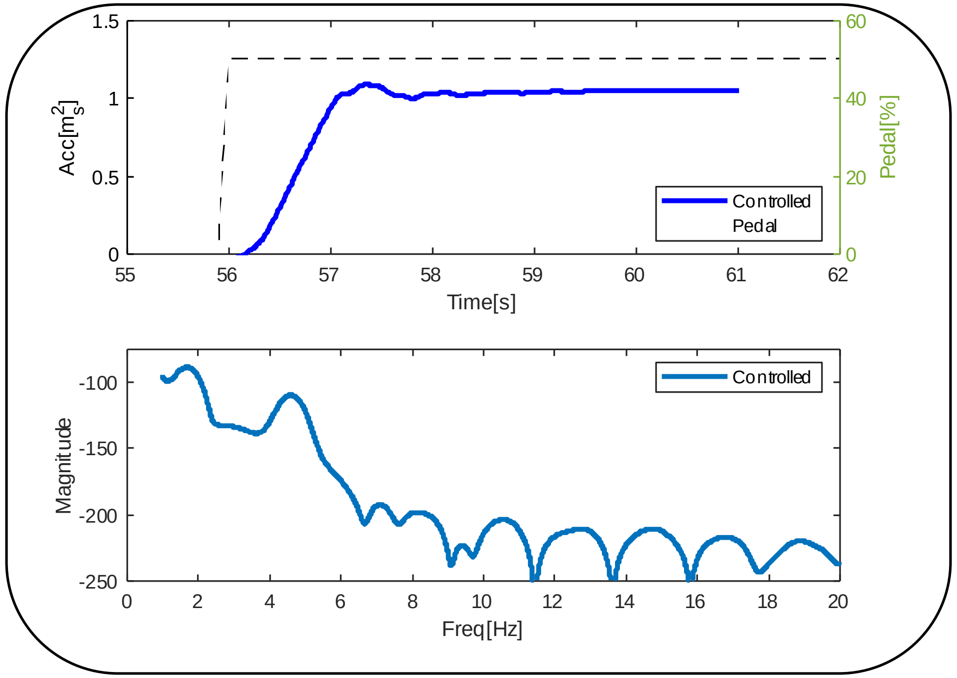
Tip-In Acceleration Response

- Initial response has large amounts of shuffle oscillations
  - Model is able to capture the first mode (shuffle) for both torque paths
  - Response attenuation is required to improve drivability



Tip-In Acceleration Response

- How to improve?
  - Spark Control (on engine side only)
  - Fixed Rate-Limit on torque request or pedal input
  - Scheduled Rate-Limit
  - Optimal Control – e.g. Model Predictive Control



Example: Manually Calibrated Rate Limit

First Pass at Improvements:

- Reduced oscillations but response is slow
- Is a function of gear, speed, and torque request → scheduled rate-limit
- Long manual process to do by hand (weeks)
- How to balance responsiveness and oscillations?

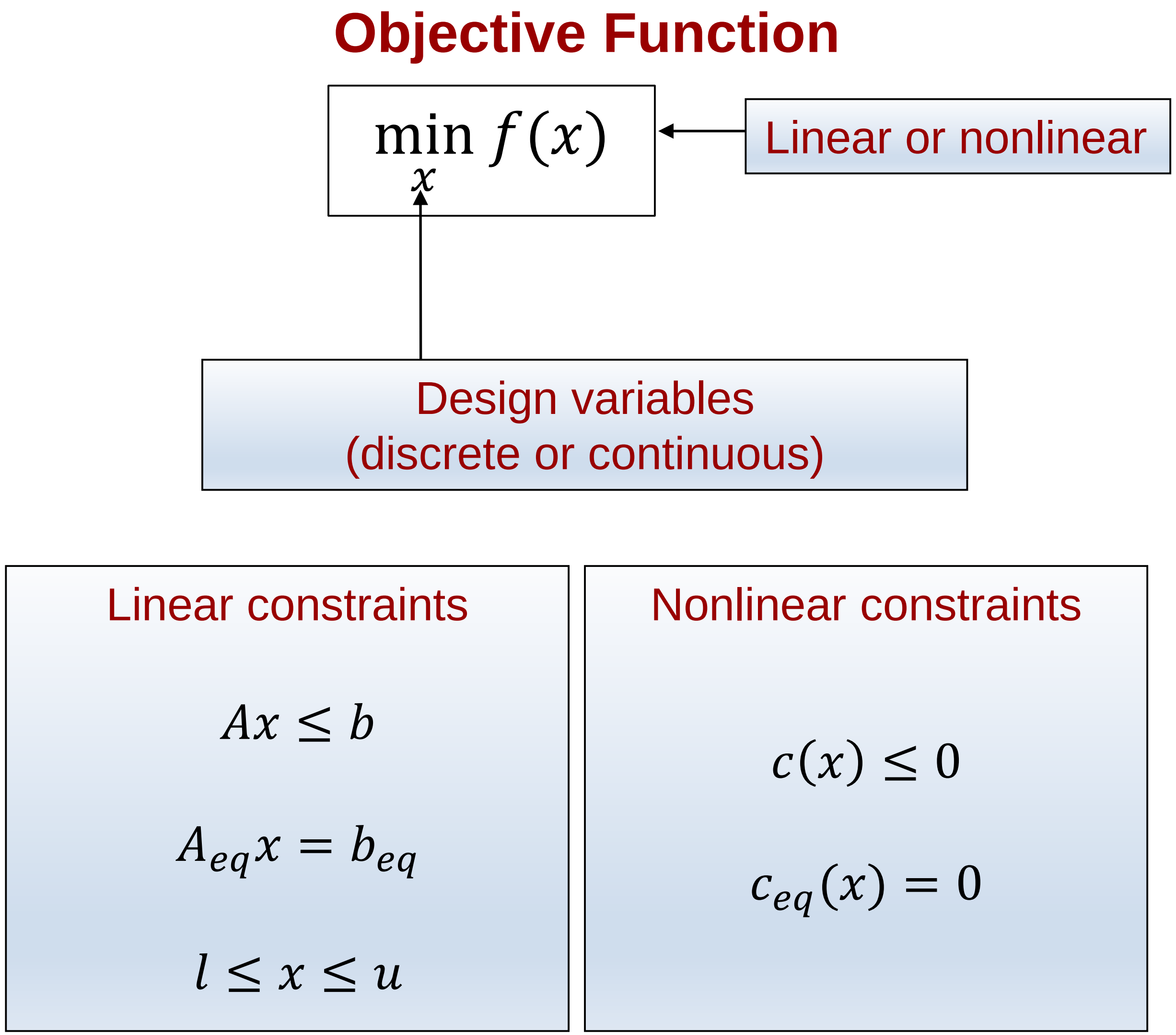
Define an Objective Function and Optimize!

Defining an Objective Function

Optimization Introduction

Minimizing (or maximizing) objective function(s) subject to a set of constraints

- **Objective** function – What you are trying to achieve?
  - Minimize measured signal
- Design **variables** – What parameters need to be adjusted?
  - Physical model parameters
  - Controller gains
- **Constraints** – What are the bounds or constraints of the design variables?
  - Min/Max values
  - Can handle inside objective function



Formulating an Optimization Problem for Objective Drivability

Objective

What are my goals?

- Minimize oscillations
- Minimize response time

Variables

What are my choices?

- Rate limit
  - Gear
  - ΔTorque Request
  - Vehicle speed

Constraints

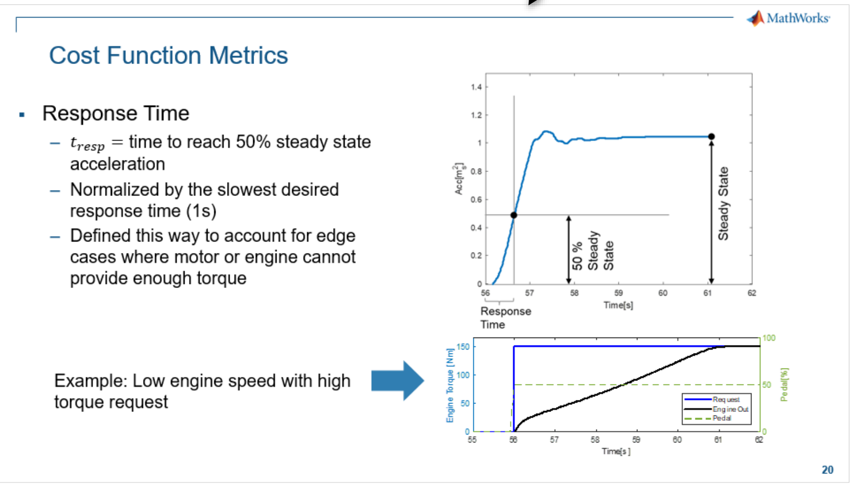
What restricts my choices?

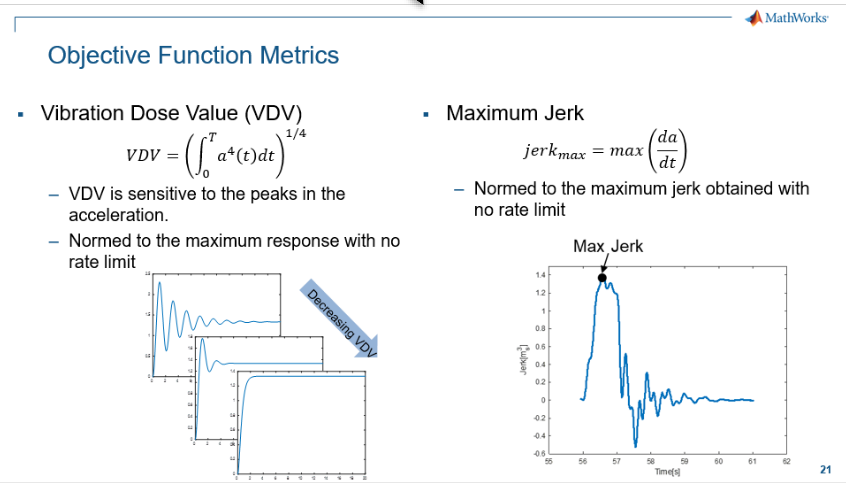
- Response Time
- Jerk
- Etc.

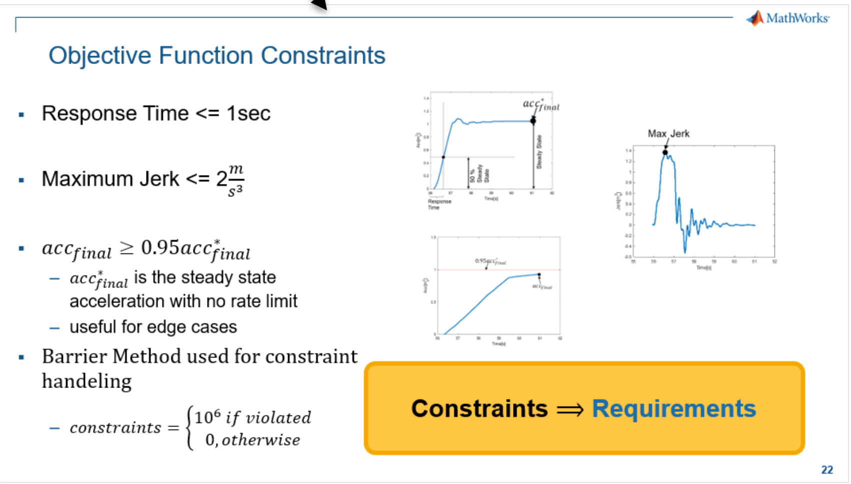
Objective Function

Shuffle Objective Function

$$\min_{RL}\left(t_{resp} + jerk_{max} + VDV + constraints\right)$$

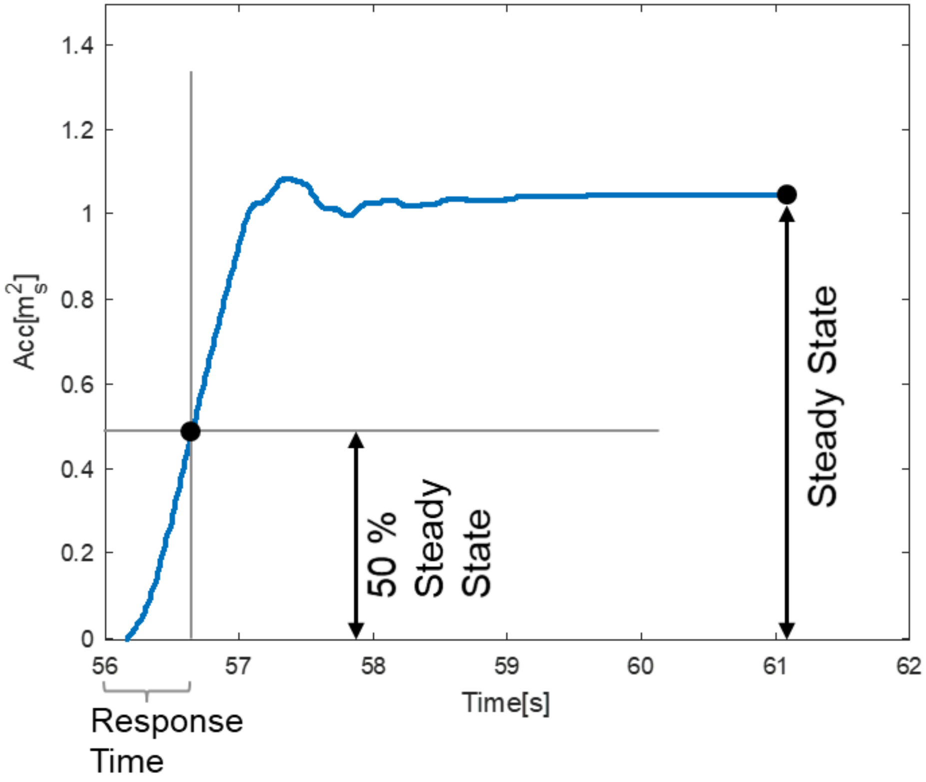




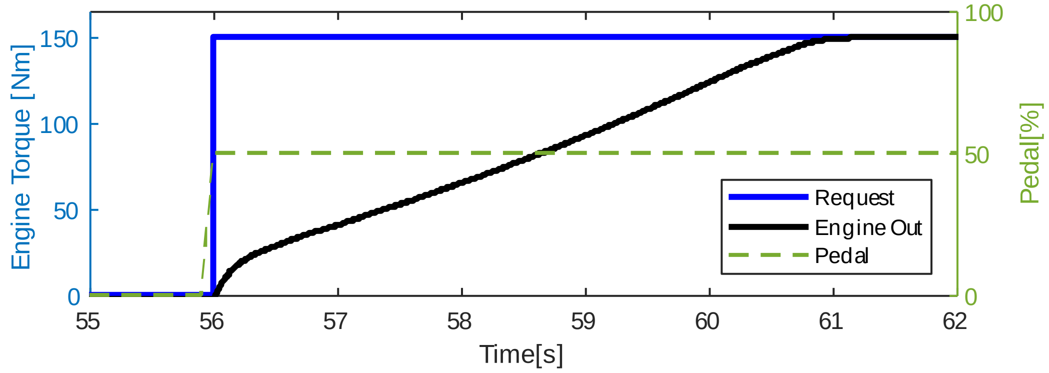


Cost Function Metrics

- Response Time
  - t_{resp} = time to reach 50% steady state acceleration
  - Normalized by the slowest desired response time (1s)
  - Defined this way to account for edge cases where motor or engine cannot provide enough torque



Example: Low engine speed with high torque request

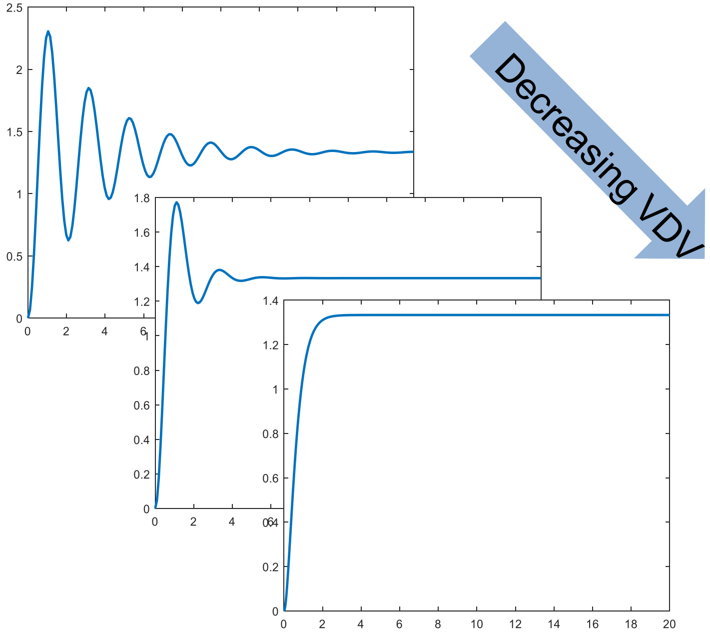


Objective Function Metrics

- Vibration Dose Value (VDV)

$$VDV = \left(\int_0^T a^4(t)dt \right)^{1/4}$$

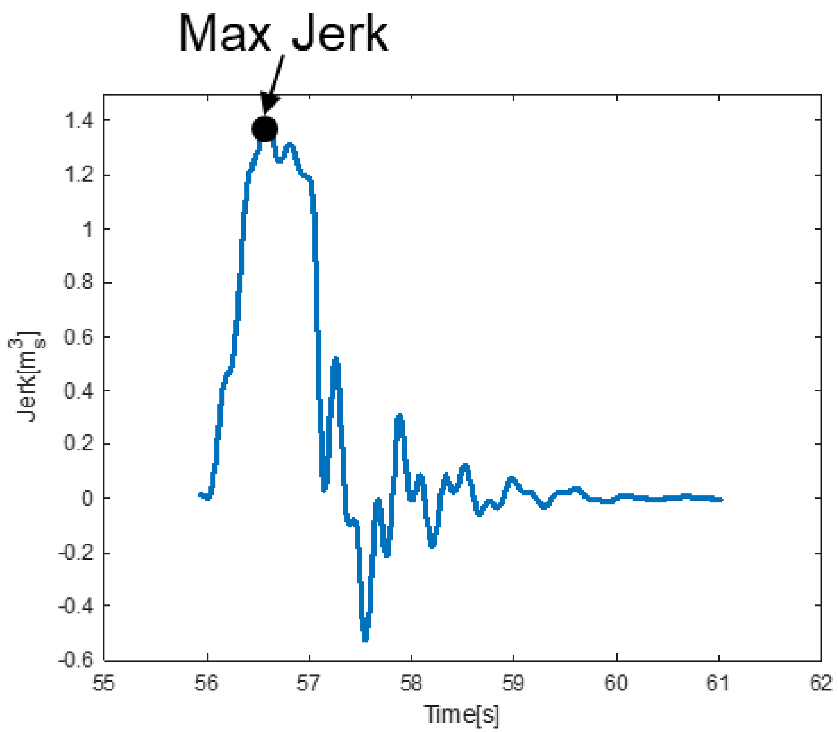
  - VDV is sensitive to the peaks in the acceleration.
  - Normed to the maximum response with no rate limit



- Maximum Jerk

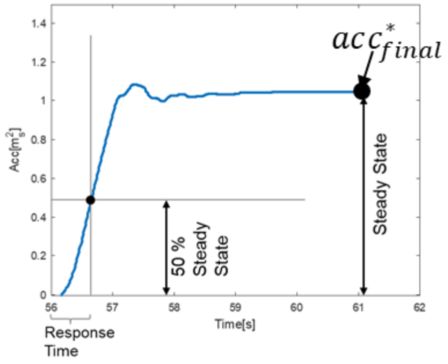
$$jerk_{max} = max\left(\frac{da}{dt}\right)$$

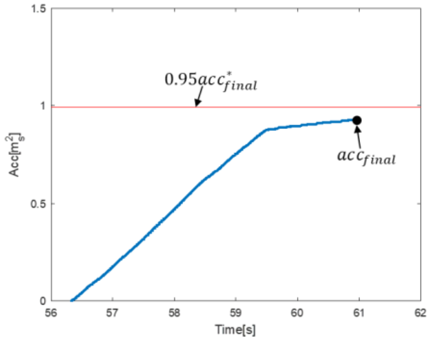
  - Normed to the maximum jerk obtained with no rate limit

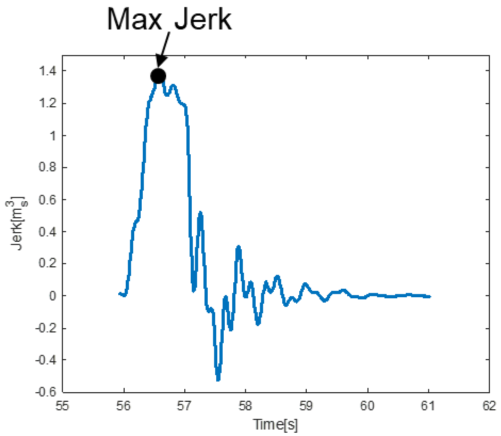


Objective Function Constraints

- Response Time <= 1sec
- Maximum Jerk <= $2\frac{m}{s^3}$
- $acc_{final} \geq 0.95 acc^{*}_{final}$
  - acc^{*}_{final} is the steady state acceleration with no rate limit
  - useful for edge cases
- Barrier Method used for constraint handeling
  - $constraints = \begin{cases} 10^6 \; if \; violated \\ 0, otherwise \end{cases}$





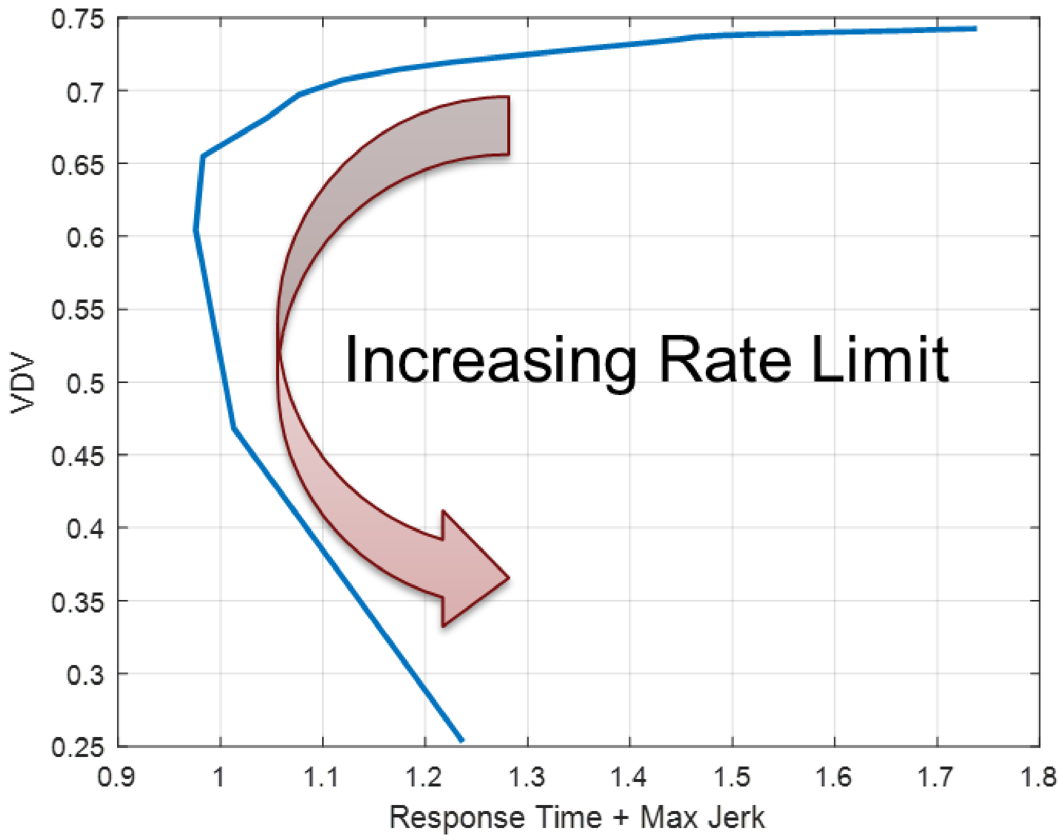


Constraints ⟹ Requirements

Objective Function

Observations

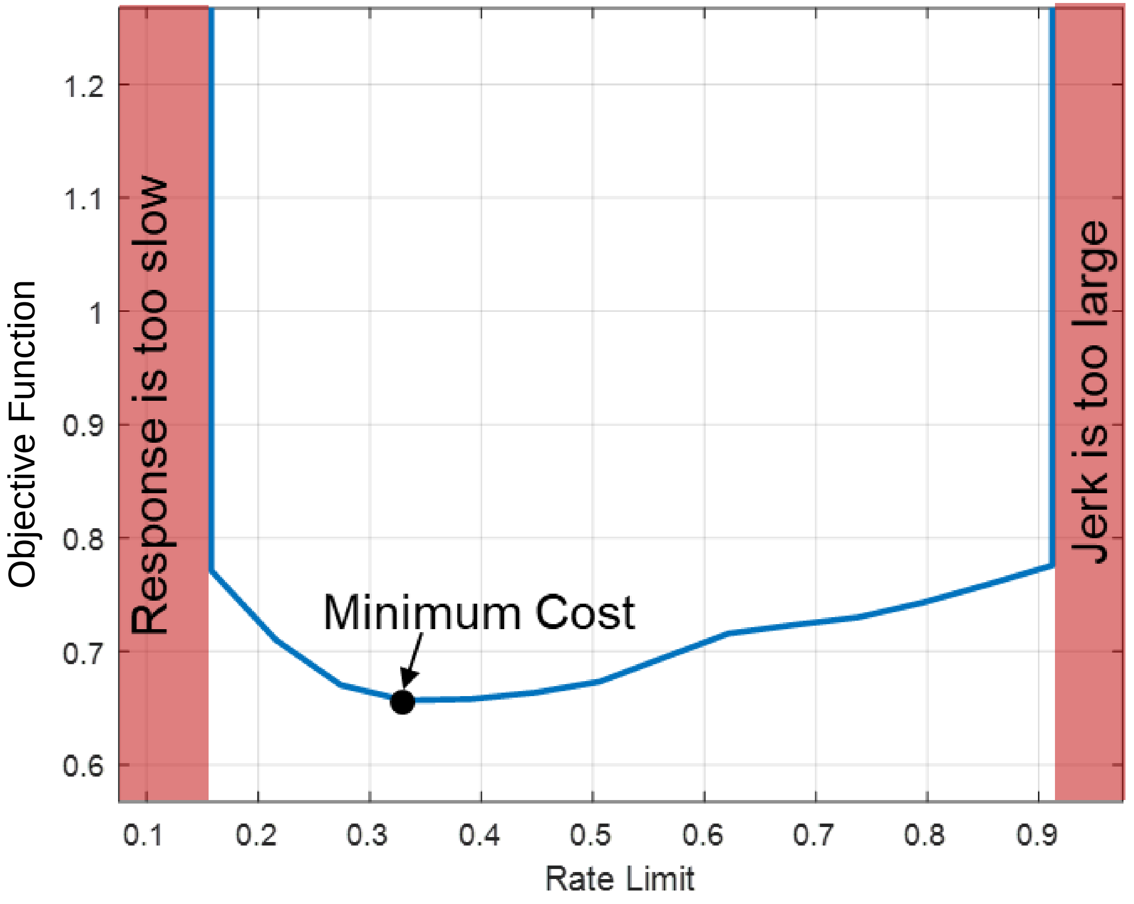
- Pareto curve exists between oscillations and response time
  - the faster the response, the more oscillations



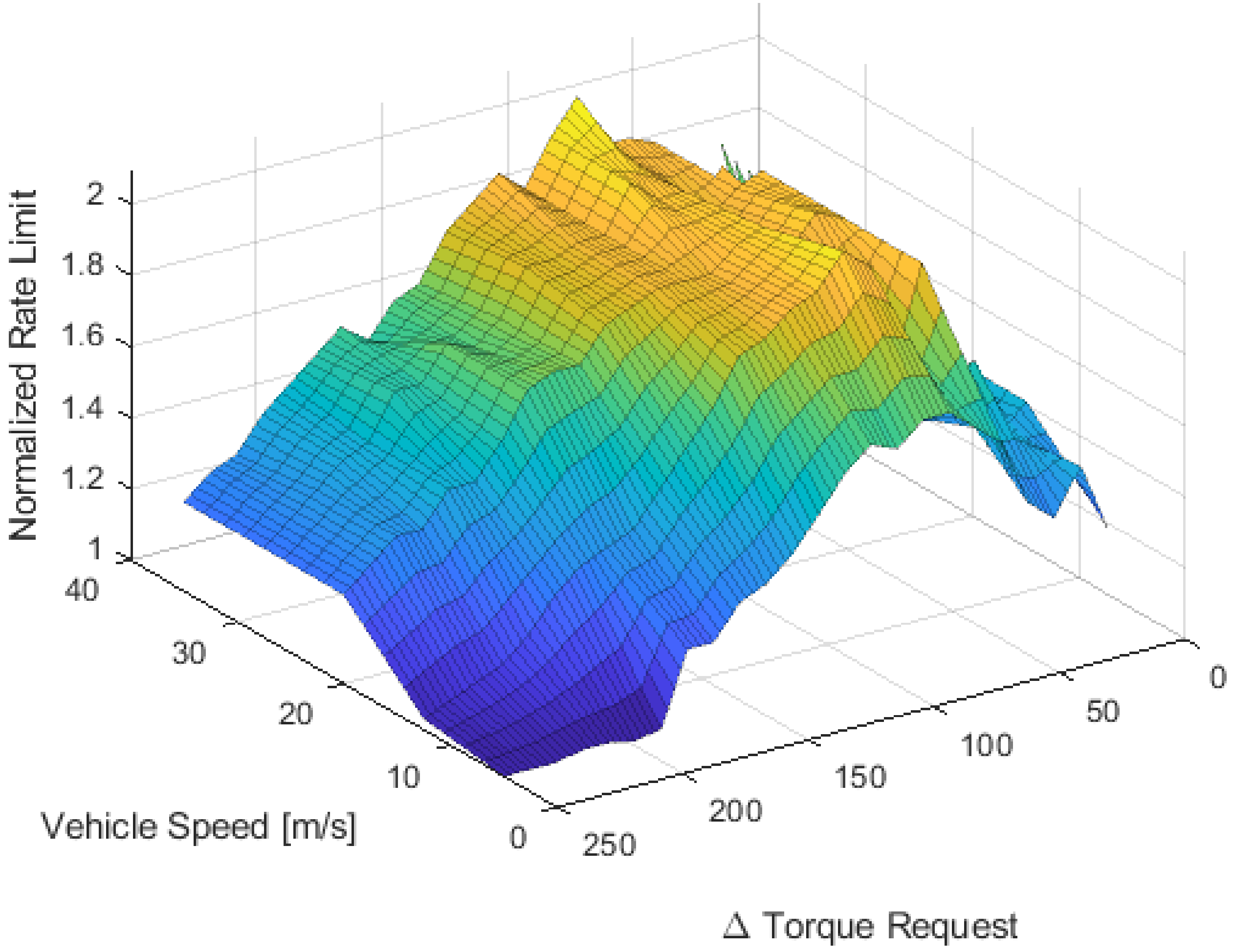
Objective Function

<u>Observations</u>

- Objective function:
  - Can be non-smooth
  - Can have multiple minima

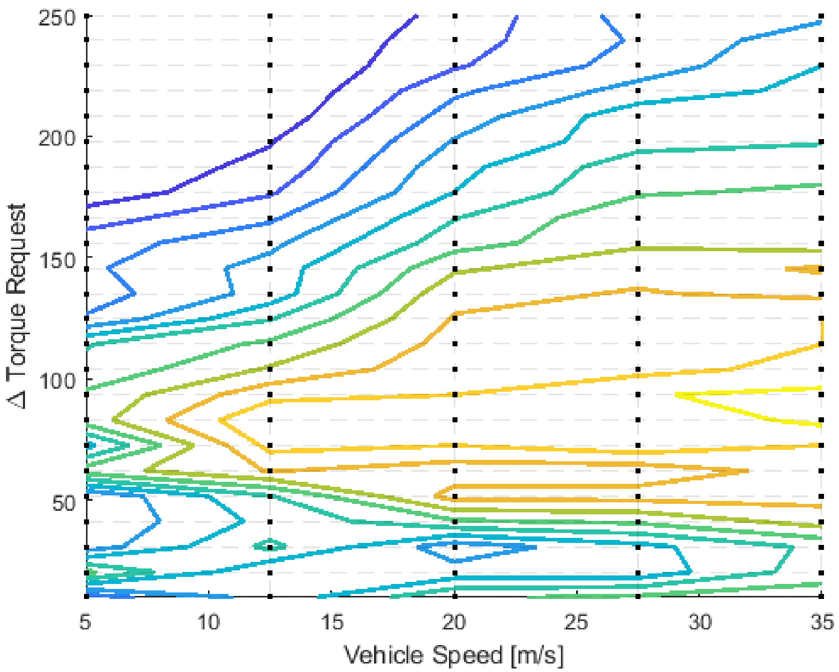


Optimal Calibration



Calibration Process

- Intel Xeon E5 processor – 3.6GHz, 6 cores
- 64GB RAM
- 1806 Optimal Rate-Limits
  - 7 total maps (6 for engine, 1 for motor)
  - 24 Δtorque breakpoints
  - 5 speed breakpoints

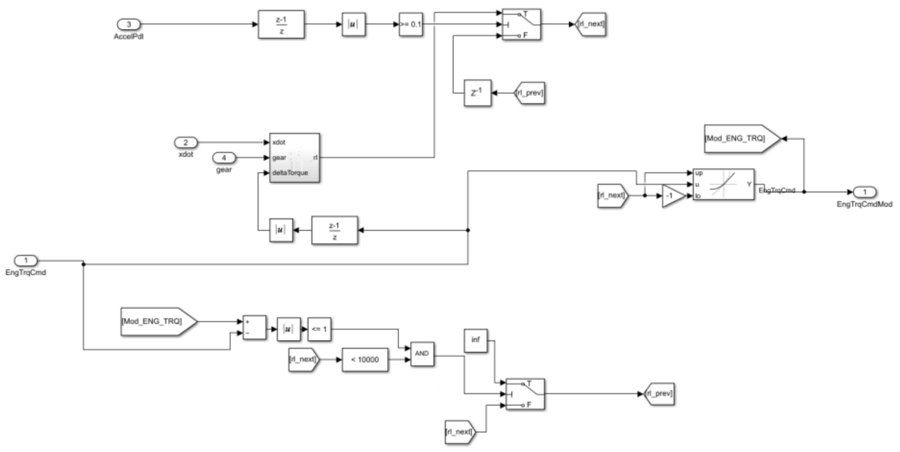


- Traditionally, this process could take days or weeks for manual calibration
- 10 hours to automatically calibrate using pattern search global optimization algorithm

Search Algorithm	Time	Solution Found
fmincon	1.5minutes	✘
Particle Swarm	5 minutes	✓+
Pattern Search	1.5minutes	✓

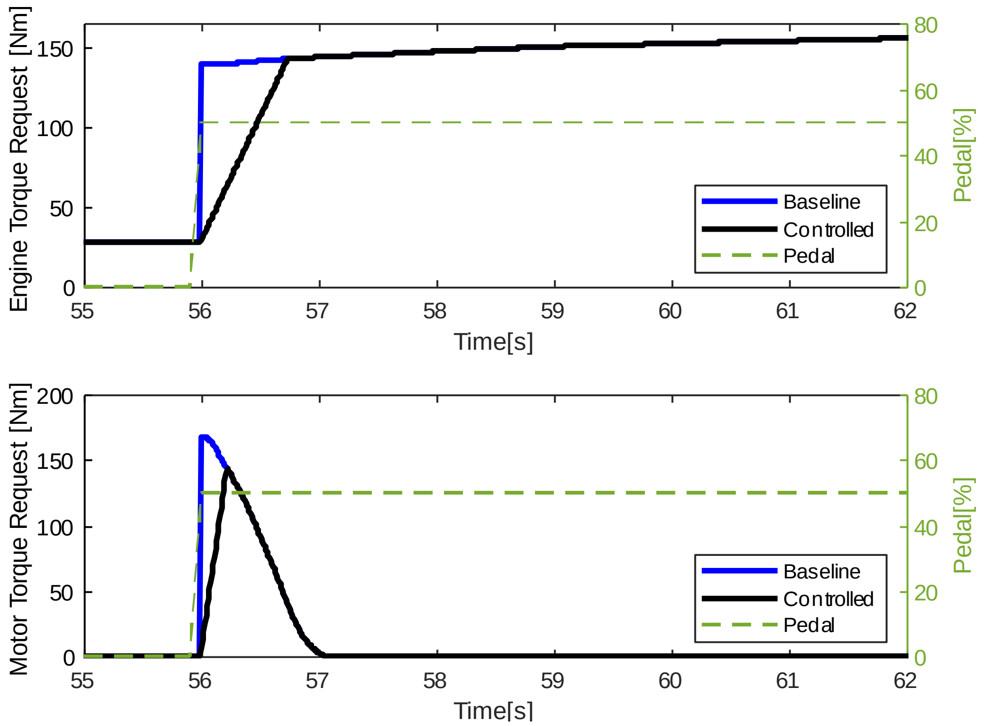
Tip-In Controller

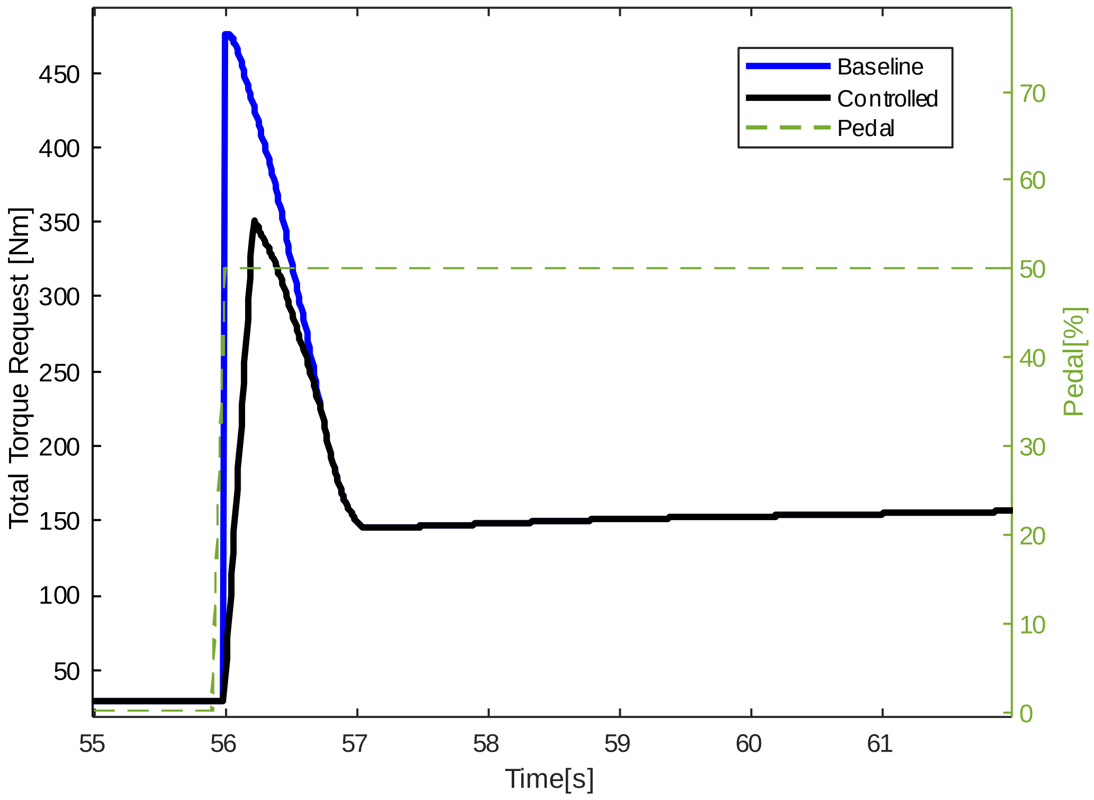
- Rate limit is calculated as a function of |ΔTorque request|, vehicle speed, and Gear (engine side only)
- Rate limit is applied when judged a tip in response
  - |ΔTorque request| >10Nm
  - Vehicle Speed > 2 MPH
- Rate limit held until modified torque is near final desired torque value.



Tip-In Controller

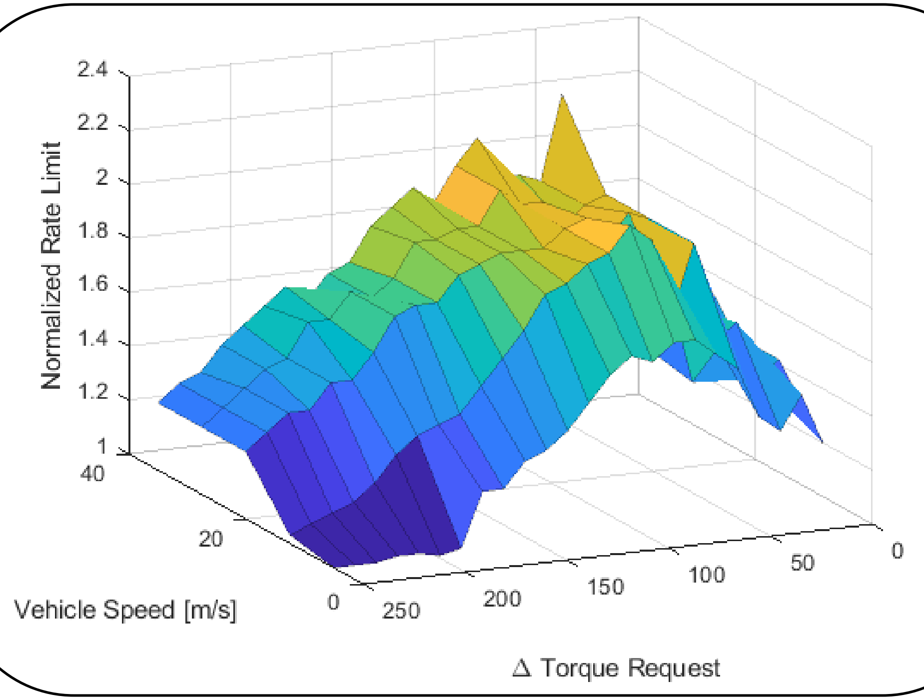
- Controlled Response



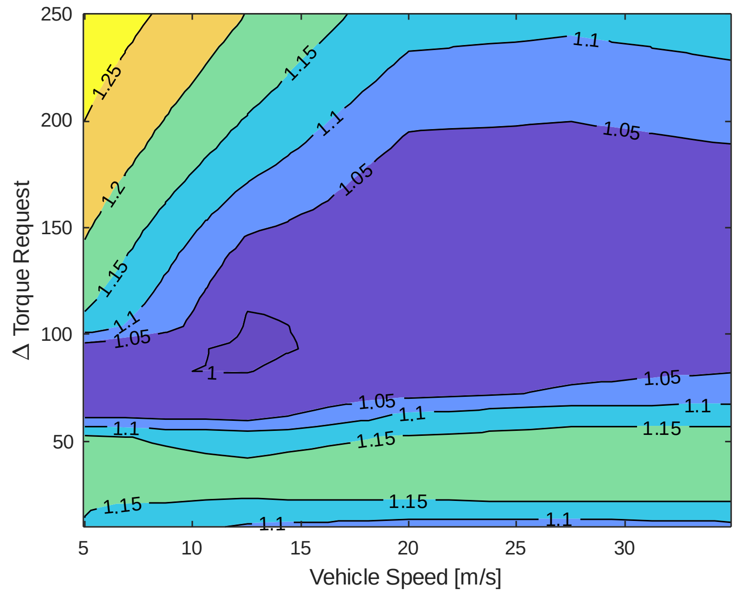


Calibration Tables

- Areas of high sensitivity in the objective function can be used to redefine map breakpoints
- Example results for 5th gear

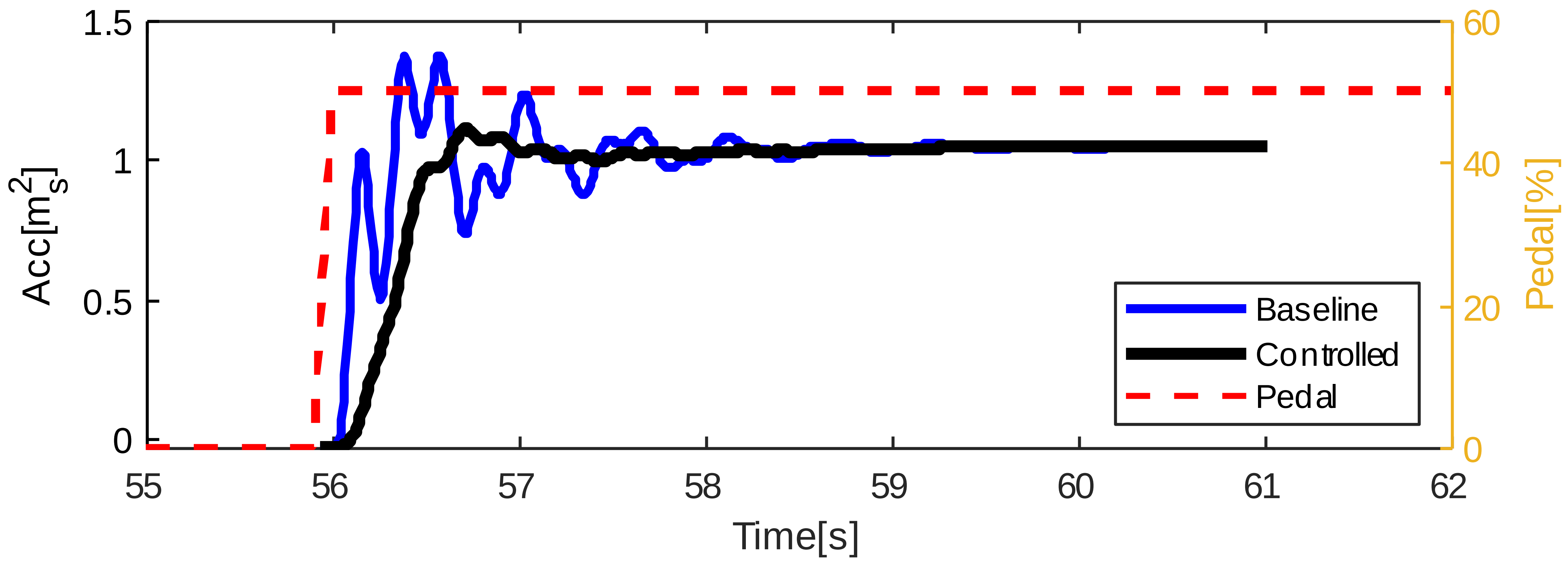


Calibration Map



Optimized Objective Function Values

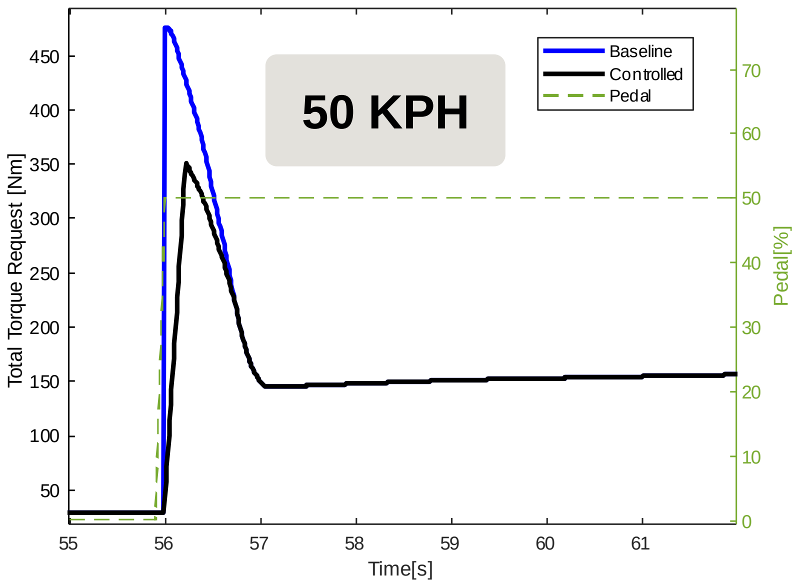
Validation

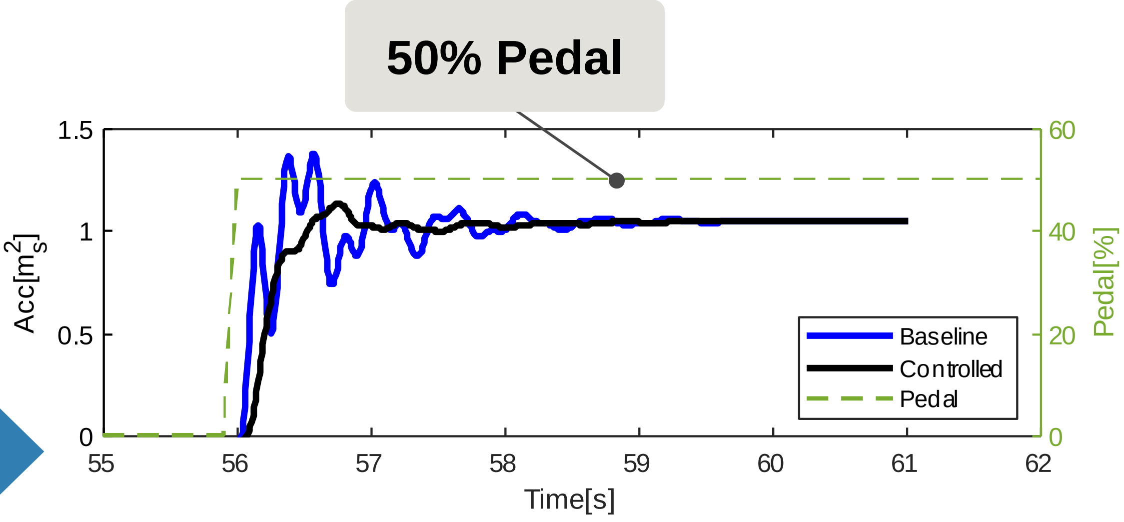


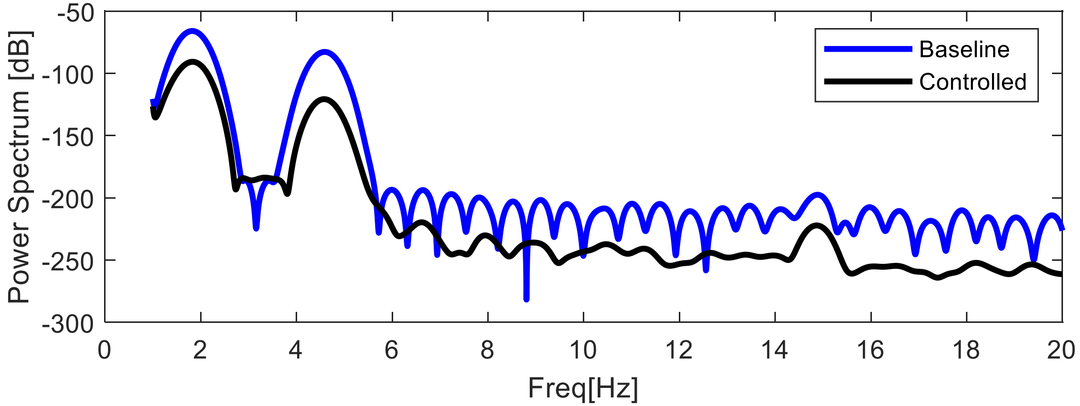
1.5
1
0.5
0
Acc[m/s²]
60
40
20
0
Pedal[%]
55
56
57
58
59
60
61
62
Time[s]
Baseline
Controlled
Pedal

Tip-In Results

- First engine and motor modes have decreased greatly (~50dB)
- Fast Tip-In response – 0.5s

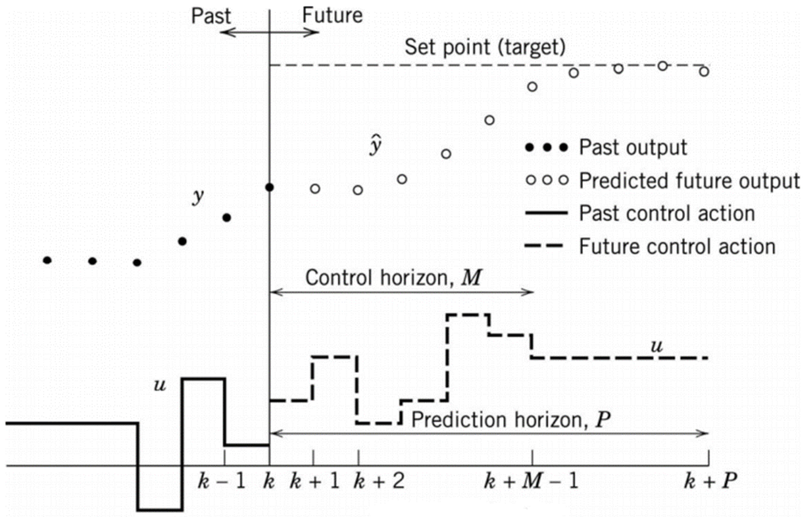


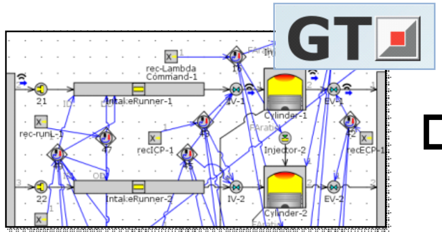


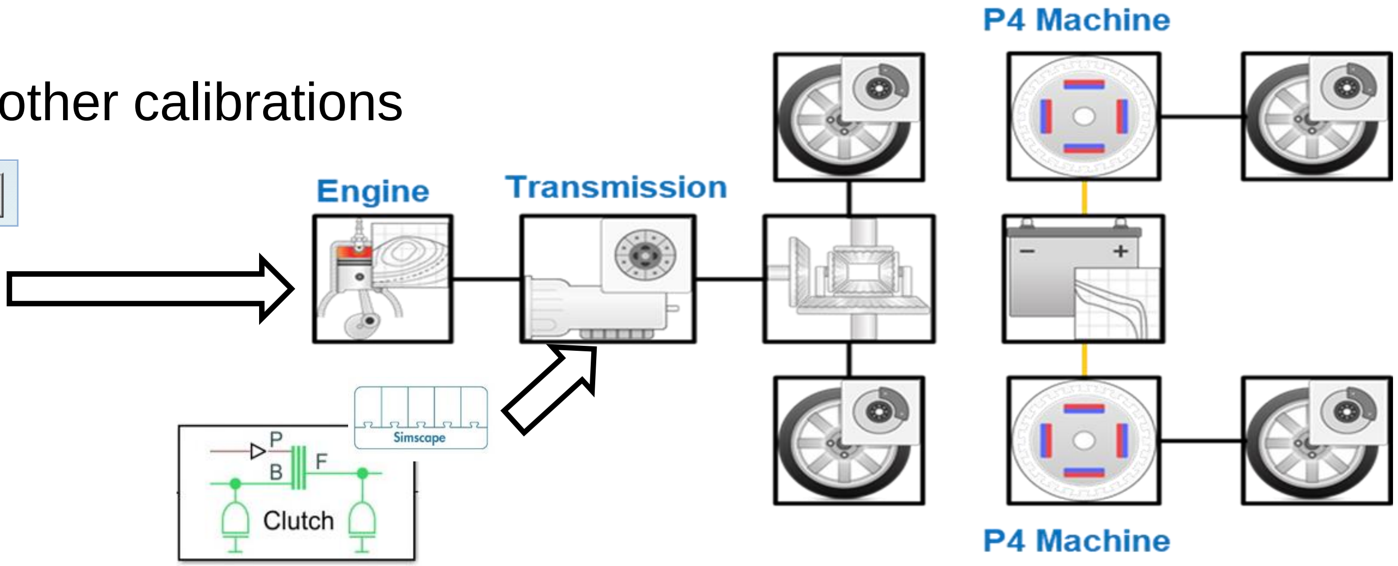


Next Steps

- What are possible next steps?
  - Investigate more control options
    - Use sensitivity analysis to refine breakpoints in calibrated maps
    - Model Predictive Control with consideration for Fuel Economy
  - Process can be reused as model fidelity increases
    - GT Engine model
    - Simscape Driveline
  - Utilize process for other calibrations

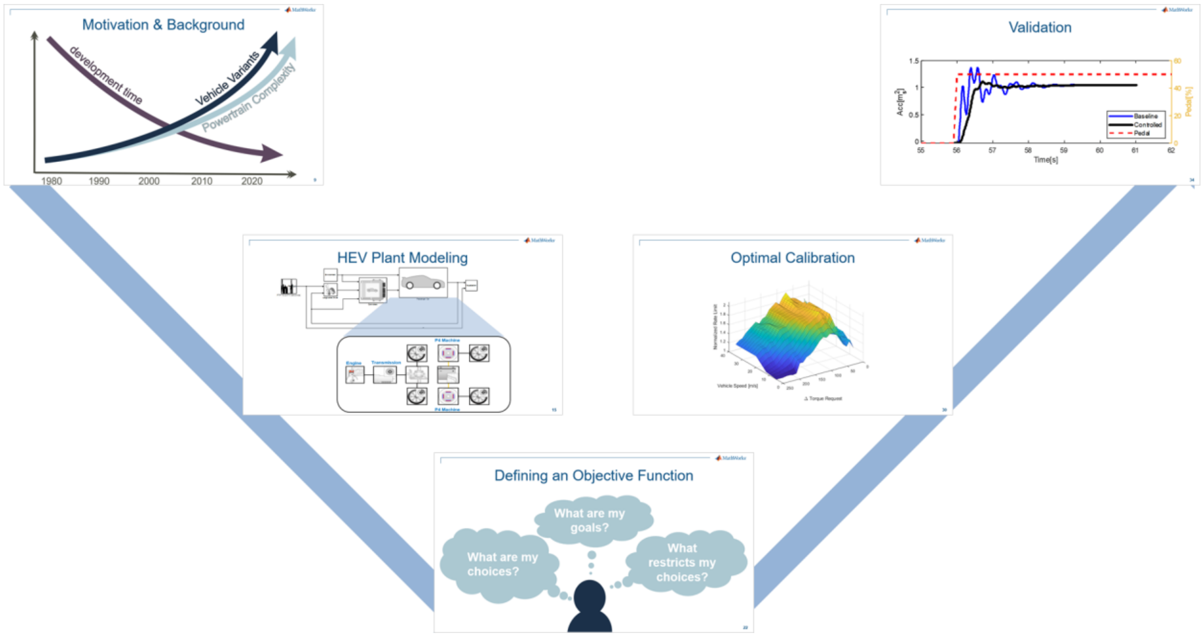






Summary

- A process for using an objective function to automate and improve shuffle response was shown
- Virtual calibration allowed process to be done in hours instead of weeks
- Along with FE and Acceleration characteristics, can also start to consider some drivability metrics during early phase planning



Thank You

Jason Rodgers, MS
Senior Application Engineer
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References

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