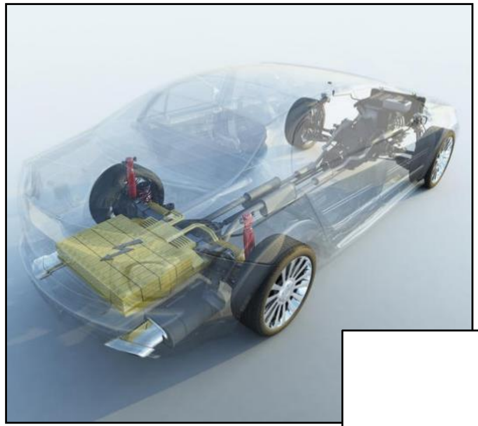
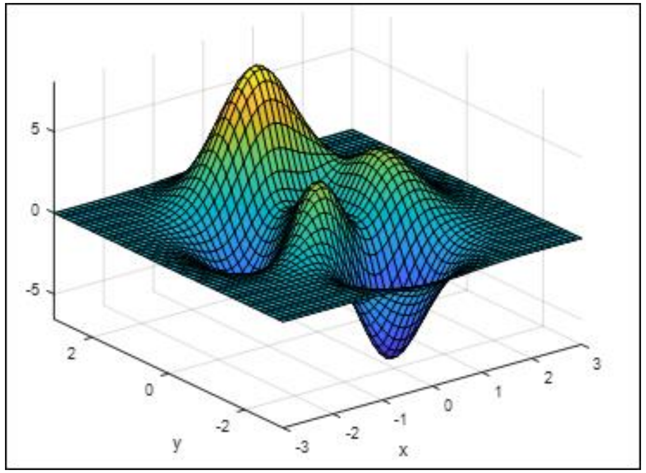
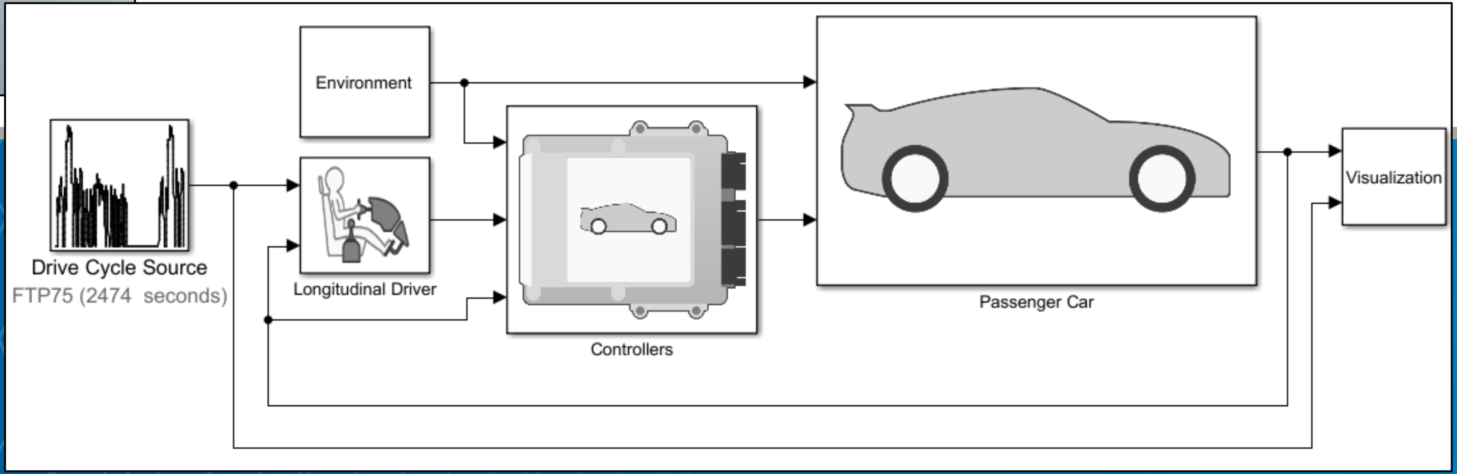
Objective Drivability Calibration

MathWorks Automotive Conference

April 11th, 2019





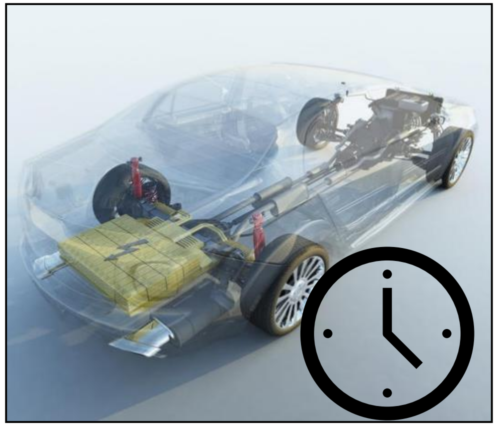


Co-Authors:
Jason Rodgers &
Jan Janse van Rensburg*

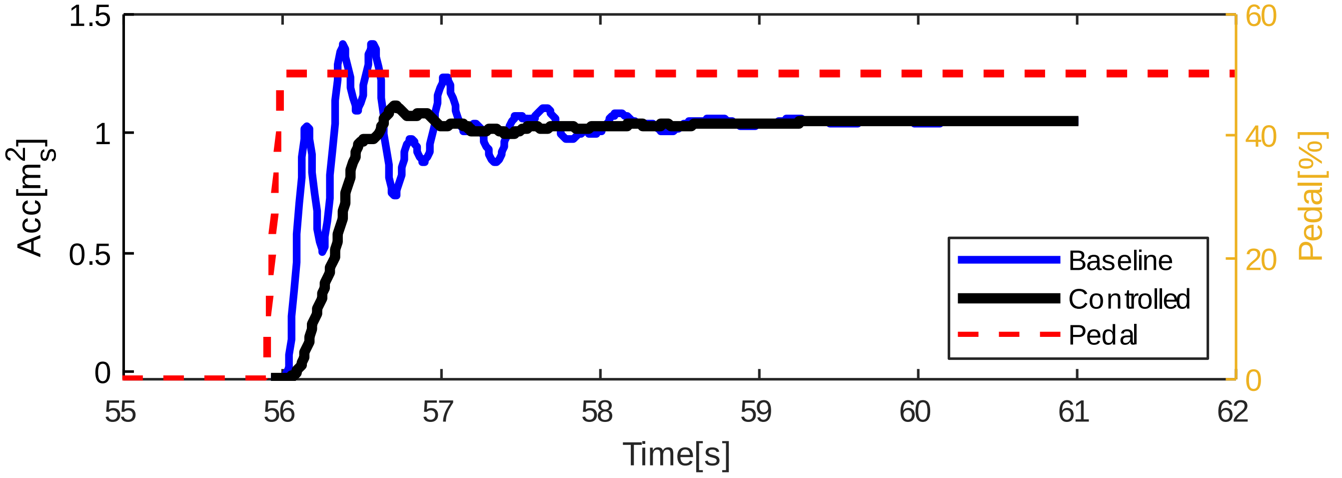
MathWorks

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



- How to solve the problem?
  - Use objective based approach to tune ECU calibration parameters
    - I. Requirements driven
    - II. Repeatable and automated
    - III. Objective based

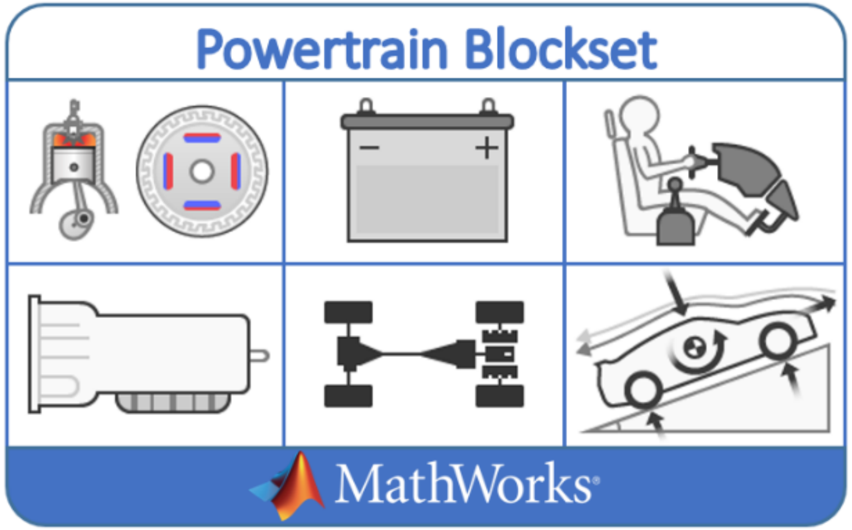


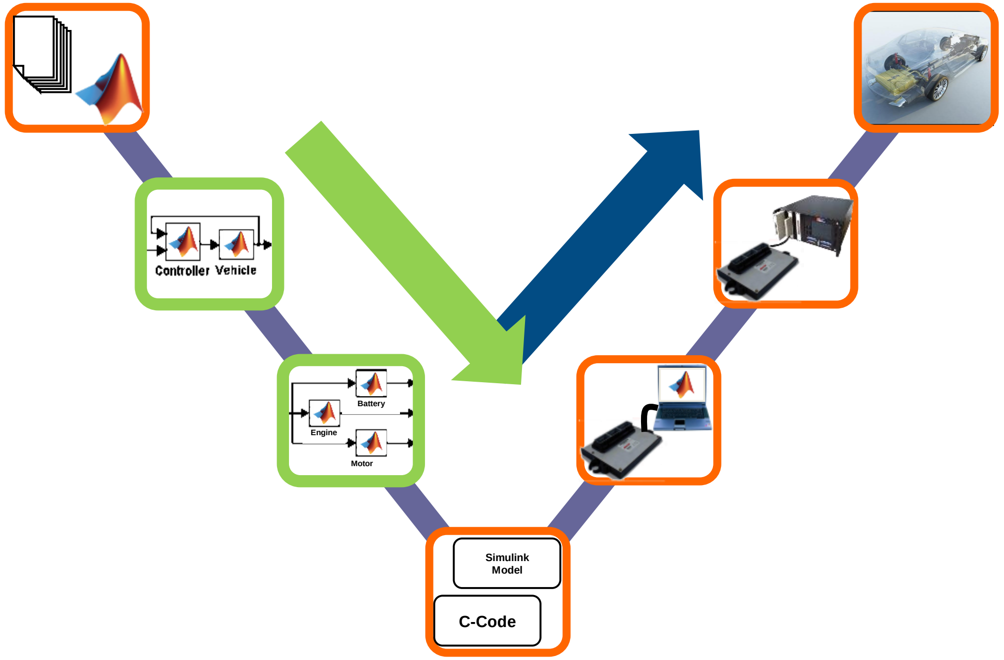
Key Takeaways

- Powertrain Blockset is capable of simulating some low frequency drivability behavior

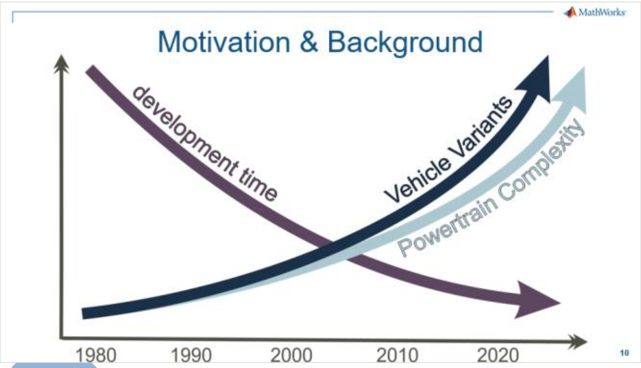
- Model re-use from early planning phase can be used to jumpstart calibration efforts

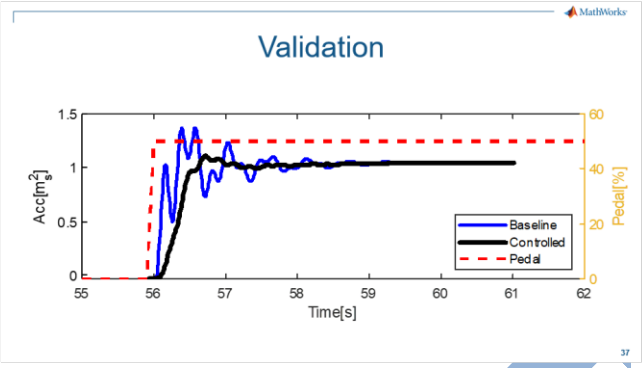
- Objective-based calibration can:
  - Improve calibration time
  - Account for performance trade-offs
  - Trace back to requirements
  - Objective and not subjective

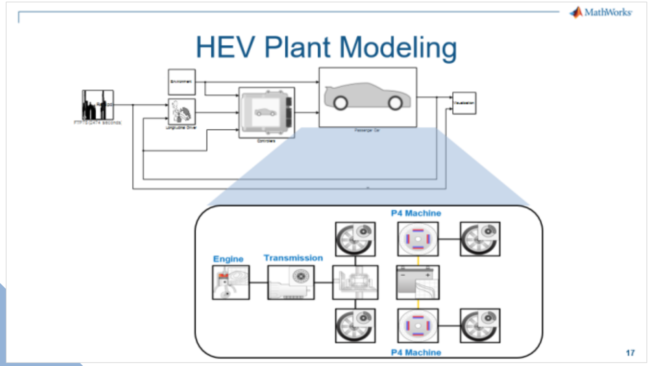


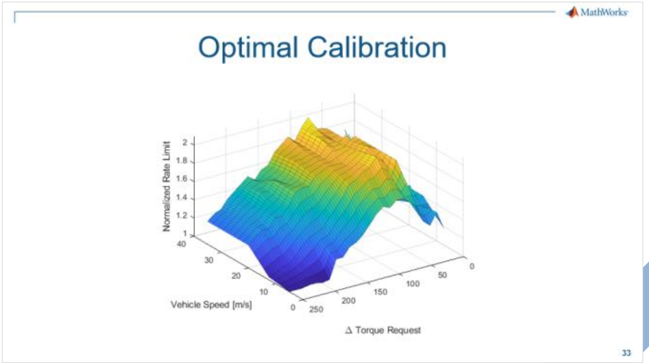


Agenda


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

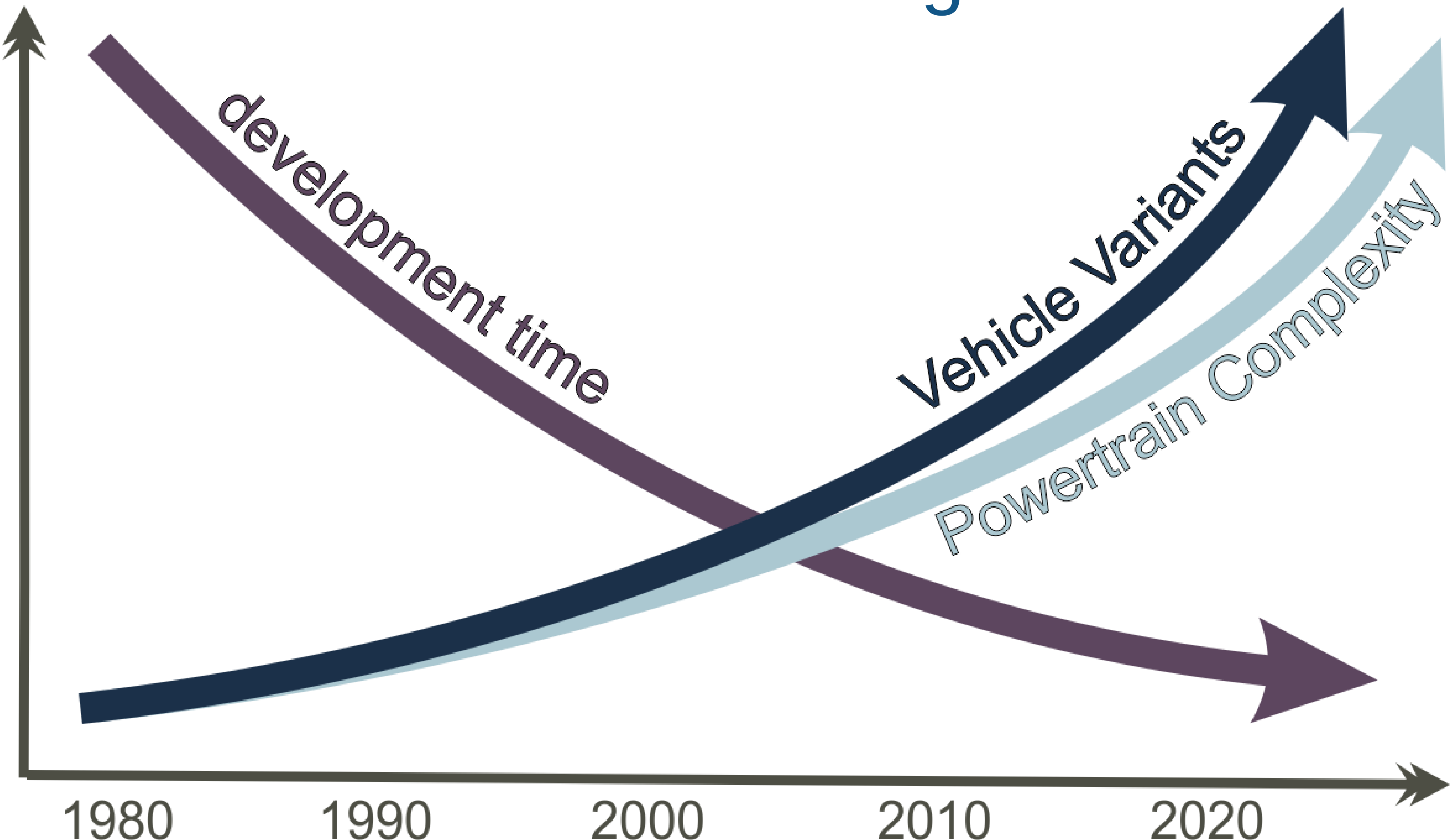

Validation
Acc[m/s2]
Pedal[%]
Time[s]
Baseline
Controlled
Pedal


HEV Plant Modeling
P4 Machine
Engine
Transmission
P4 Machine


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


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

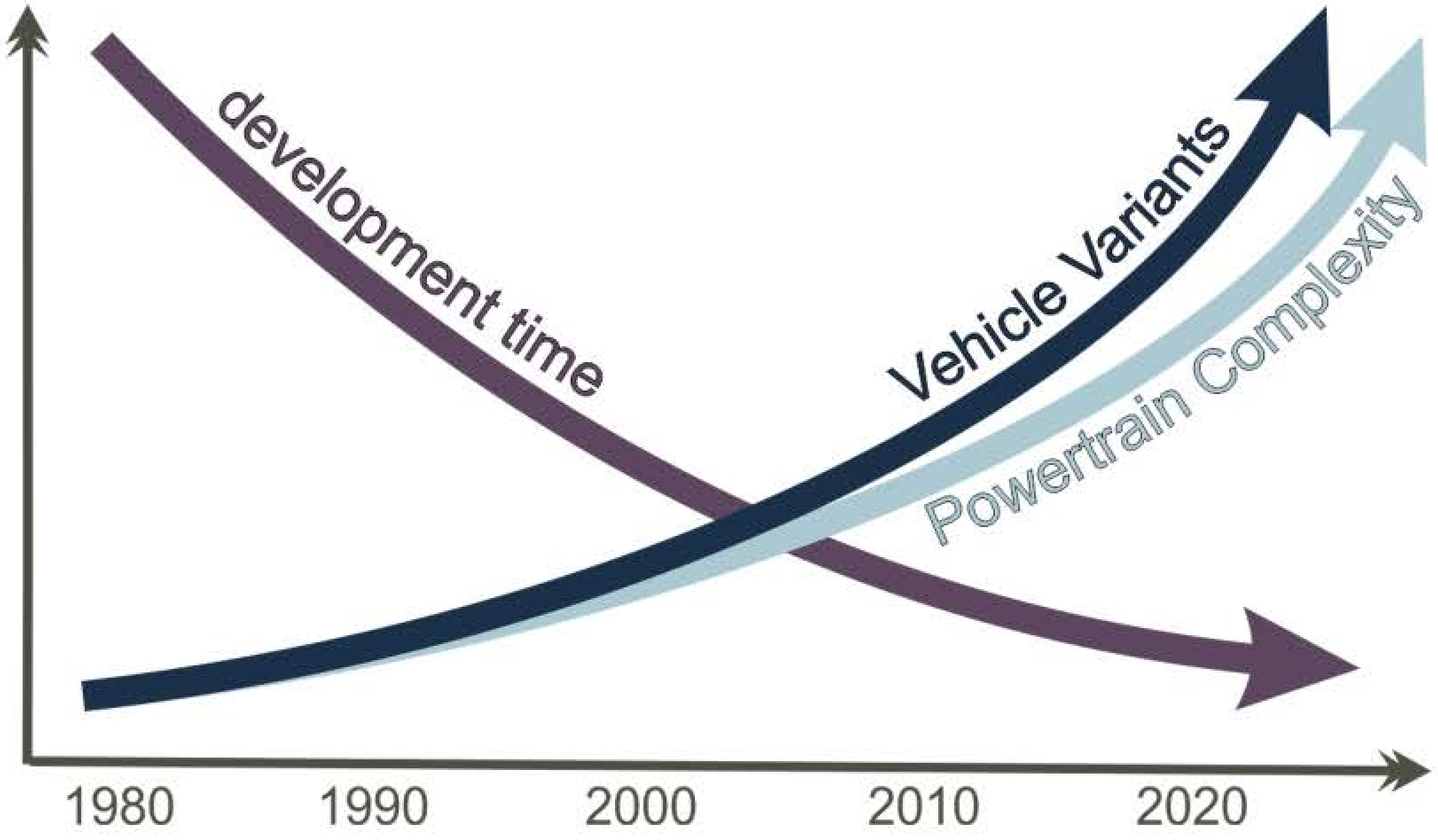
Motivation & Background



Motivation

- Current OEM Requirements
  - Reduce overall operating costs
  - Improvement of vehicle quality for higher customer satisfaction
  - Develop Brand-Specific performance

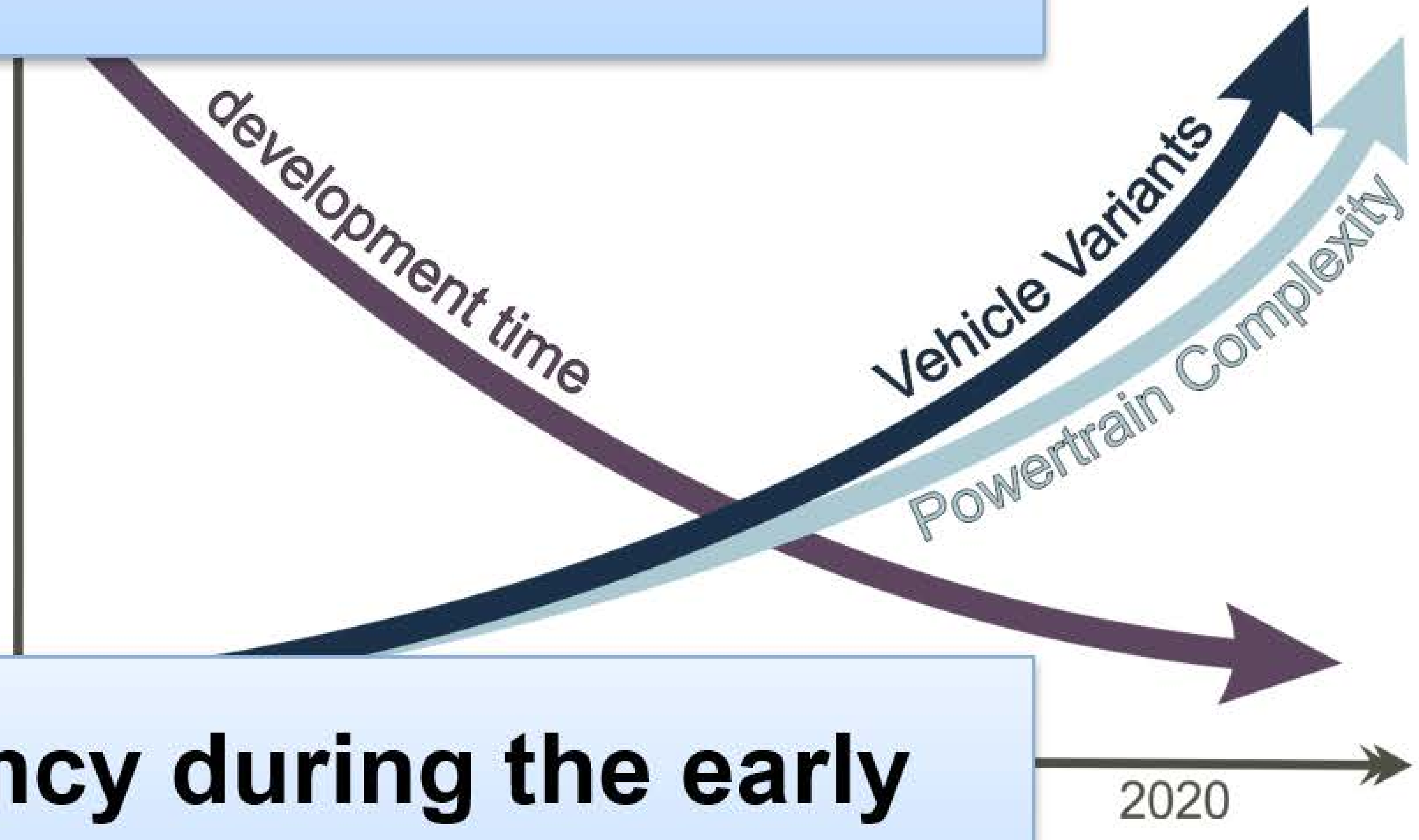
- Current OEM Constraints
  - Decreased development time
  - Increased Powertrain complexity
  - Increasing number of vehicle variants



Motivation

- Current OEM Requirements
  – Reduce overall c
  – Improvement of v
  – Develop Brand-S

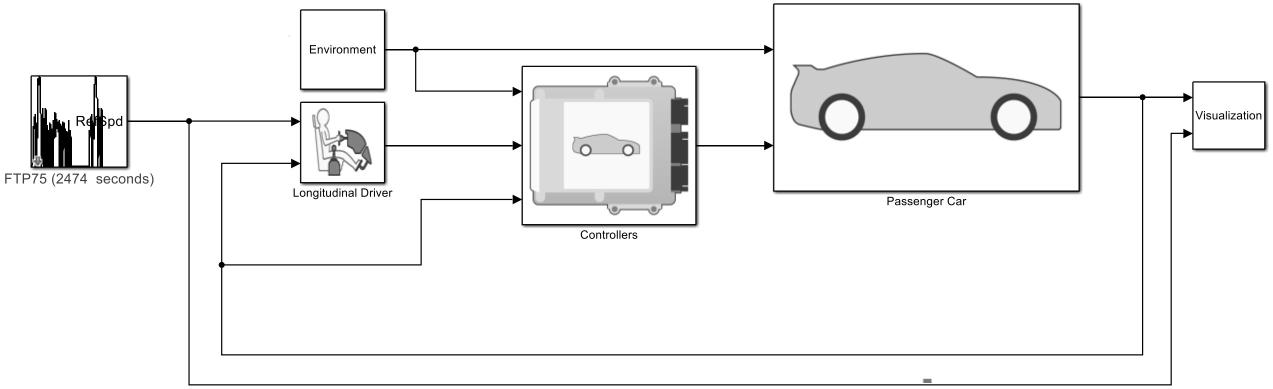
How to juggle requirements and constraints?



- Current OEM Constraints
  – Decreased development time
  – Increased Powertrain complexity
  – Increasing number of vehicle variants

Increase efficiency during the early development process!

Motivation

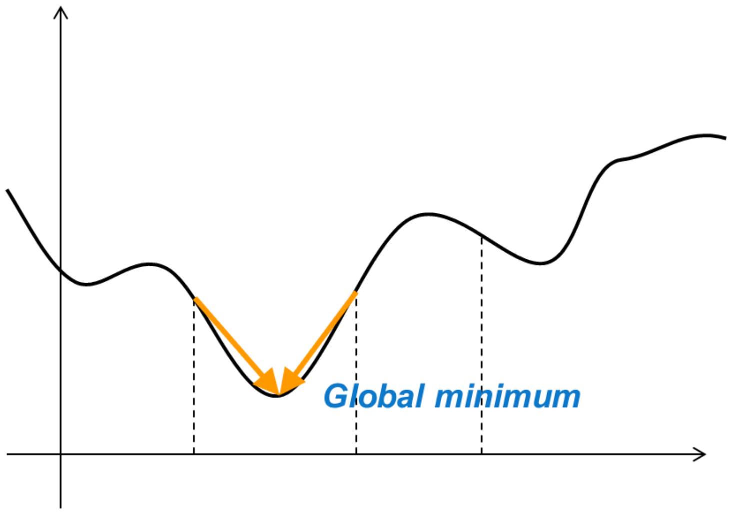


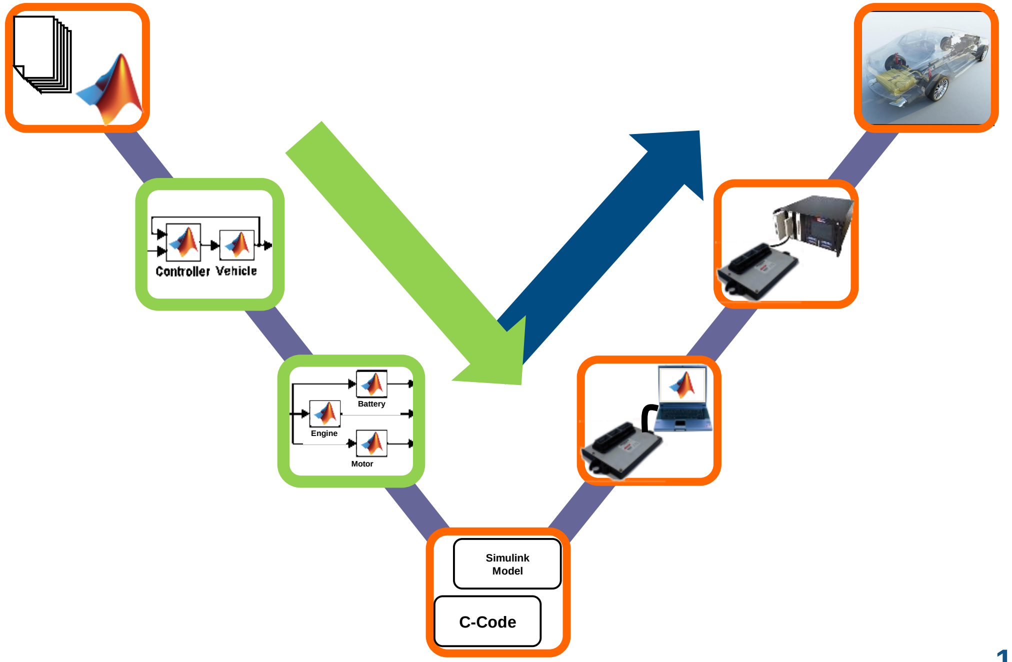
Efficiency Improvements

- Model-Based Development (Process Virtualization)

- Model Reuse

- Objective-Based Calibration Process

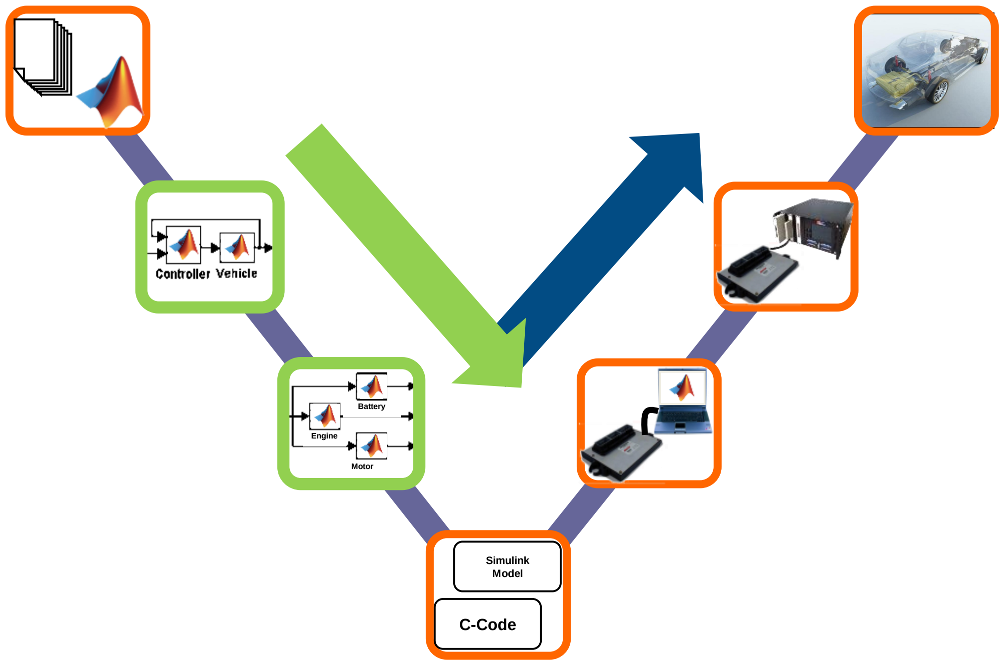




Motivation

Efficiency Improvements

- Model-Based Development (Process Virtualization)
  - Front-Loading Development Process
  - Virtual Calibration
  - Check new controller designs
  - Early detection of design deficiencies
  - Reduced number of prototypes
  - Etc.

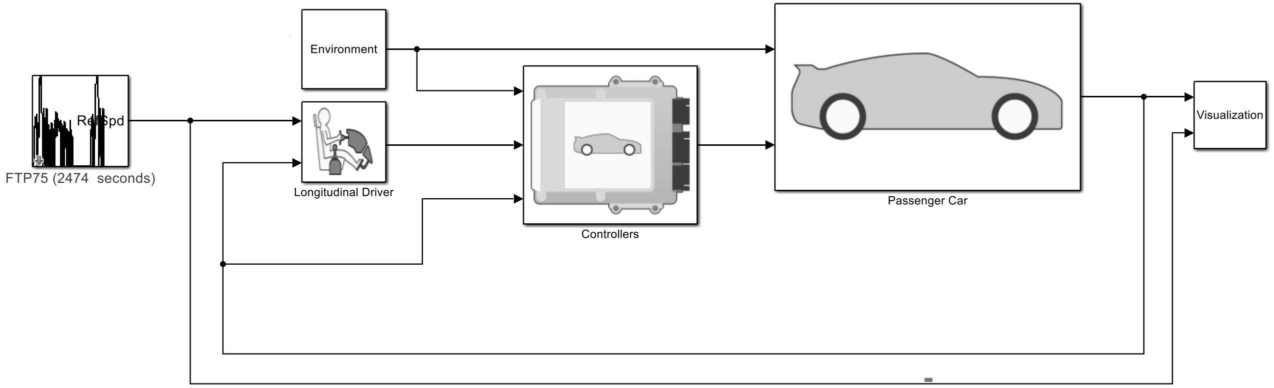


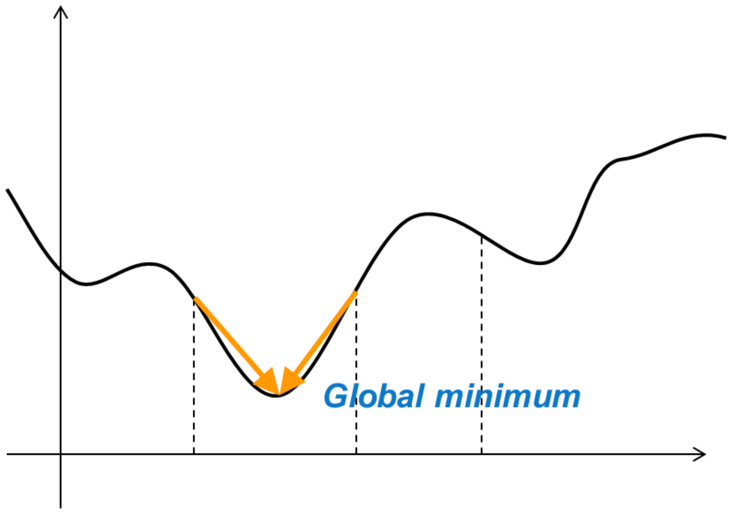
Motivation

Efficiency Improvements

- Model Reuse
  - FE/Acceleration models for tip-in
  - Early calibration

- Objective-Based Calibration Process
  - Requirements driven
  - Traceable
  - Repeatable
  - Automated
  - Optimal





Background

What is drivability?

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

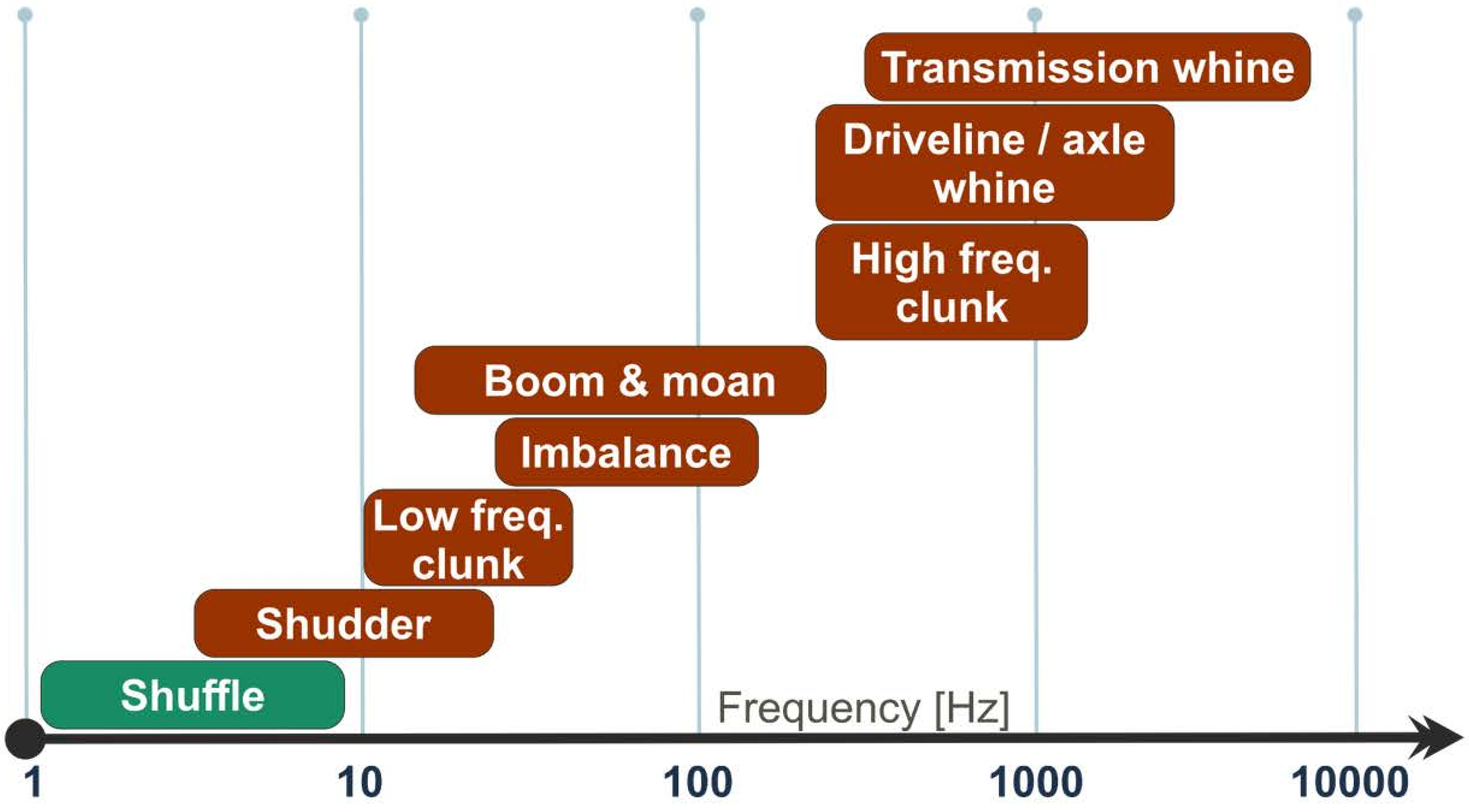
- Want the driver to be as comfortable as possible
  - Hesitation
  - Sluggish
  - Hard start
  - Noise/Oscillations

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

Wei,X.,&Rizzoni,G.(2004).Objective metrics of fueleconomy,performanceand driveability–Areview.SAETechnicalPaper,2004(2004-01-1338), http://dx.doi. org/10.4271/2004-01-1338.

Background

What are we focusing on?



Wellmann, T., Govindswamy, K., Braun, E., and Wolff, K., "Aspects of Driveline Integration for Optimized Vehicle NVH Characteristics," SAE Technical Paper 2007-01-2246, 2007

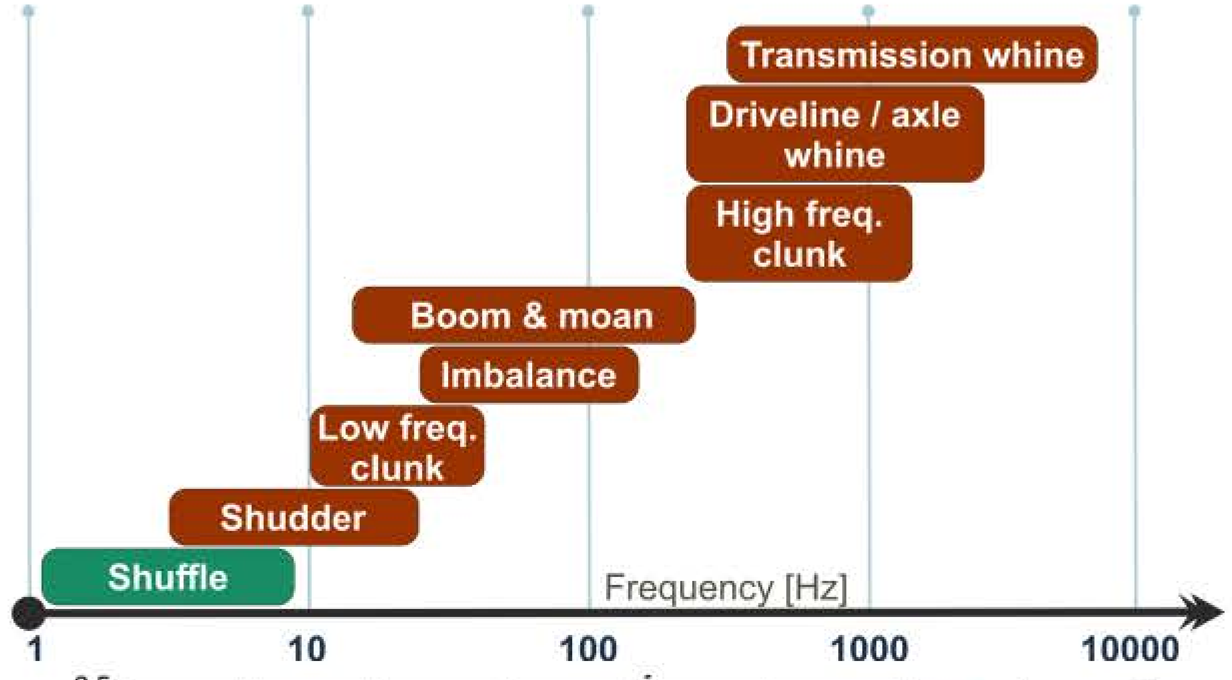
Atabay, O., Ötkür, M., & M Ereke, İ. (2018). Model based predictive engine torque control for improved drivability. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, *232*(12), 1654–1666. https://doi.org/10.1177/0954407017733867

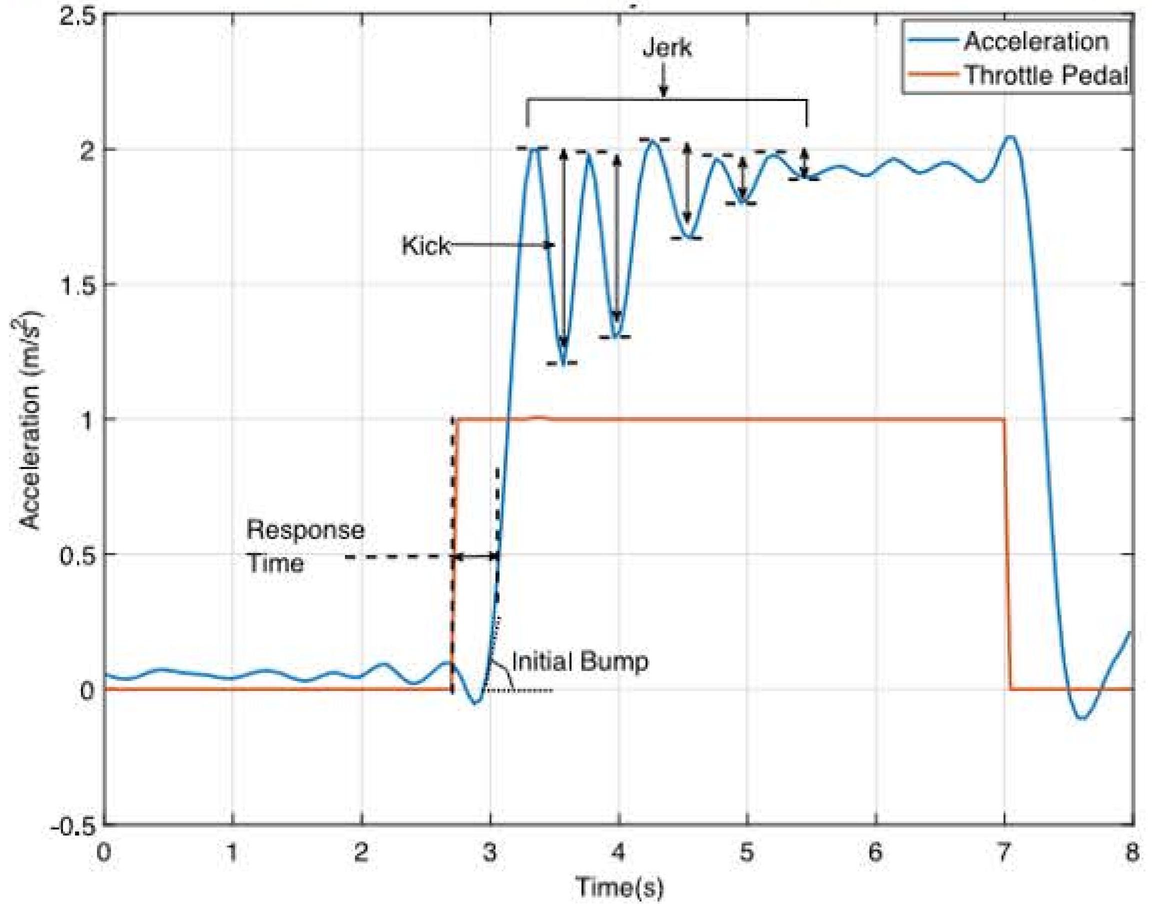
Jauch, C.; Tamilarasan, S.; Bovee, K.; Guvenc, L.; Rizzoni, G. Modeling for drivability and drivability improving control of HEV. Control Eng. Pract. 2018, 70, 50–62. [CrossRef]

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
- <5hz – human feel threshold
- Acceleration is measured at CG



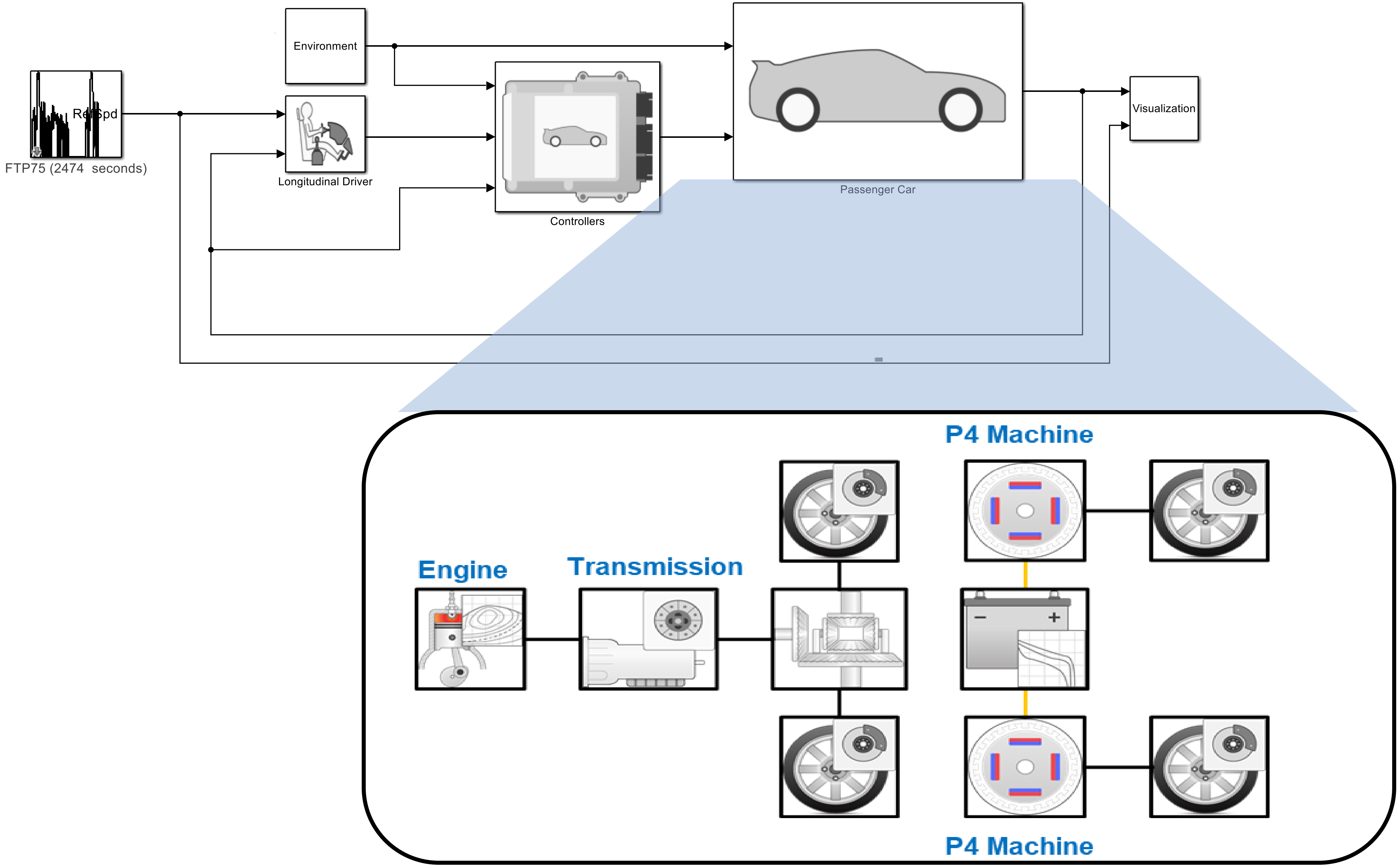


Wellmann, T., Govindswamy, K., Braun, E., and Wolff, K., "Aspects of Driveline Integration for Optimized Vehicle NVH Characteristics," SAE Technical Paper 2007-01-2246, 2007

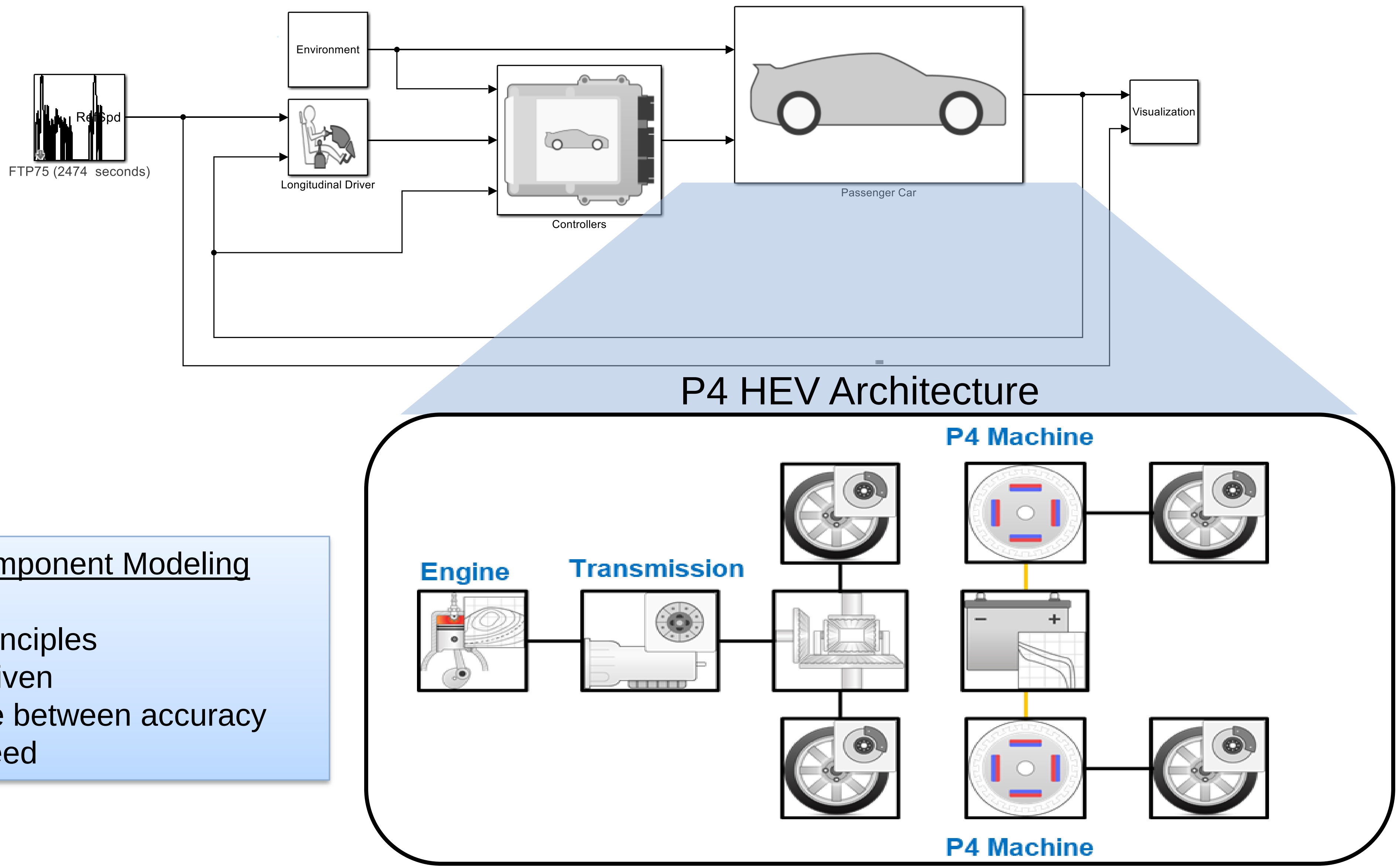
Atabay, O., Ötkür, M., & M Ereke, İ. (2018). Model based predictive engine torque control for improved drivability. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, *232*(12), 1654–1666. https://doi.org/10.1177/0954407017733867

Jauch, C.; Tamilarasan, S.; Bovee, K.; Guvenc, L.; Rizzoni, G. Modeling for drivability and drivability improving control of HEV. Control Eng. Pract. 2018, 70, 50–62. [CrossRef]

HEV Plant Modeling



Powertrain Blockset – P4 HEV Model

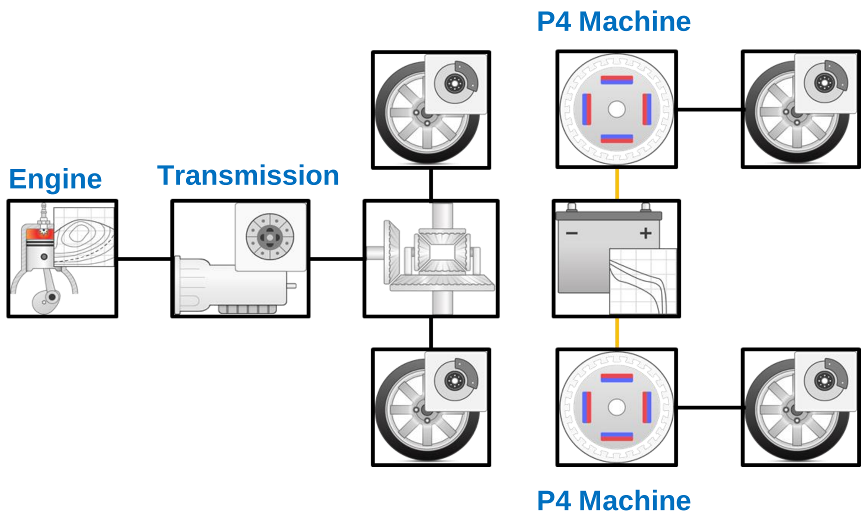


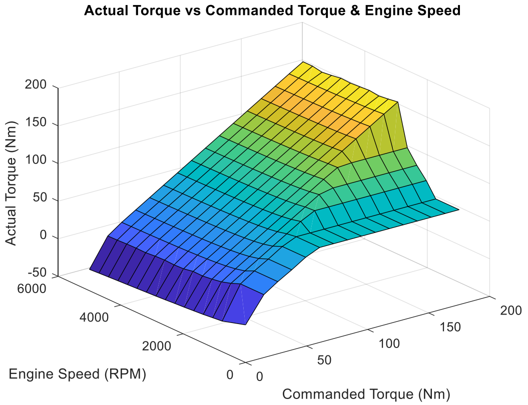
Various Component Modeling Types

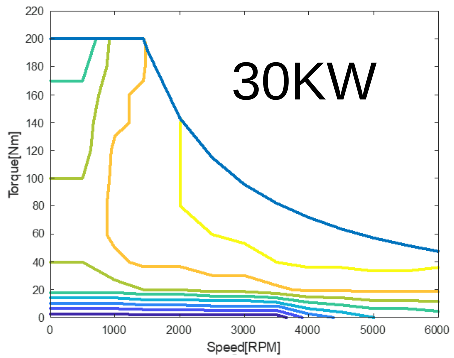
- First Principles
- Data-driven
- Balance between accuracy and speed

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 FE and acceleration studies
- Engine
  - 1.5L L4 95kW(126hp) @5500RPM
  - Map-based Model
- 2 P4 30kW Motors
  - Map Based Model
- 1.3 kWh Battery
  - Map-Based Model

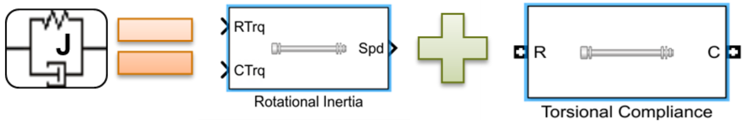




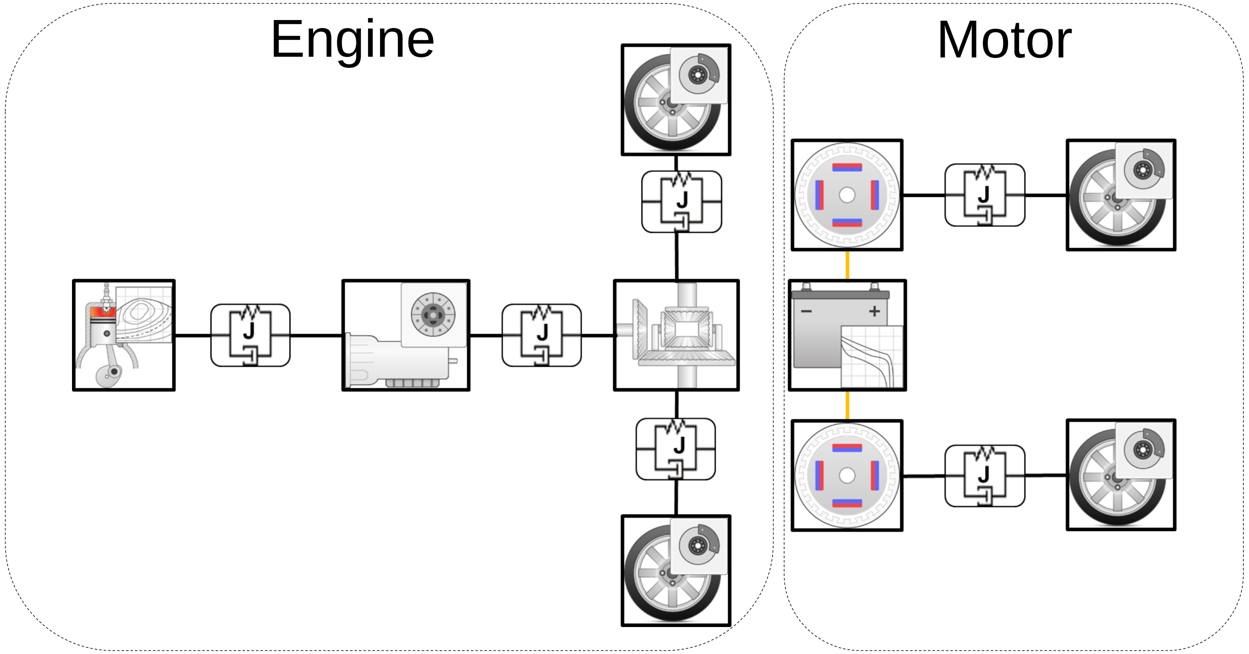


P4 Component Modeling

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



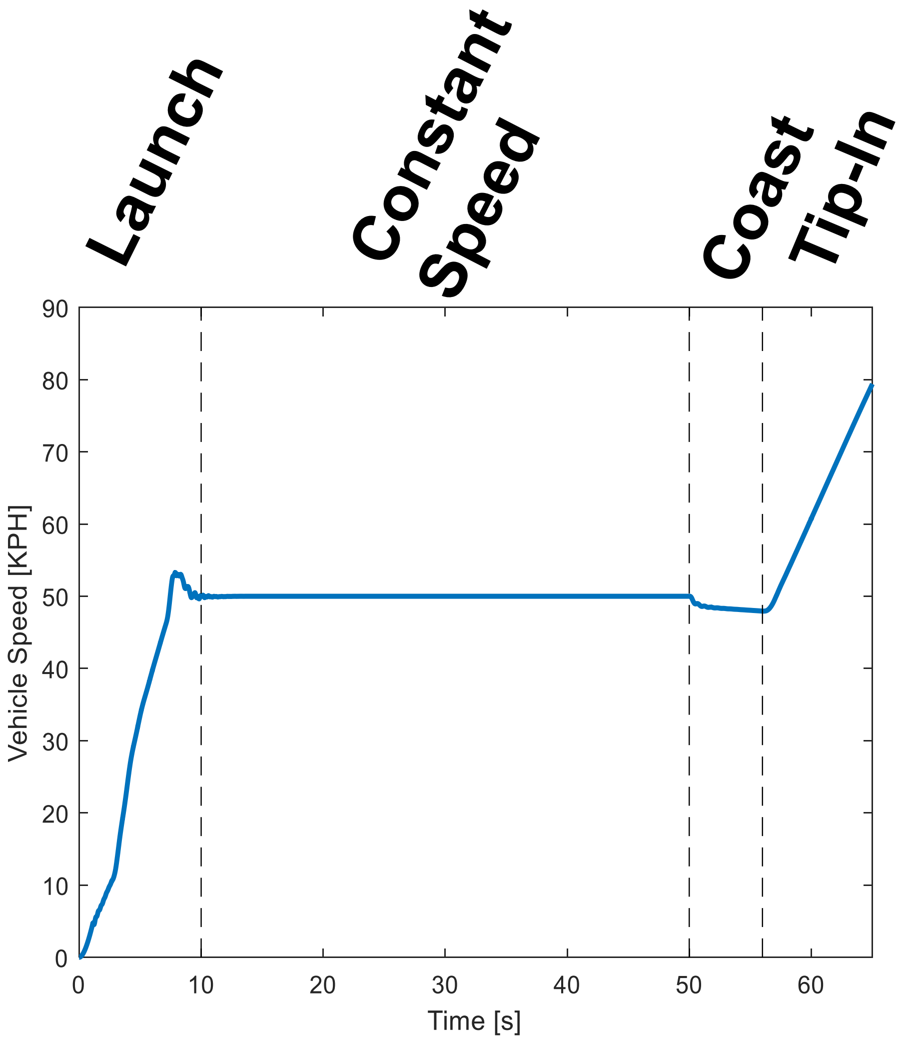
- Linear damping and stiffness
  – Openness of model allows for replacing K/B with nonlinear terms
- 2 Torque Paths
  – Engine
  – Motor



Driving Scenario

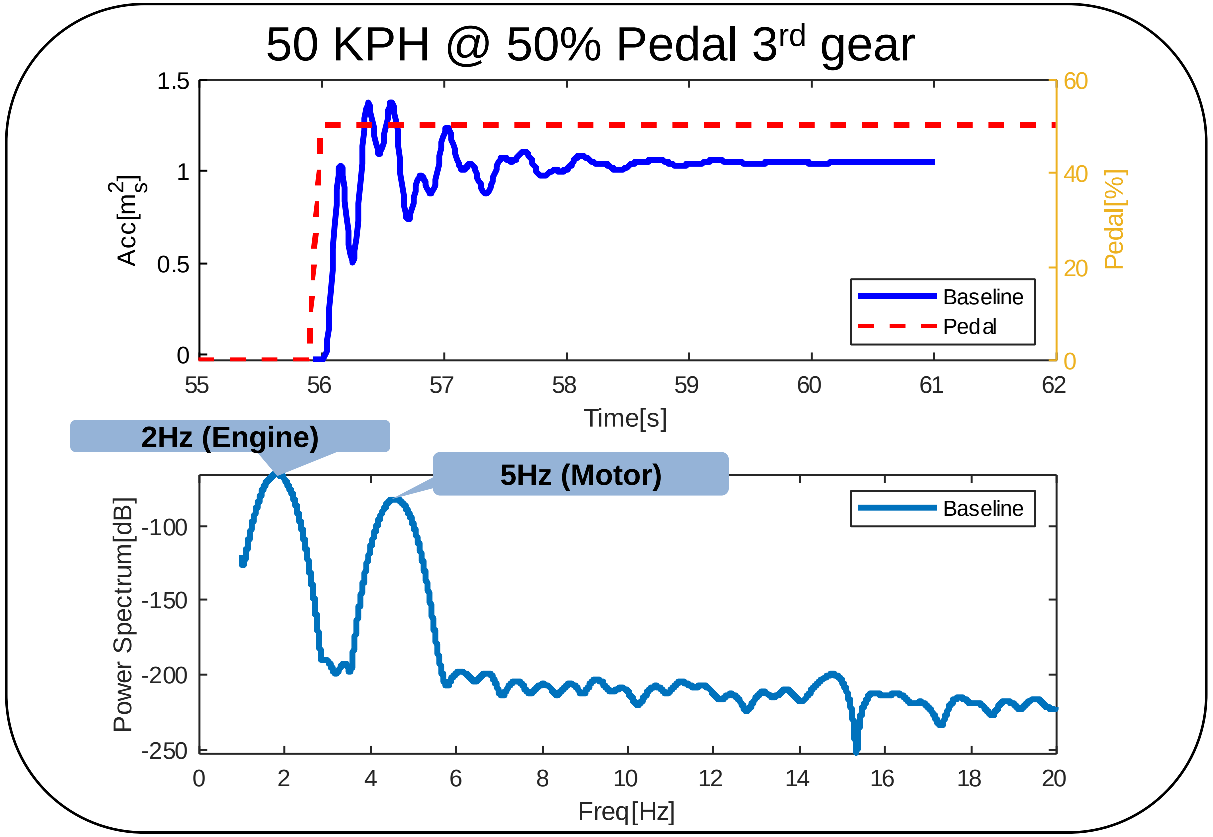
- What scenario are we using?

    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



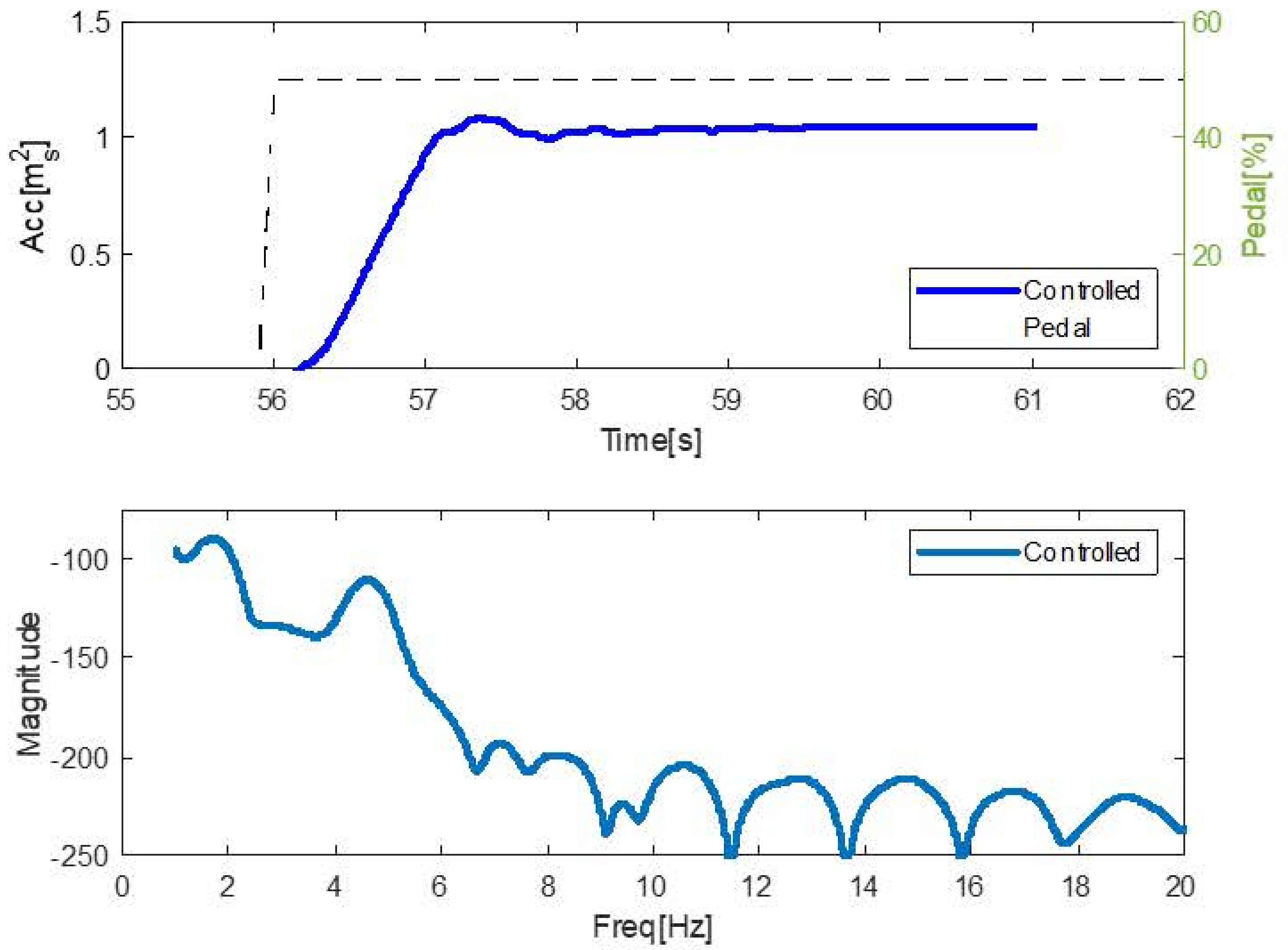
Tip-In Acceleration Response

- 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

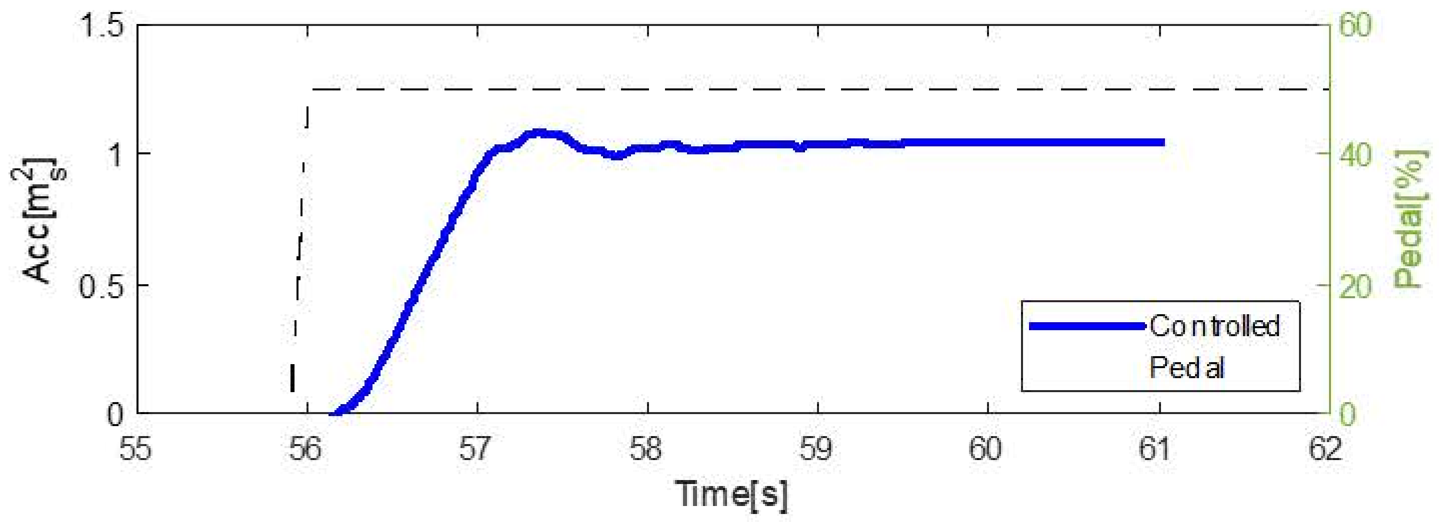
- How to improve?
  - Spark Control (on engine side only)
  - Fixed Rate Limit on torque request or pedal input
  - Scheduled Rate Limit
  - Optimal Control – e.g. Model Predictive Control

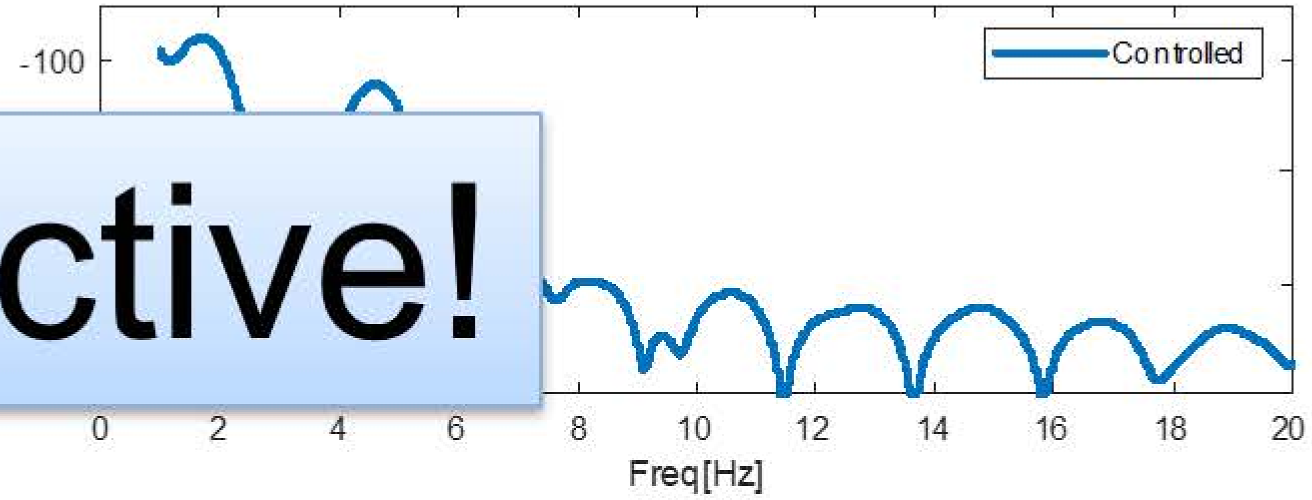


- Scheduled Rate Limit can be tuned for each case by engineer-> long manual process (weeks)
- Reduced oscillations but response is slow
- How to balance responsiveness and oscillations

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 Contr





Define an objective!

- Scheduled Rate Limit can be tuned for each case by engineer-> long manual process (weeks)
- Reduced oscillations but response is slow
- How to balance responsiveness and oscillations

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
  - Parameter dependencies

Objective Function

$$\min_{x} f(x)$$

Linear or nonlinear

Design variables
(discrete or integer)

Linear constraints

$$Ax \leq b$$

$$A_{eq}x = b_{eq}$$

$$l \leq x \leq u$$

Nonlinear constraints

$$c(x) \leq 0$$

$$c_{eq}(x) = 0$$

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

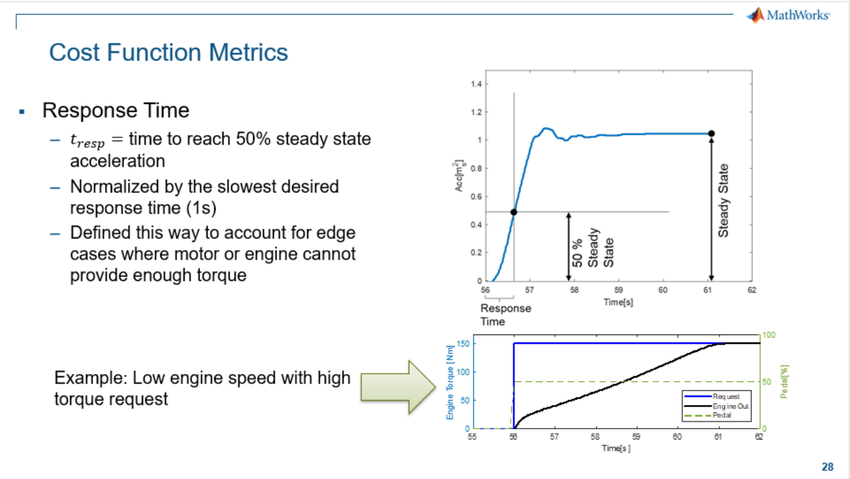
Constraints

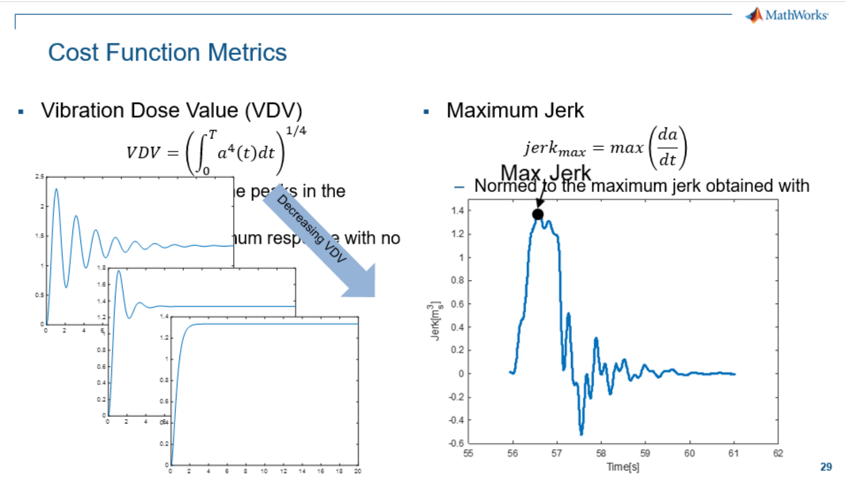
What restricts my choices?

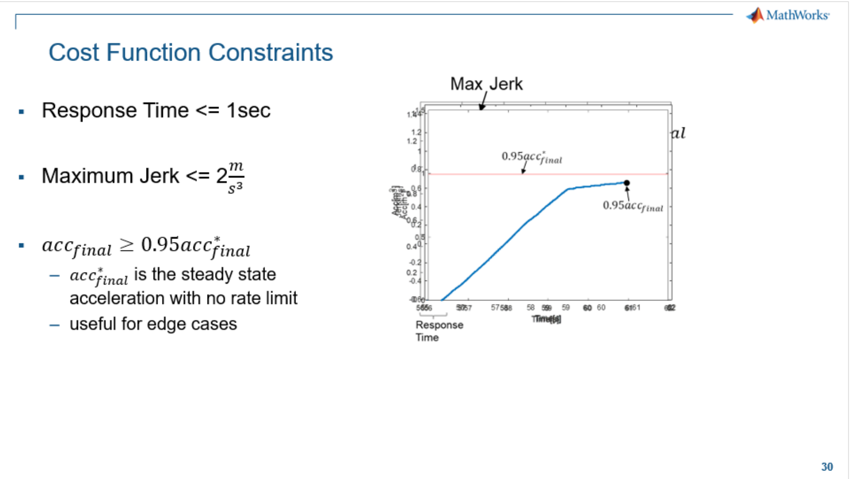
- Response Time
- Jerk
- Etc.

Objective Function

$$\min_{RL^*} J = 0.5\left(t^*_{resp} + jerk^*_{max}\right) + 0.5\left(VDV^*\right) + constraints$$

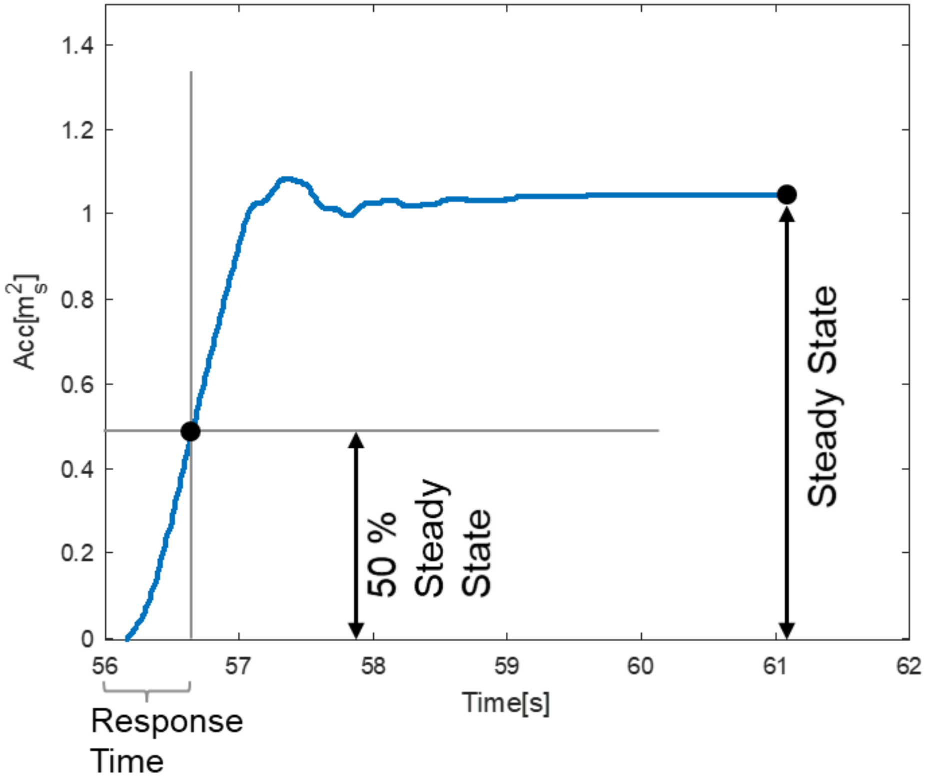




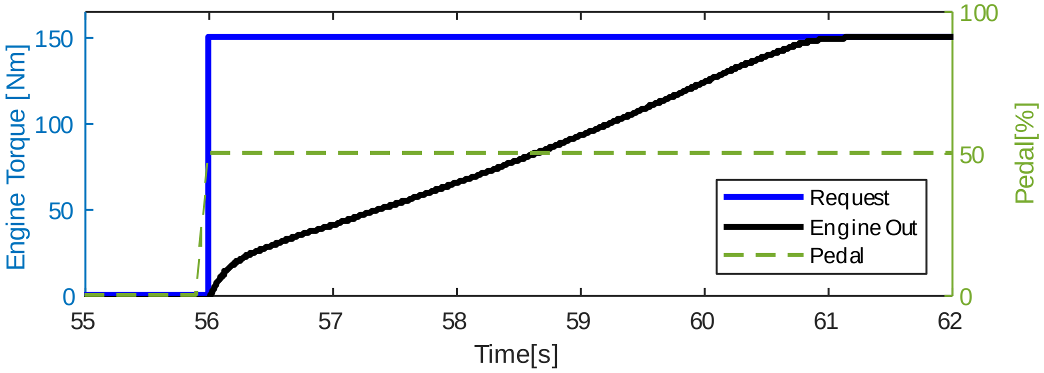


Cost Function Metrics

- 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



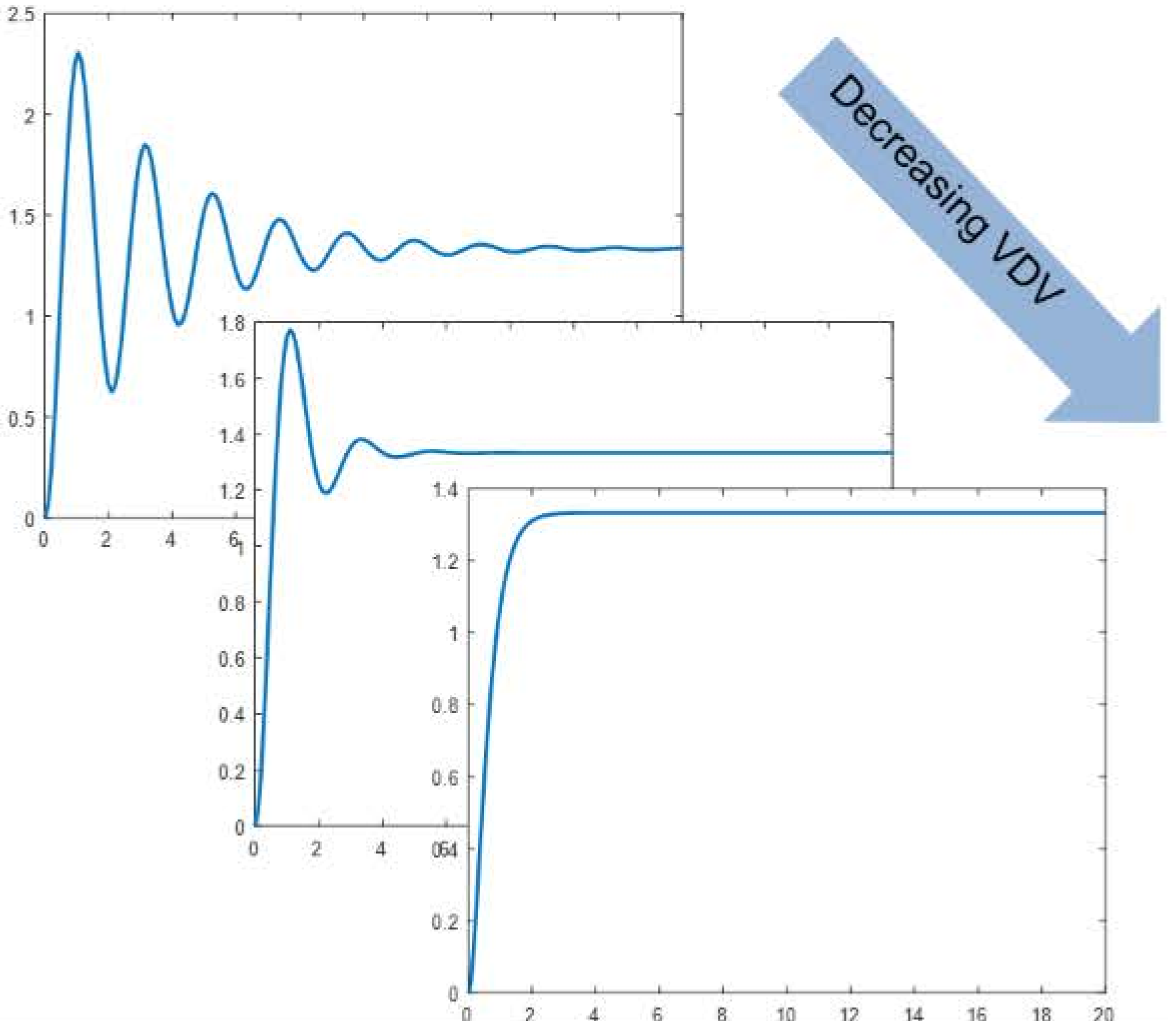
Cost Function Metrics

- 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.

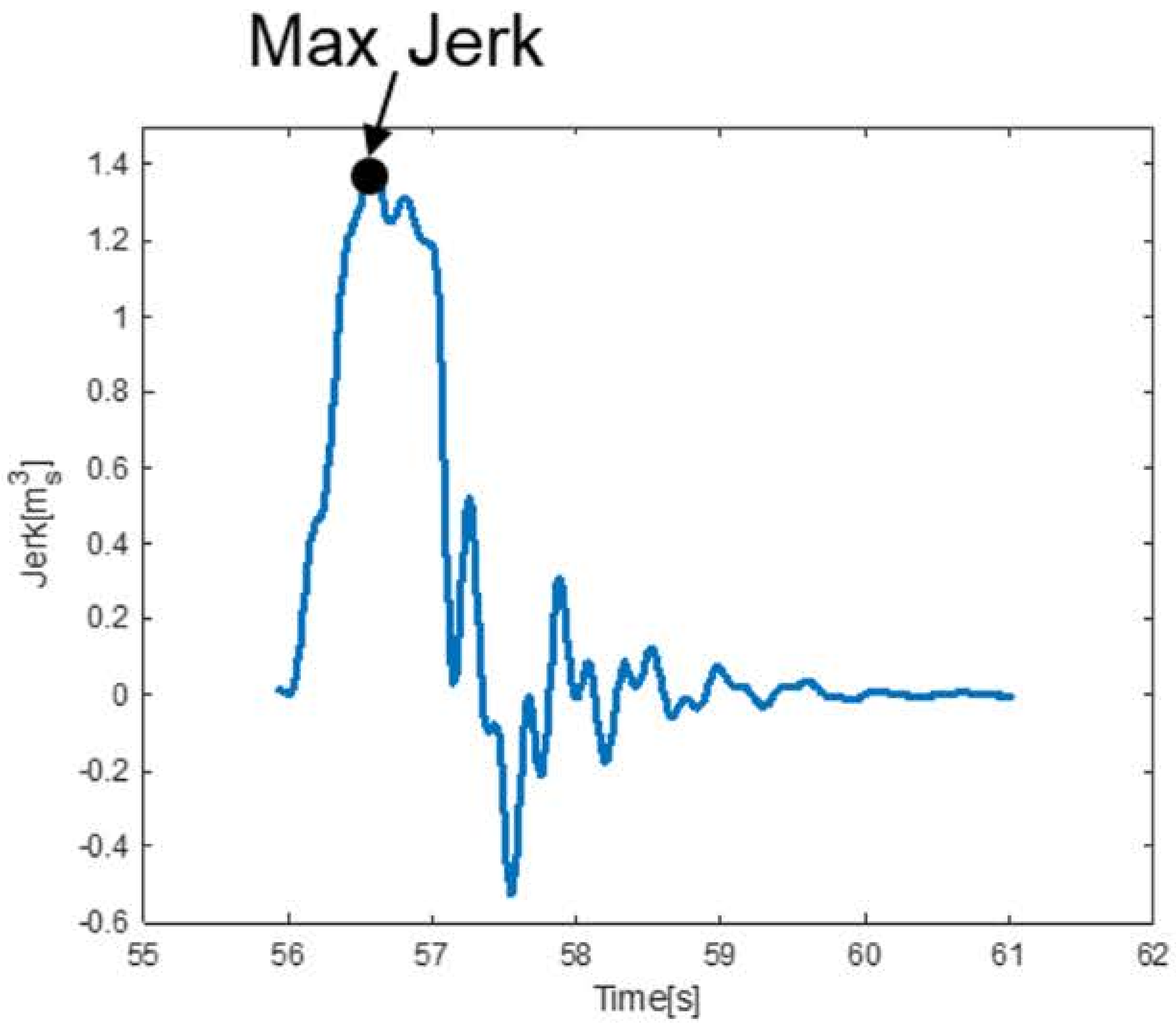
  – Normed to the maximum response with no rate limit



- Maximum Jerk

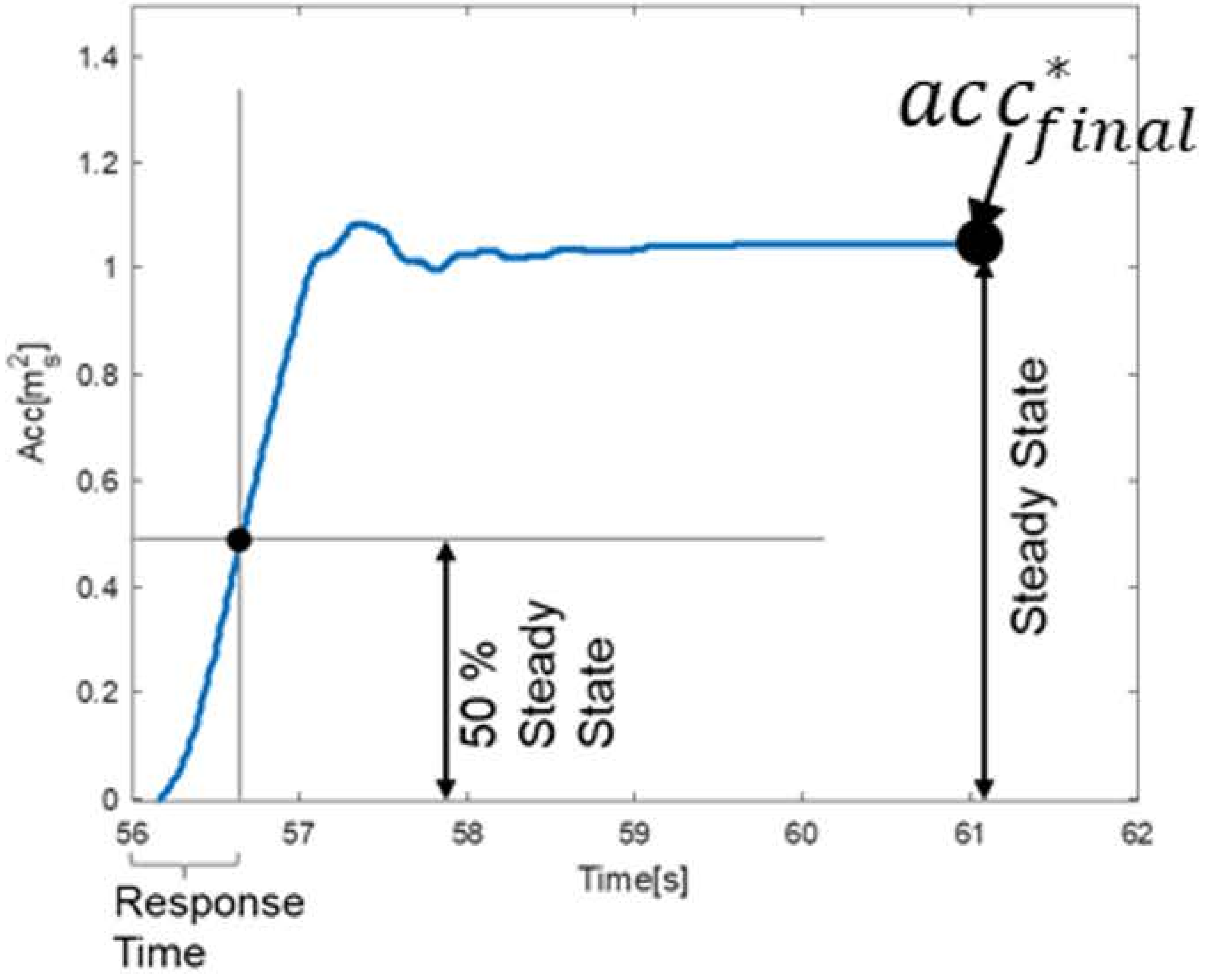
$$jerk_{max} = max\left(\frac{da}{dt}\right)$$

  – Normed to the maximum jerk obtained with no rate limit



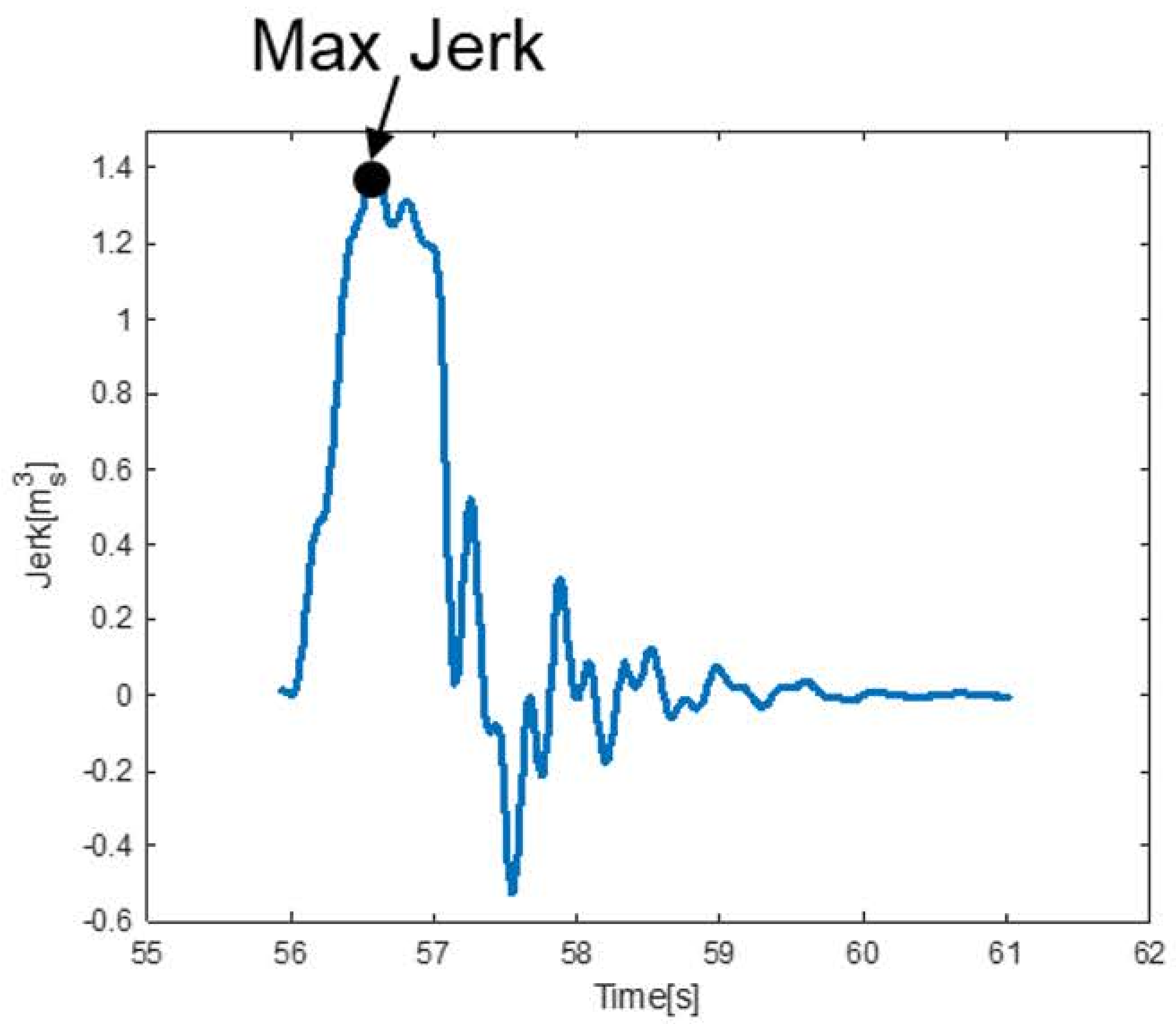
Cost Function Constraints

- Response Time <= 1sec



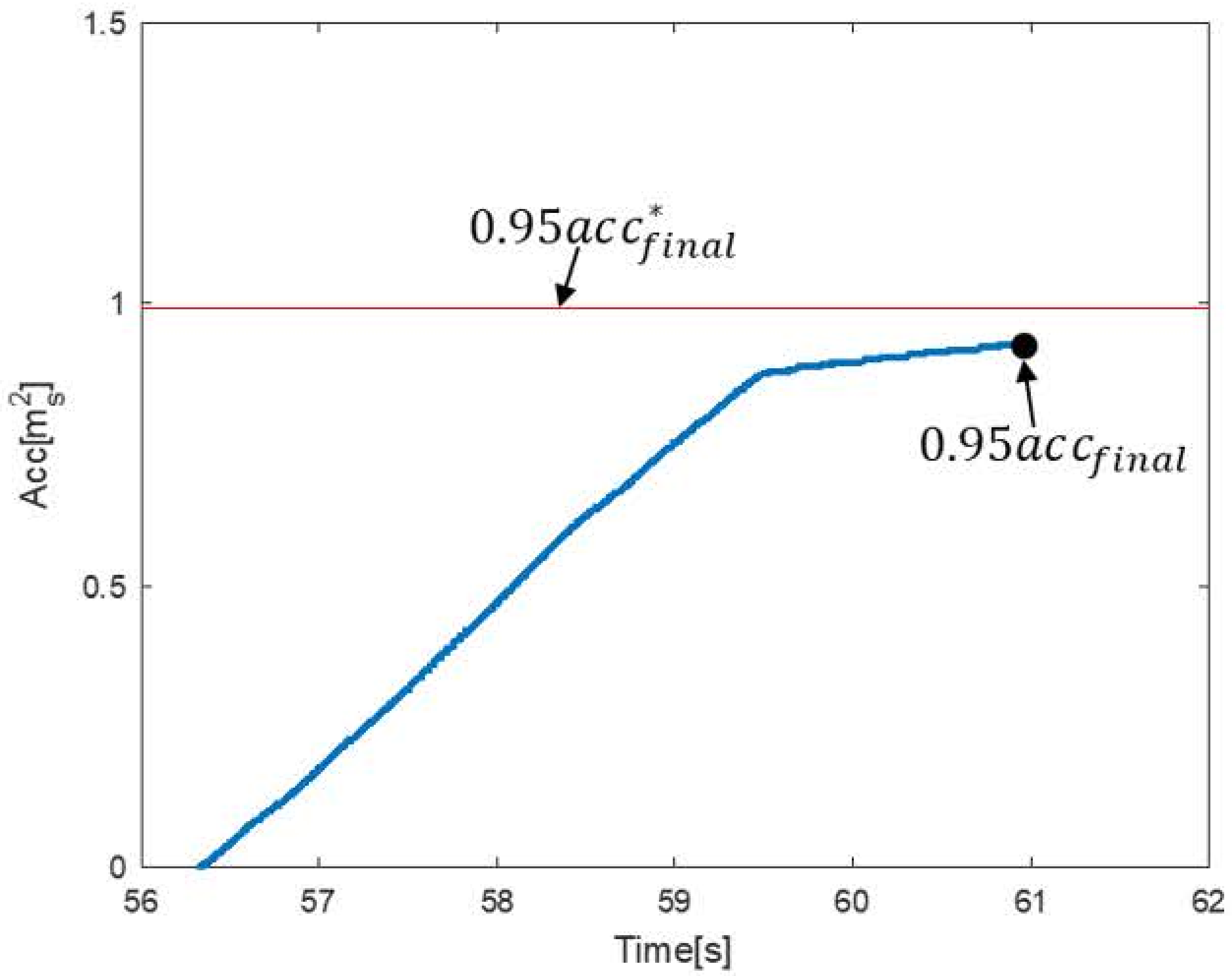
Cost Function Constraints

- Response Time <= 1sec
- Maximum Jerk <= $2\frac{m}{s^3}$



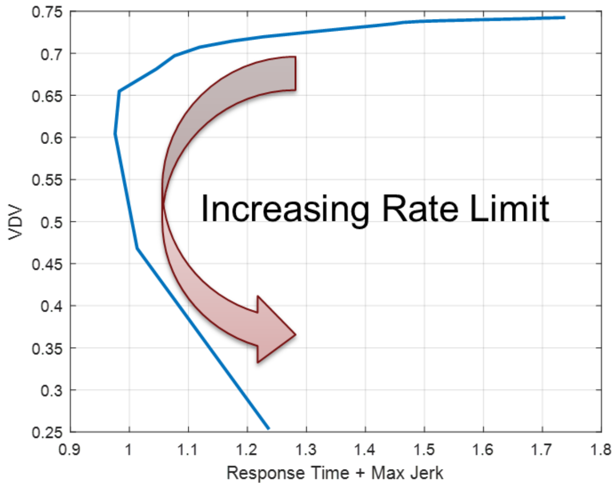
Cost Function Constraints

- Response Time <= 1sec
- Maximum Jerk <= $2\frac{m}{s^3}$
- $acc_{final} \geq 0.95acc^{*}_{final}$
  - acc^{*}_{final} is the steady state acceleration with no rate limit
  - useful for edge cases



Objective Function

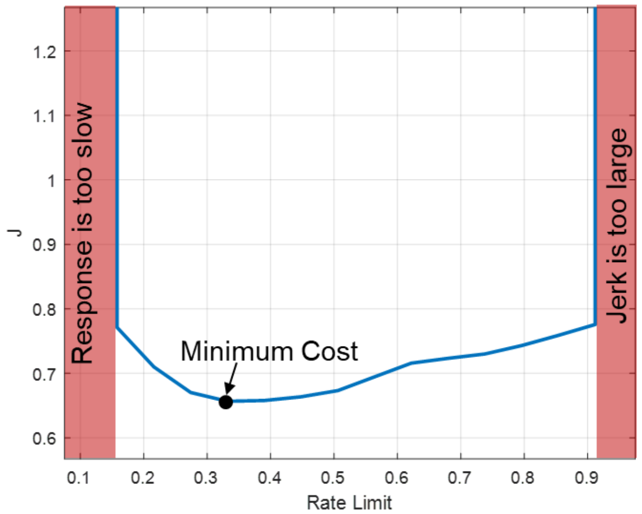
- Pareto curve exists between oscillations and response time – the faster the response, the more oscillations



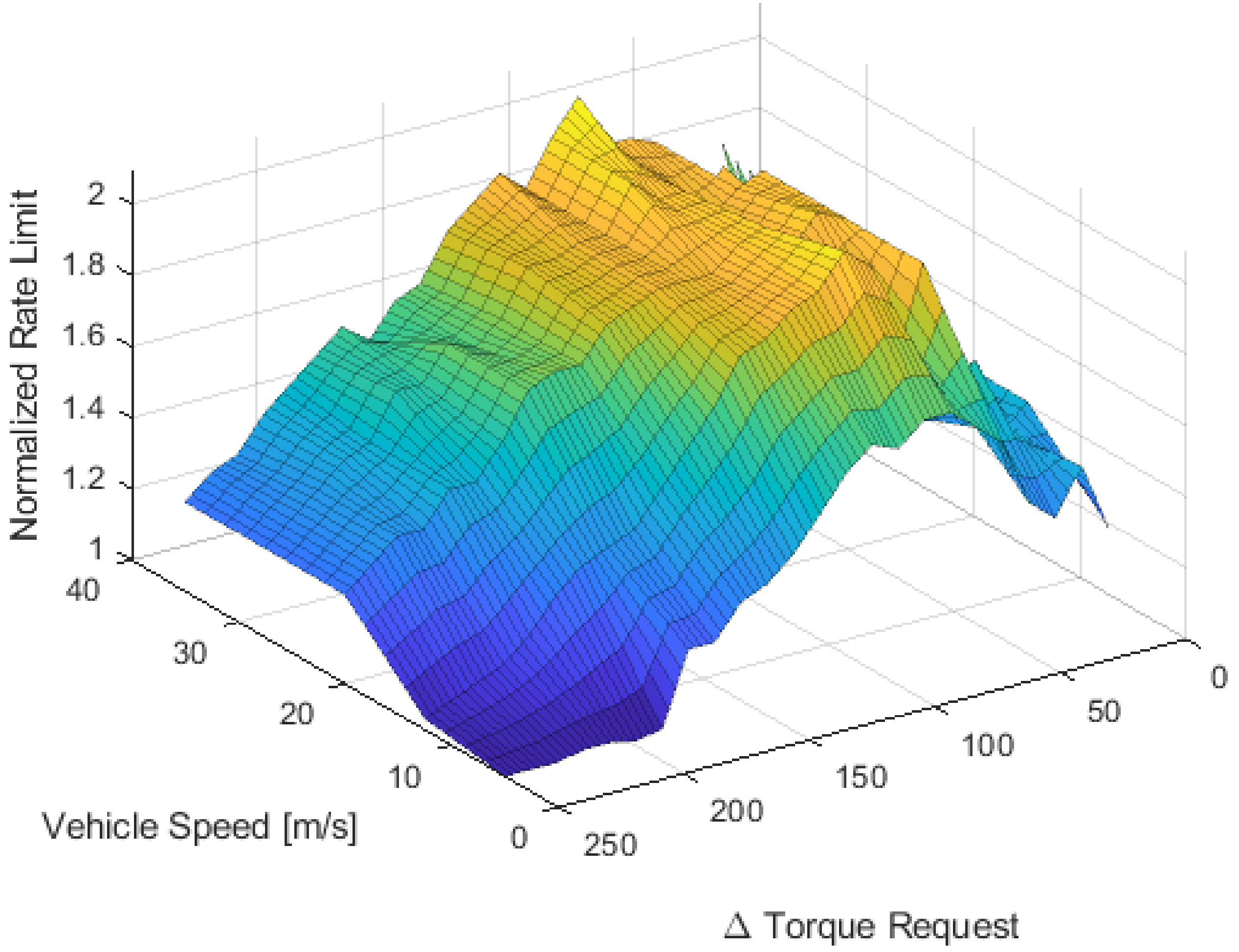
- $$\min_{RL^*} J = 0.5\left(t^*_{resp} + jerk^*_{max}\right) + 0.5(VDV^*) + constraints$$

With, $constraints = \begin{cases} 10^6 \; if \; violated \\ 0, otherwise \end{cases}$

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

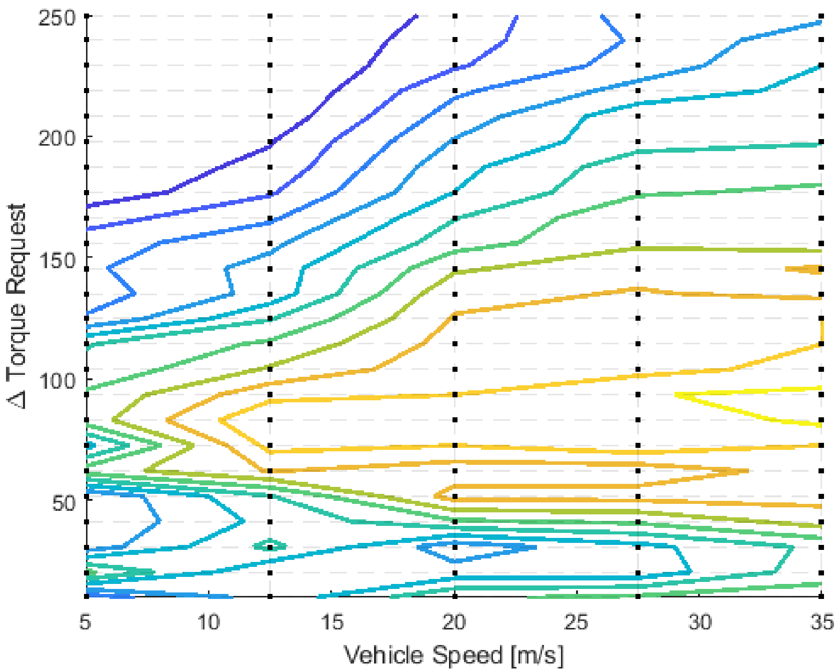


Optimal Calibration



Calibration Process

- Intel Xeon E5 processor – 3.6GHz, 6 cores
- 64GB RAM
- 1806 speed, torque change points
  - 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

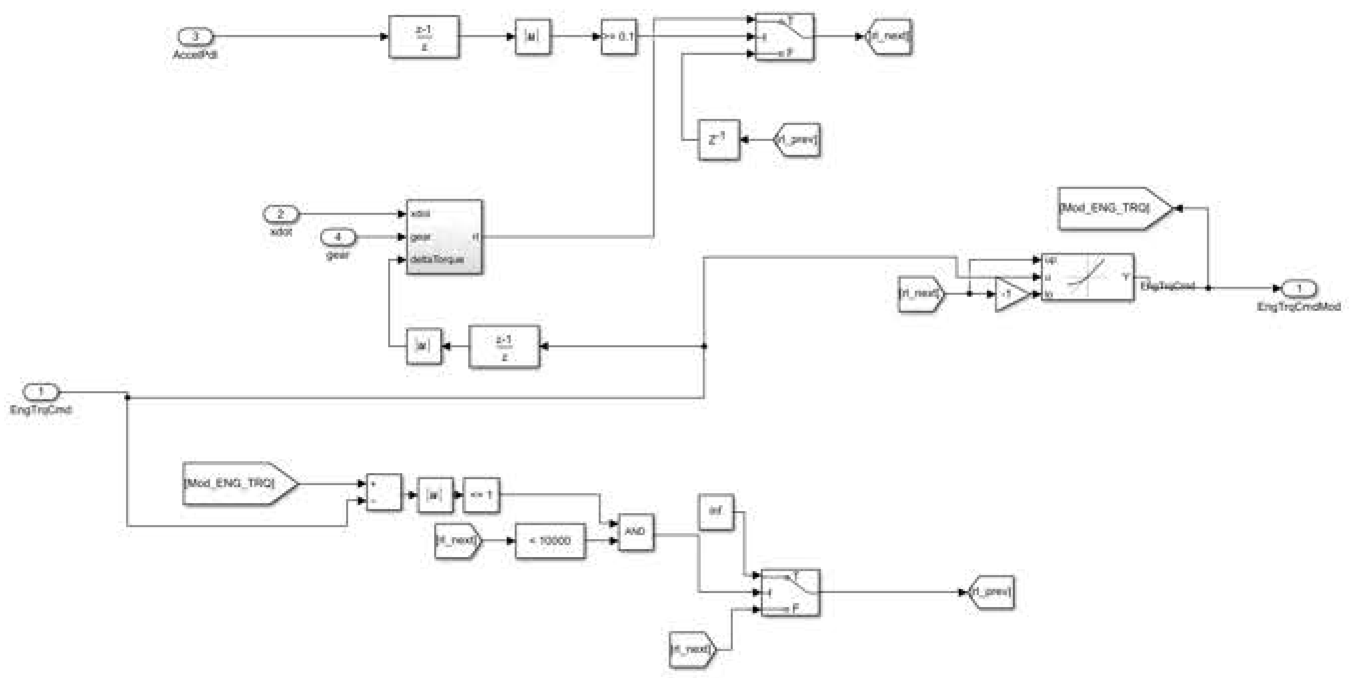
Search Algorithm	Time	Solution Found
fmincon	1.5minutes	✘
Particle Swarm	5 minutes	✓+
Pattern Search	1.5minutes	✓

Tip-In Controller

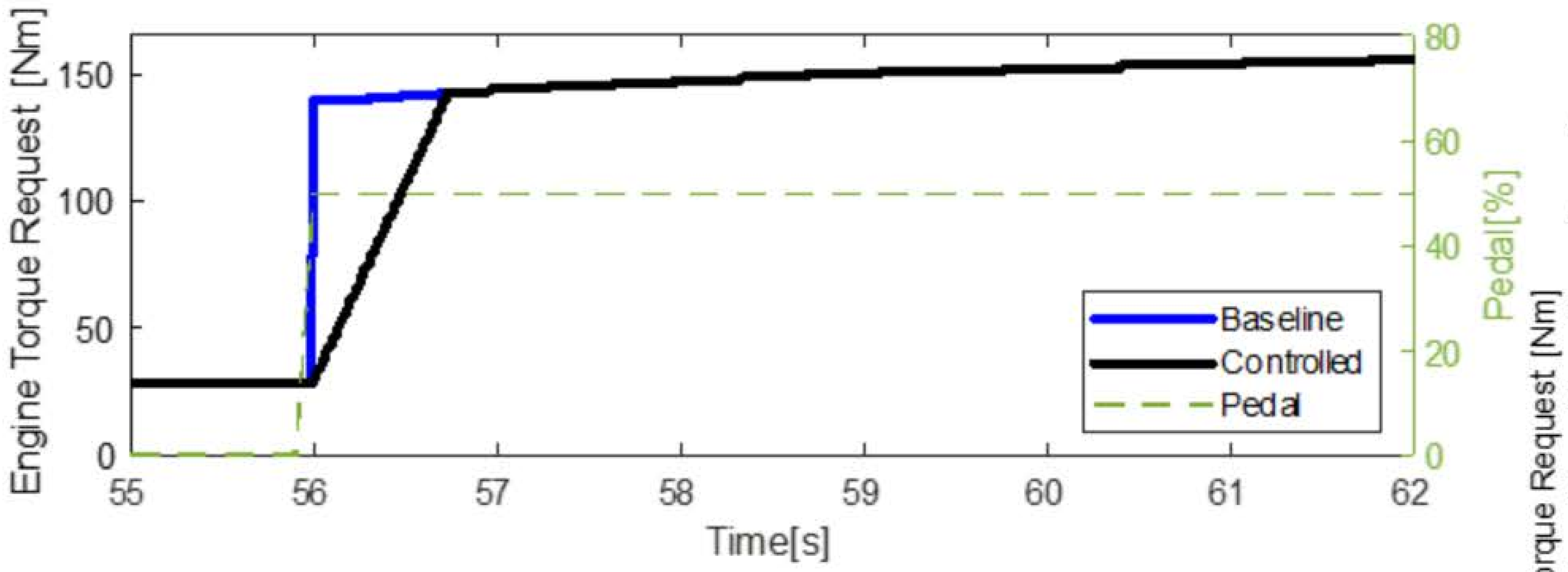
- Rate limit is calculated as a function of |ΔTorque request|, vehicle speed, and Gear (engine side only)

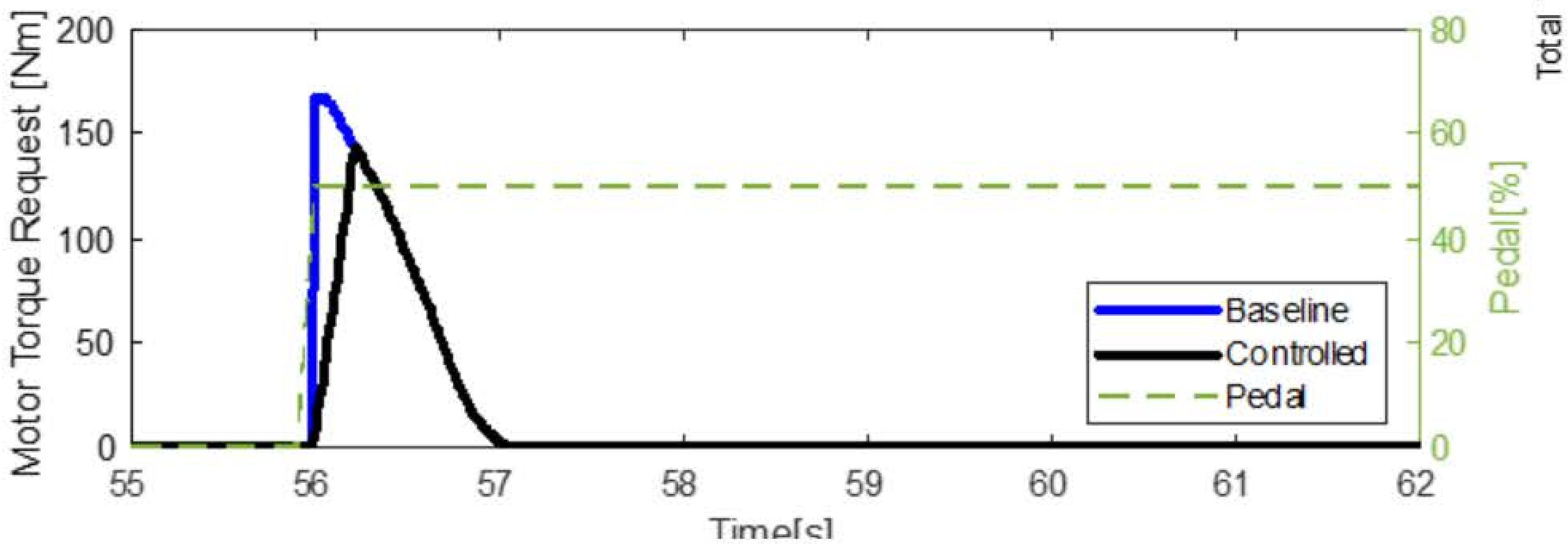
- Rate limit is applied when judged a tip in response
  - |ΔTorque request| >10Nm
  - Vehicle Speed > 2 MPH

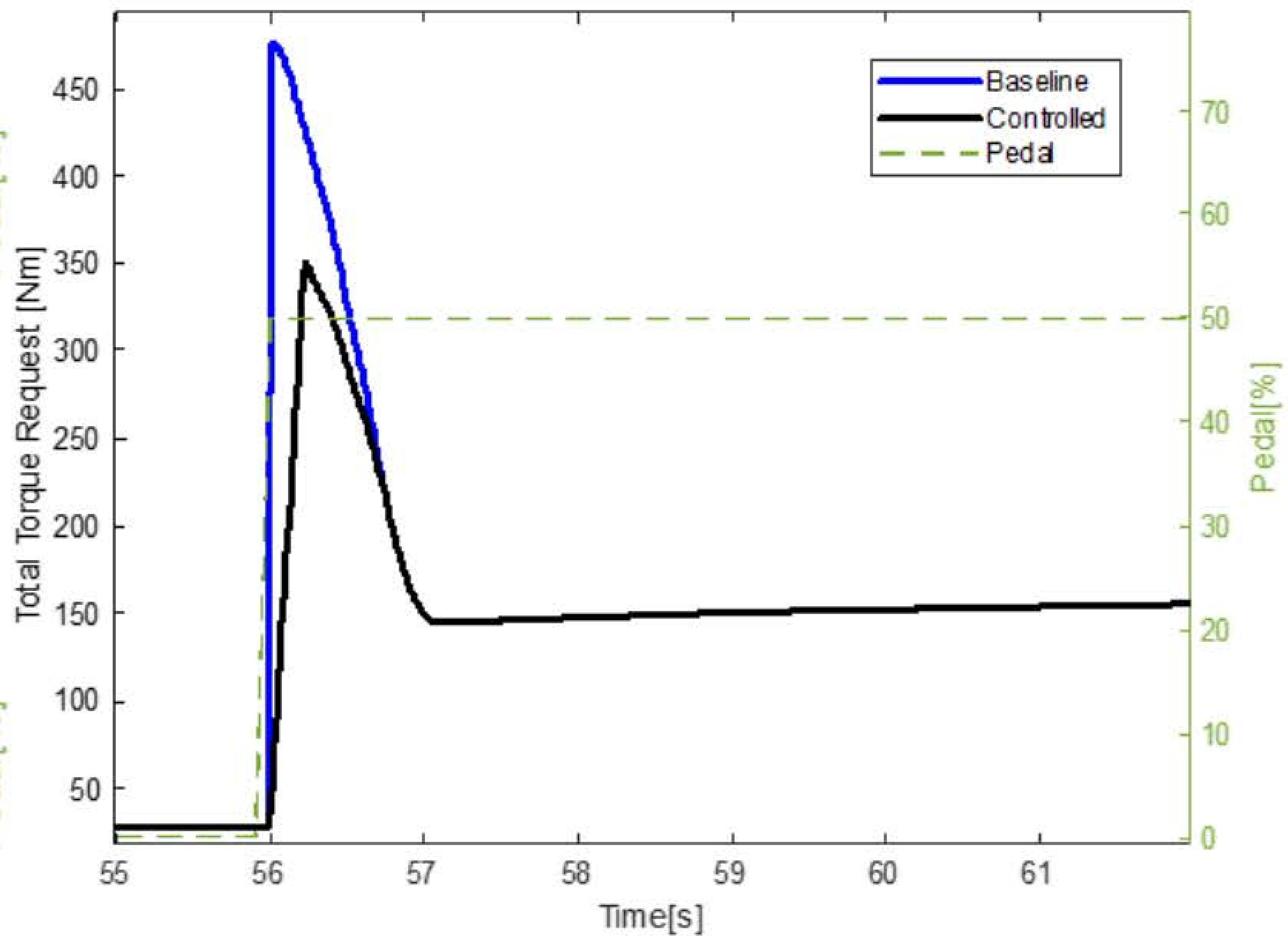
- Rate limit held until modified torque is near final desired torque value.



Tip-In Controller

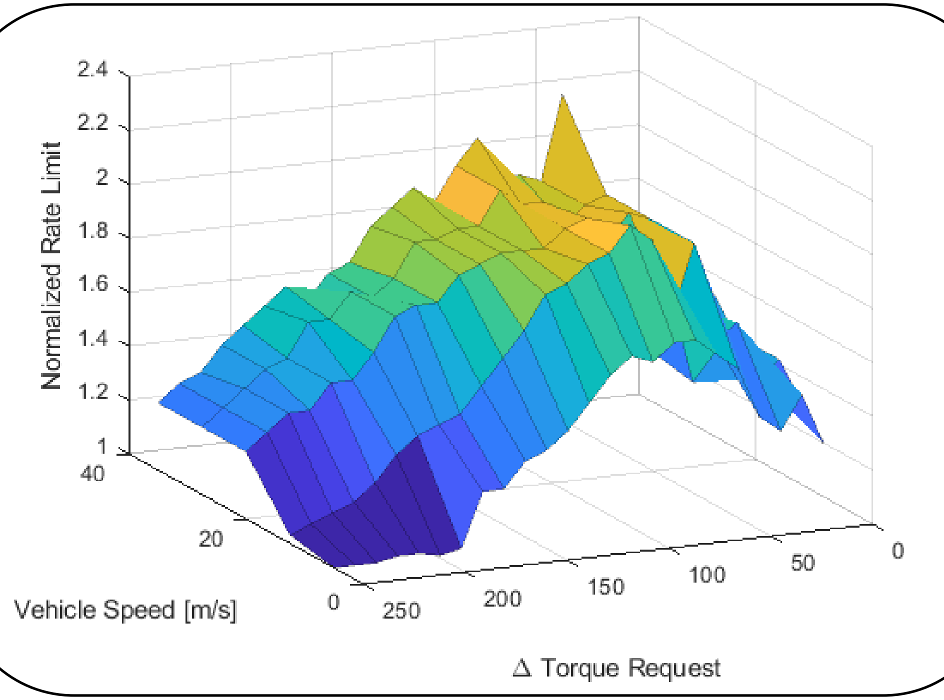




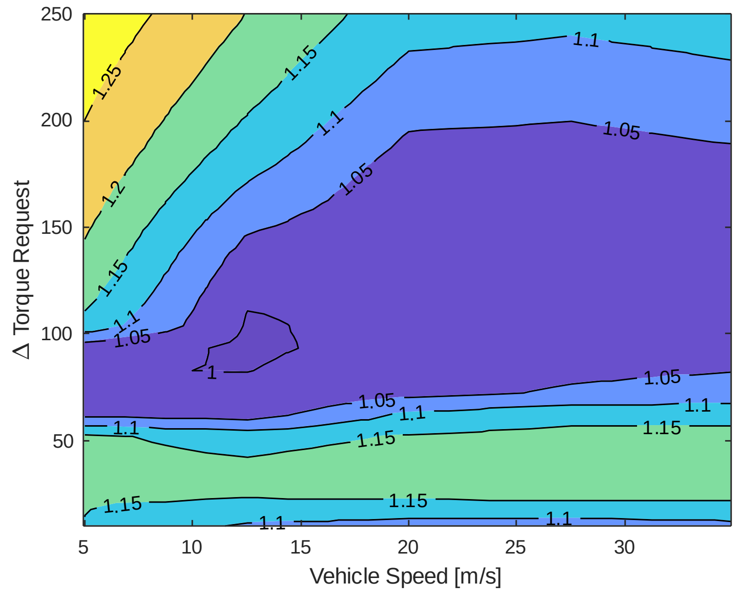


Calibration Tables

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

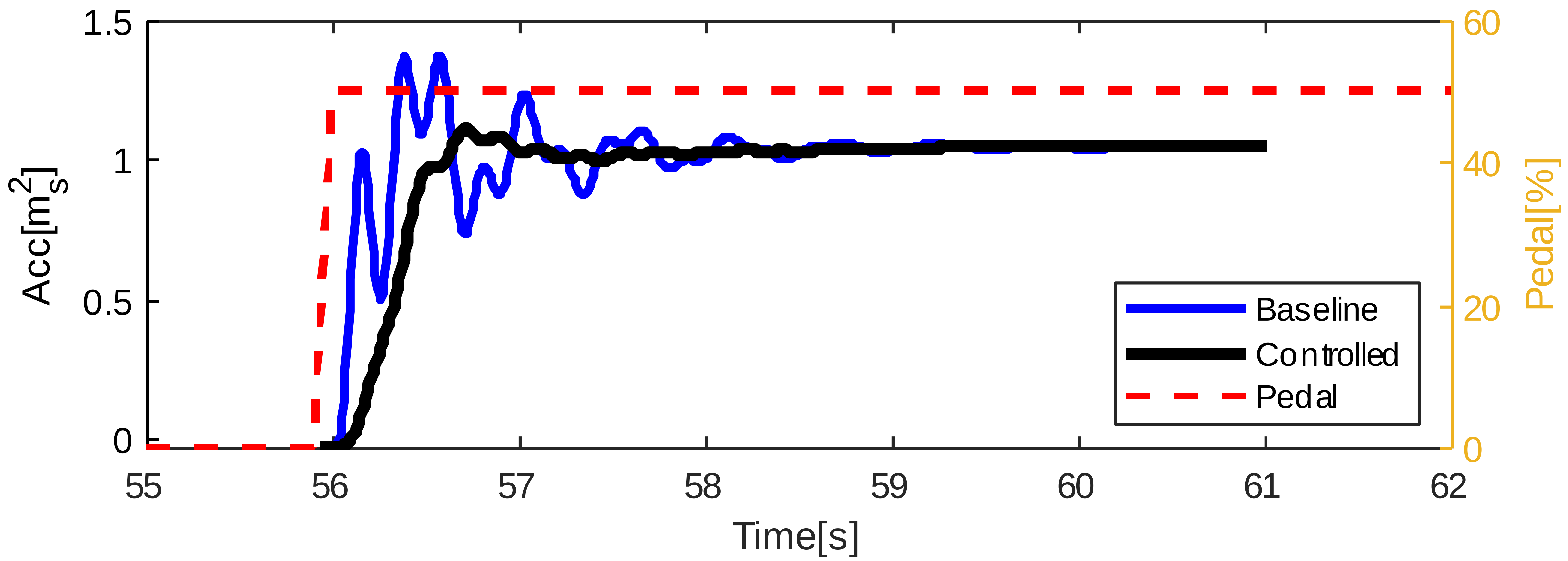


Calibration Map



Objective Function

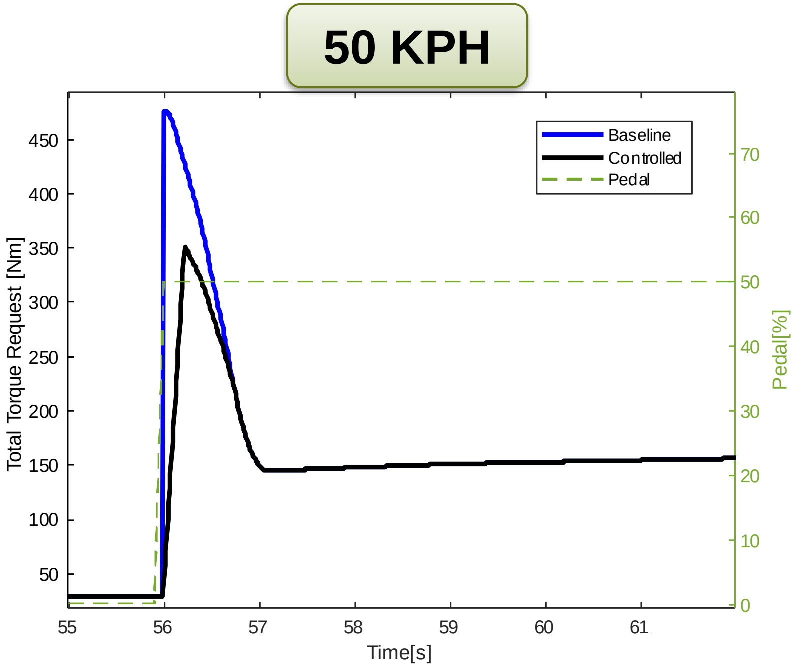
Validation

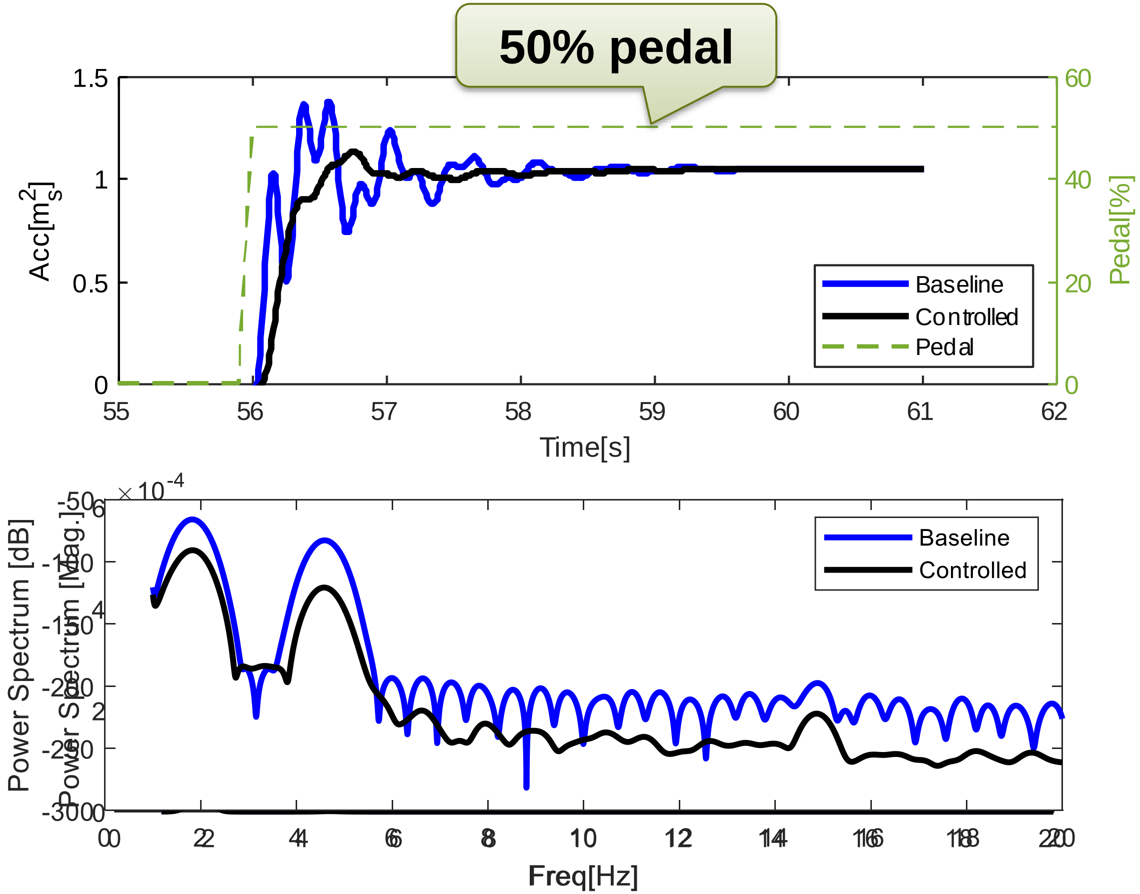


1.5
1
0.5
0
Acc[m/s²]
55
56
57
58
59
60
61
62
Time[s]
60
40
20
0
Pedal[%]
Baseline
Controlled
Pedal

Tip-In Results

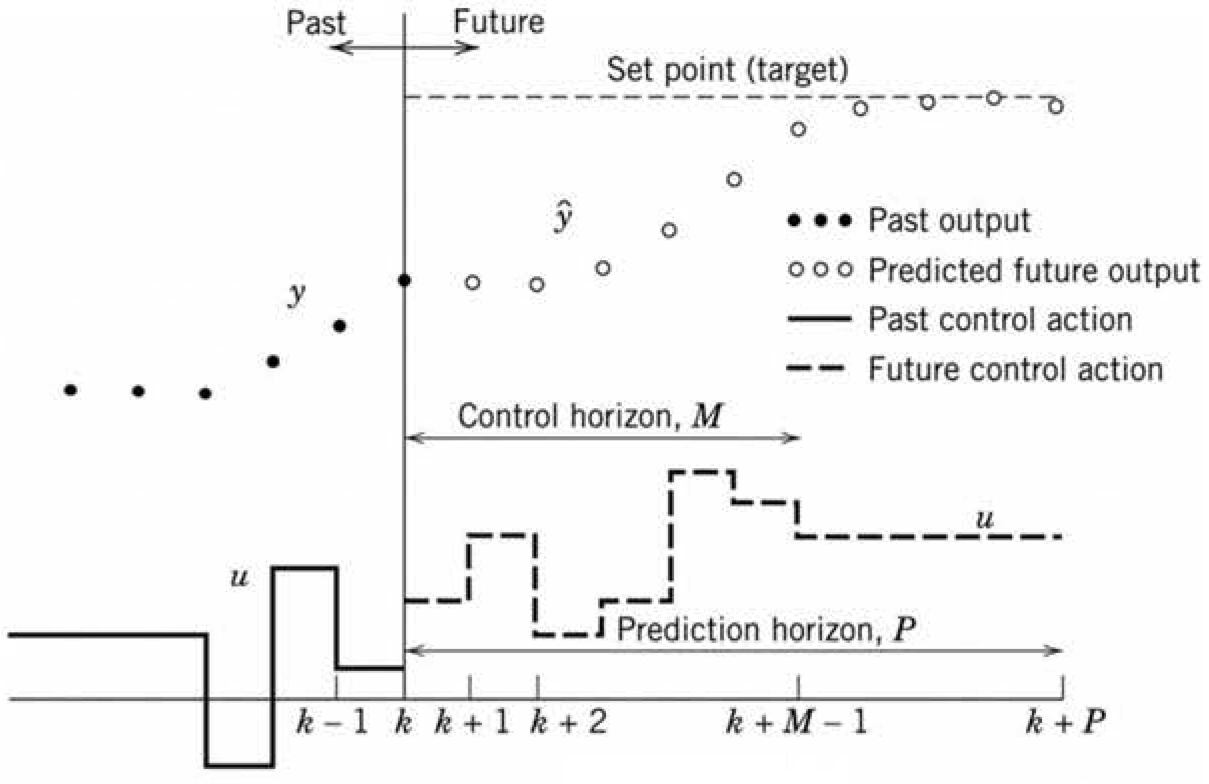
- First engine and motor modes have decreased greatly (~50dB)
- Fast Tip-In response – 0.5s





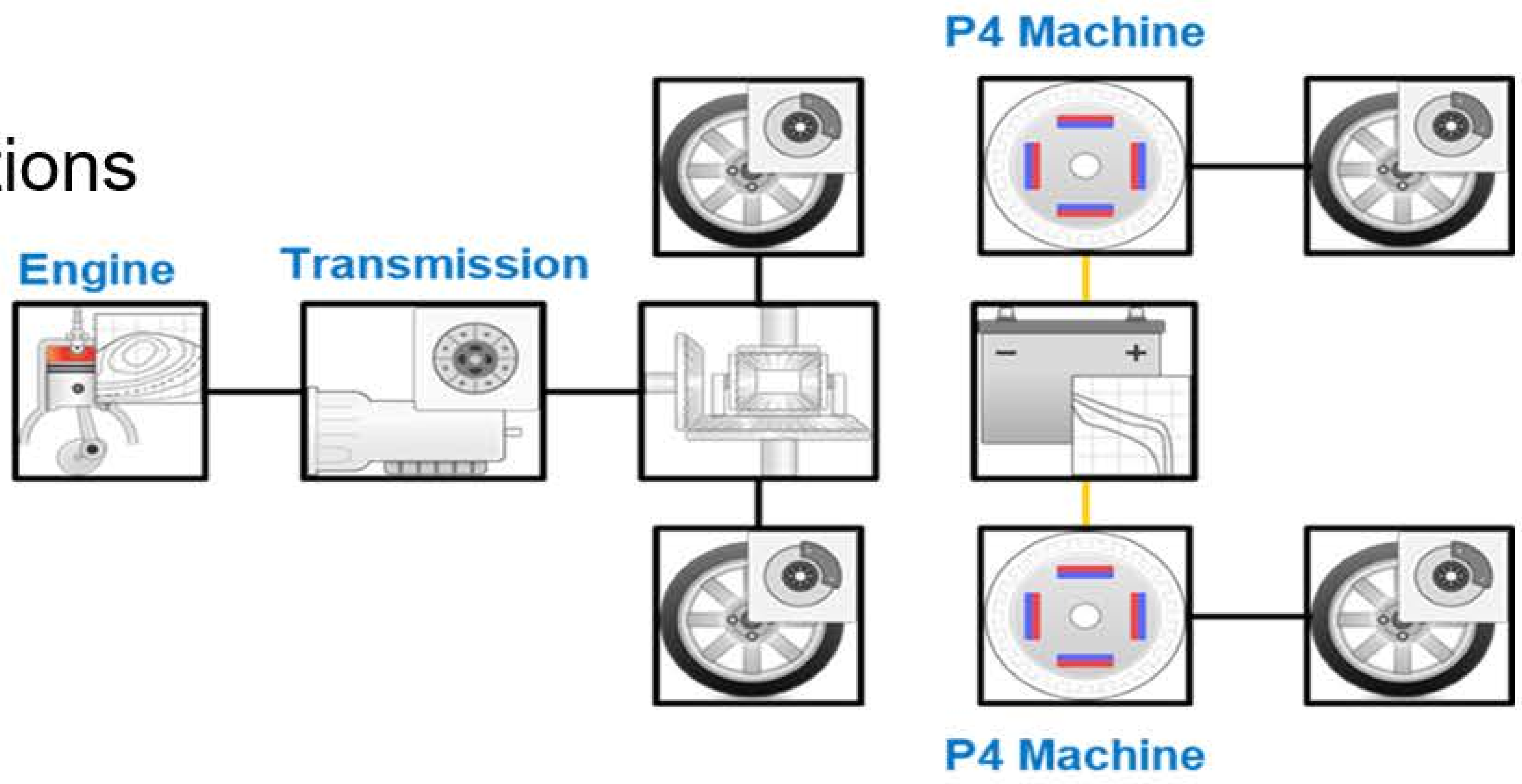
Next Steps

- What are possible next steps?
  - Investigate other control types
    - Model Predictive Control with consideration for FE for example.



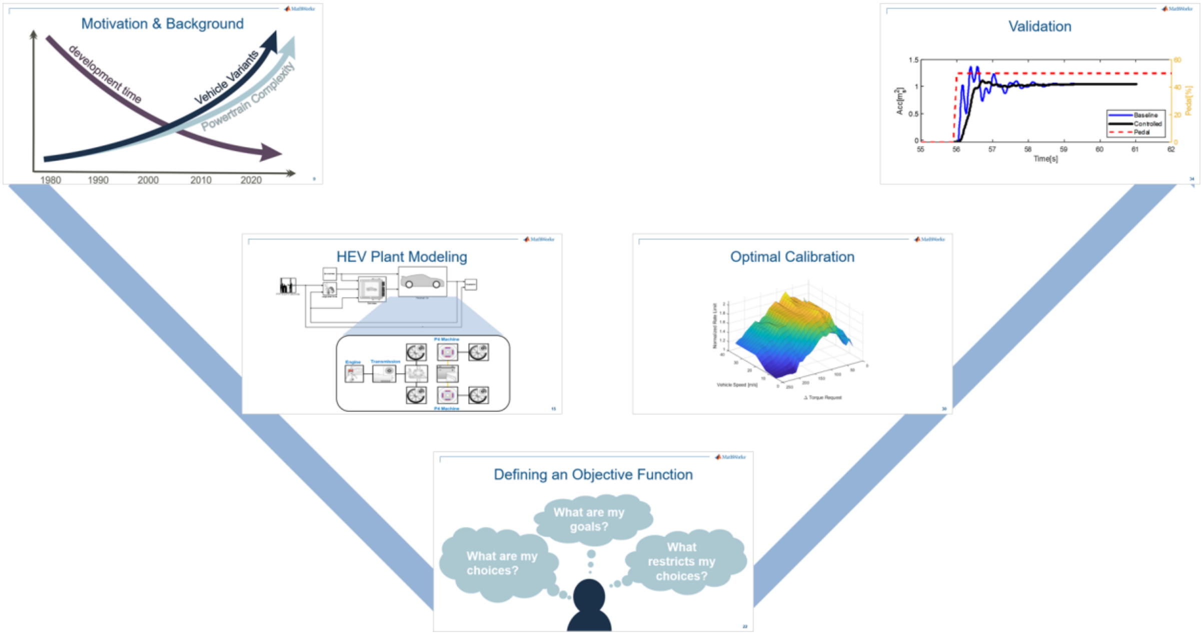
Next Steps

- What are possible next steps?
  - Investigate other control types
    - Model Predictive Control with consideration for FE for example.
  - Process can be reused as model fidelity increases
    - GT Engine model
    - Simscape driveline
  - Utilize process for other calibrations



Summary

- A process for using objectives 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

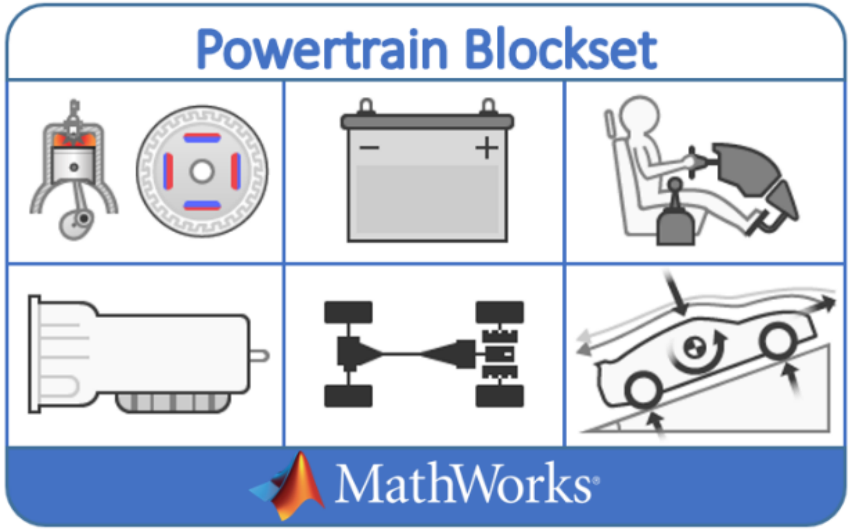


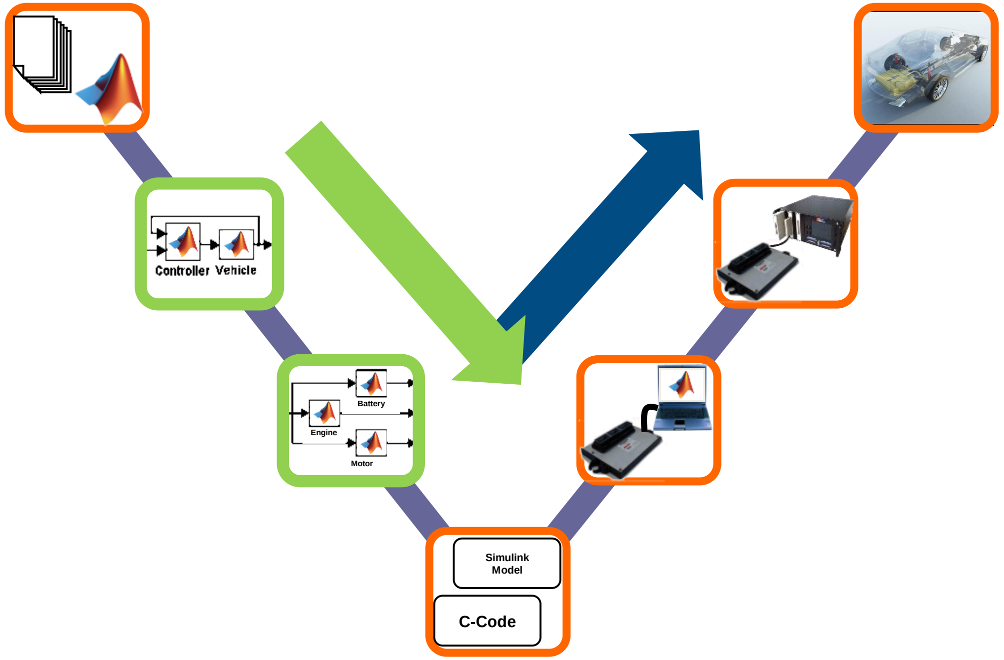
Key Takeaways

- Powertrain Blockset is capable of simulating some 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





Q&A

Questions?