



RVLT High Fidelity Motor Degradation

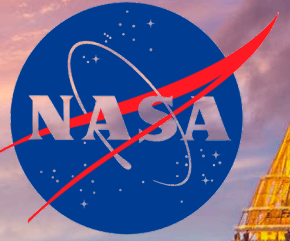
Kyle Barnes

Peter Suh

Curtis Hanson

Kurt Kloesel

George Altamirano





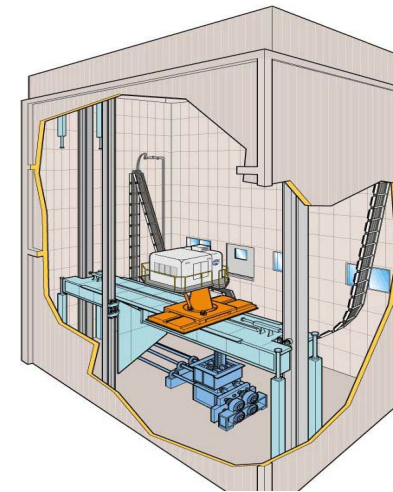
Overview

1. **Vertical Motion Simulator (VMS) Testing Context**
2. **Healthy vs. Low SOC**
 - a) Data Analysis: Impact of Low SOC on Motors
 - b) Data Analysis: Pilot in the Loop
3. **High Temp. vs. Low SOC**
 - a) Data Analysis: Impact of High Temp. on Motors
 - b) Data Analysis: Pilot in the Loop
4. **Handling Qualities**
 - a) Vertical Maneuver

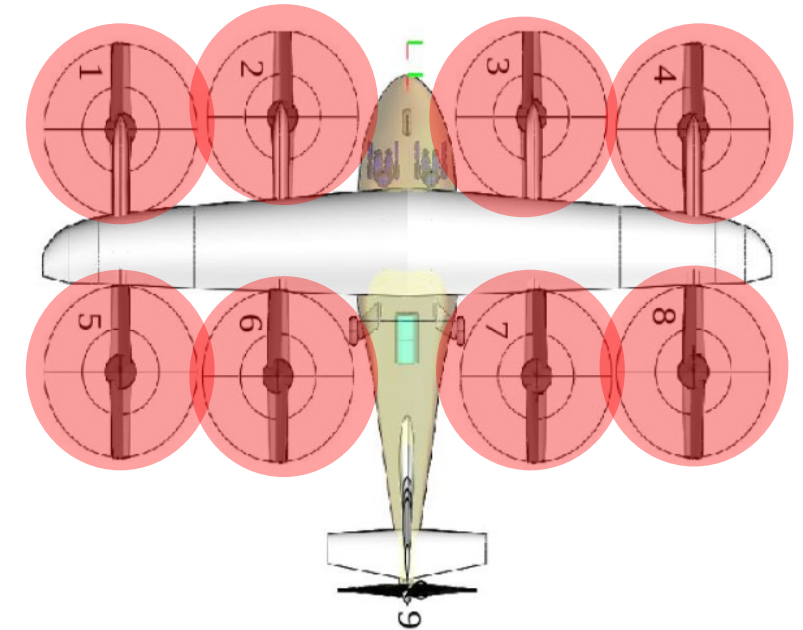
Context of VMS Testing

VMS Research:

- Low Fidelity vs. High Fidelity Motor Models
 - Are there critical components of high fidelity motor models that are being overlooked in low fidelity motor models in aircraft simulations?
- High Fidelity Motor Models
 - Test Healthy Configurations of the High Fidelity Motors
 - Test Degradations Unique to High Fidelity Motors
 - Low SOC
 - Initial SOC set to **20%**
 - High Coolant Temperature
 - Initial Coolant Temp. set to **130 °C**
 - Algorithm adjusts motor initial temperatures for:
 - Winding Temperature
 - Rotor Temperature
 - Case Temperature



Vertical Motion Simulator (VMS) located at NASA Ames

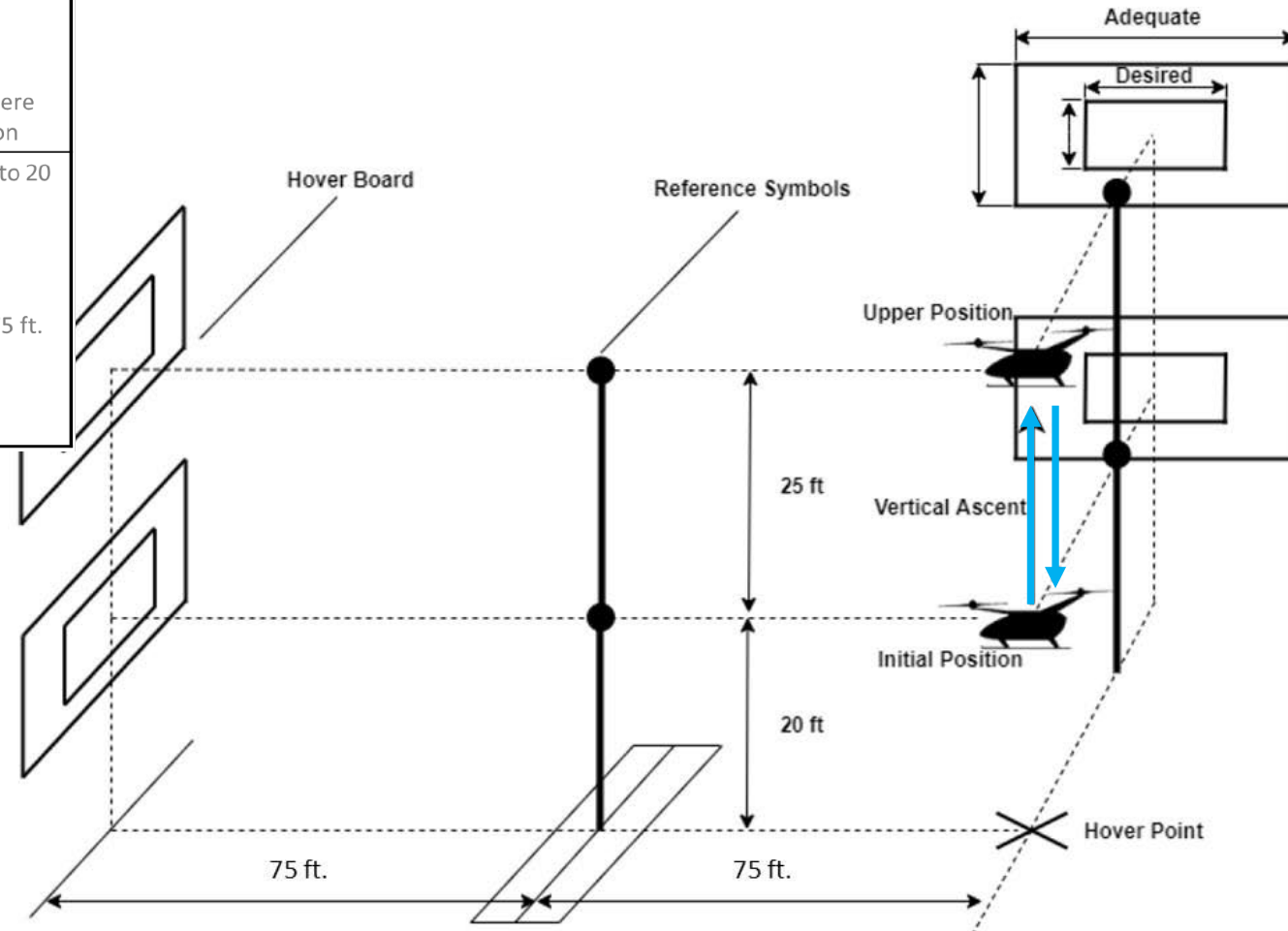


Lift-Plus-Cruise (LPC) Vehicle showing location of degraded motors

Vertical Maneuver: Task Description

		RVLt-HQ2 ADS-33E MTE	RVLt-HQ2 FAA HQTE	Changes from the published tasks to support RVLt HQ2
Criteria	Horizontal	Desired / Adequate {	3 / 6 ft.	The lower criteria of 20 and 25 sec. were removed from the FAA HQTE definition
	Altitude		3 / 6 ft.	
	Heading		5 / 10 deg.	
	Timing		13 / 18 sec.	
Method	Start Altitude	20 ft.	20 ft.	ADS-33E MTE was increased from 15 to 20 ft. for consistency
	Delta Altitude	25 ft.	25 ft.	
	Stabilize Time	2 sec.	5 sec.	
	Target / Board Spacing	75 ft.	75 ft.	FAA HQTE was increased from 50 to 75 ft. for consistency
	Reversal Following Stabilized Hover	Yes	Yes	

1. Climbs to top target from initial position
2. Holds target position for required stabilizing time
3. Returns to bottom target for initial position capture
4. Once stable, the task ends and execution time is recorded

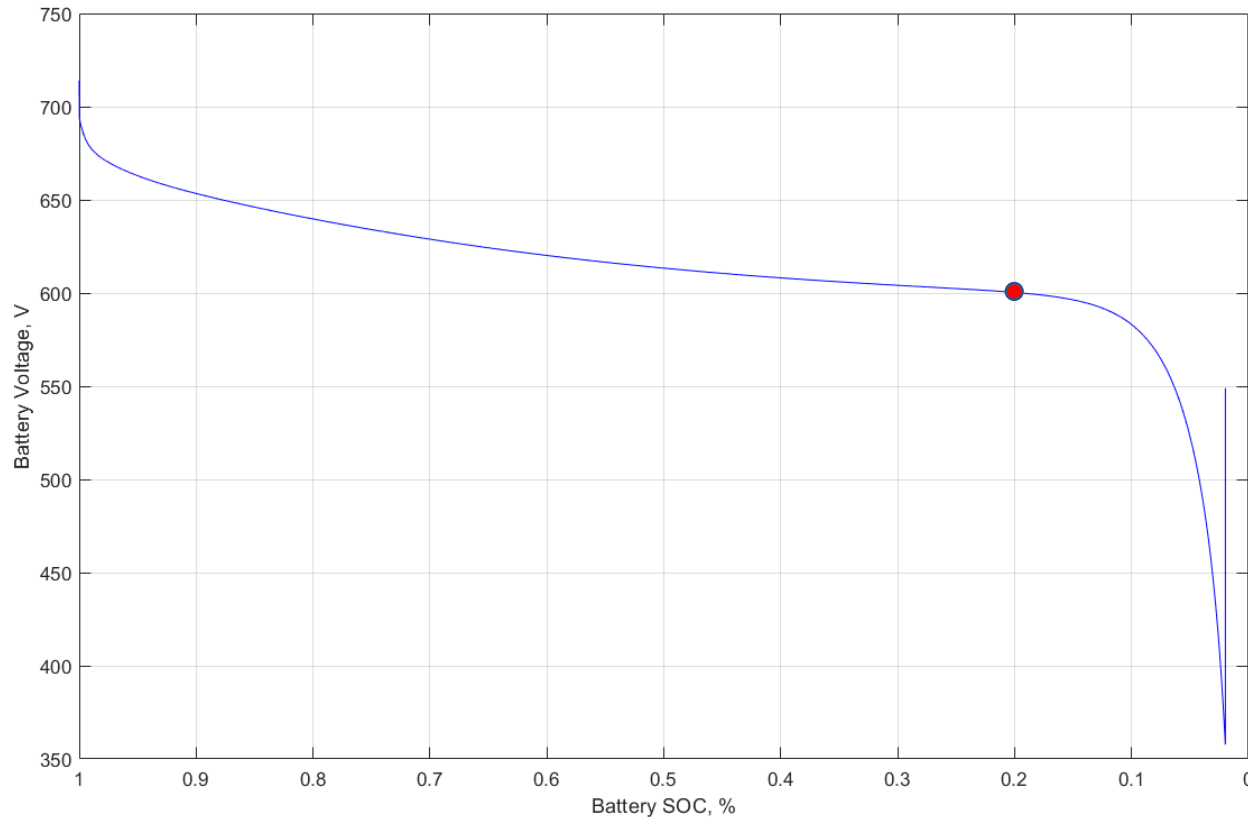




Vertical Maneuver / ACAH ADS-33E MTE / Healthy vs. Low SOC



Low SOC Effect on Available Battery Voltage



Initial Battery SOC= **20%**
Equivalent Battery Voltage=**600 V**

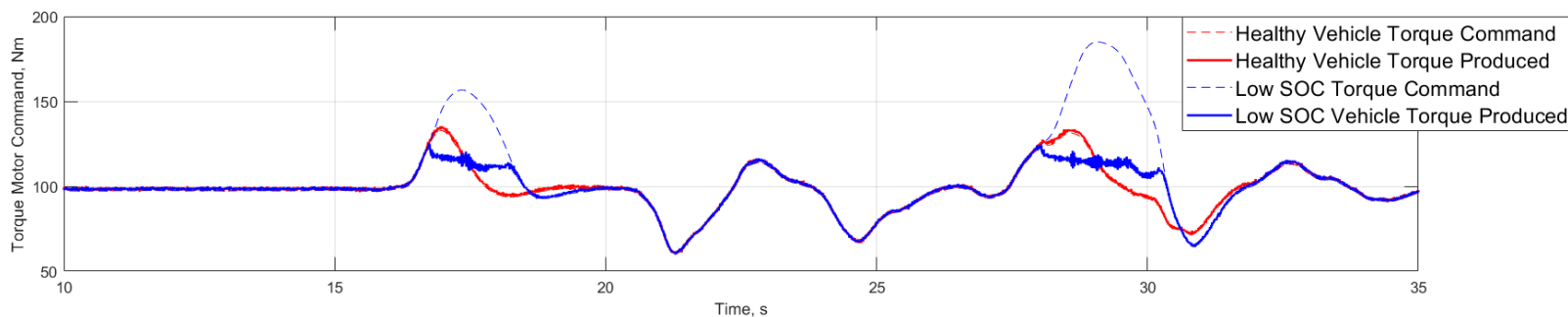
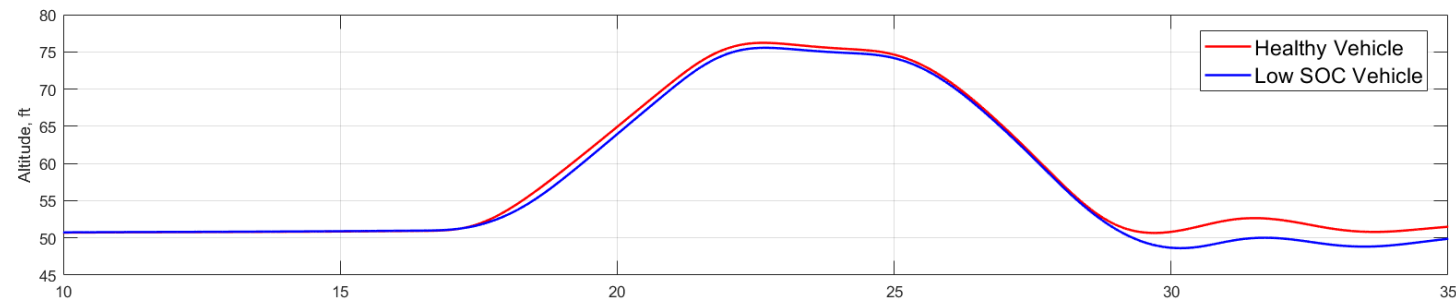
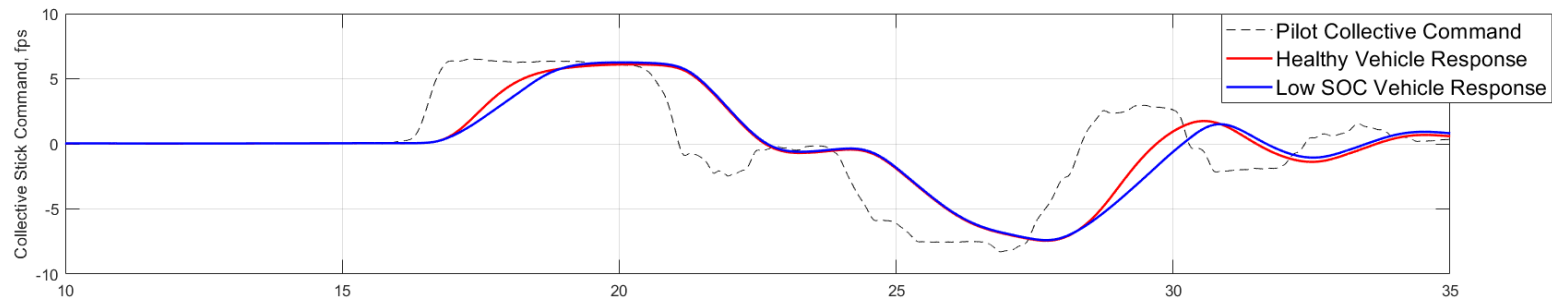
Research:

- **Objective**
 - Want to be aware of task execution capabilities when a battery has been drained, specifically to 20% SOC
- **Considerations**
 - Lower Available Battery Voltage
 - If pilot command requests too much voltage, motor limits will be hit
 - Drop off in Voltage
 - Need to be aware of what this drop off means for vehicle controllability

Data Analysis: Impact of Low SOC

- This analysis will compare a healthy vehicle to a vehicle with low SOC
- The same stick tracing will be run through both a healthy and low SOC vehicle through computer simulation in order make a distinction between the two vehicle conditions

Heave Rate / Altitude / Torque Response



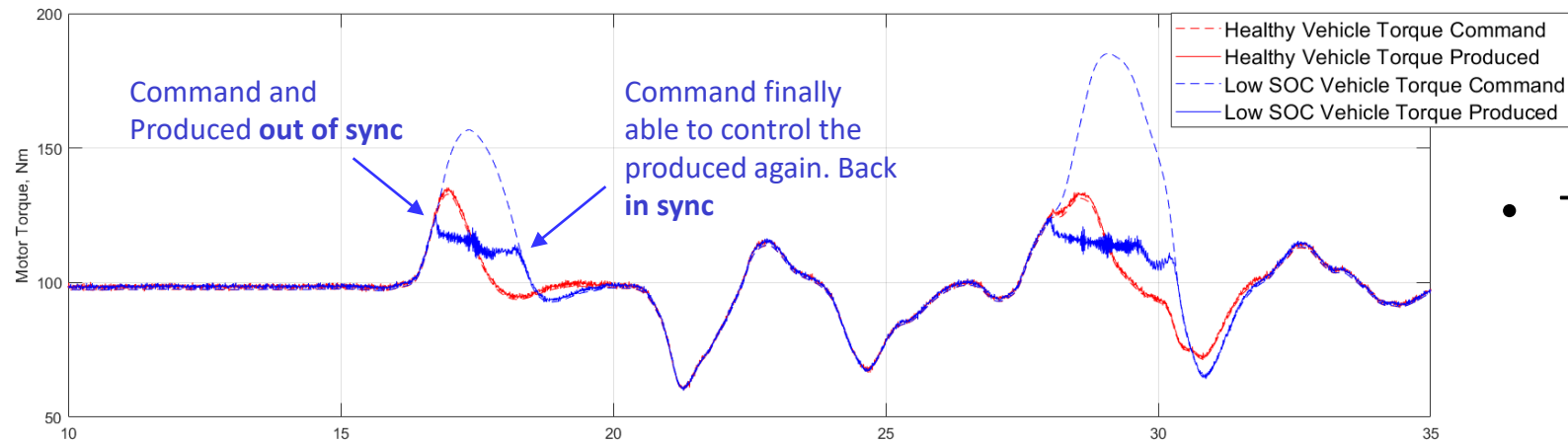
What We See

- Different Heave Response
 - The low SOC vehicle has a much slower heave response to the pilot stick command.
- Different Altitude Reached
 - The low SOC vehicle reaches a lower altitude.

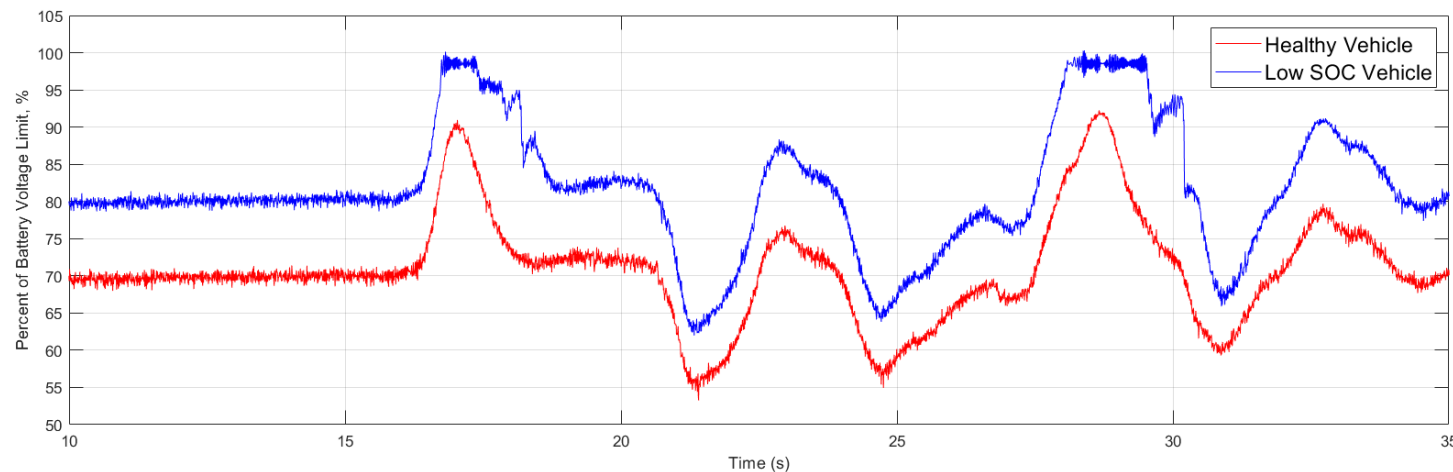
Why??

- Motor Torque Produced is Limited
 - The motor is not able to produce enough torque to match the command that is being given by the controller.

Limited Motor Torque Caused by Voltage Limit



- Torque Commanded/Produced
 - Torque produced being limited causes **delayed response to pilot input.**

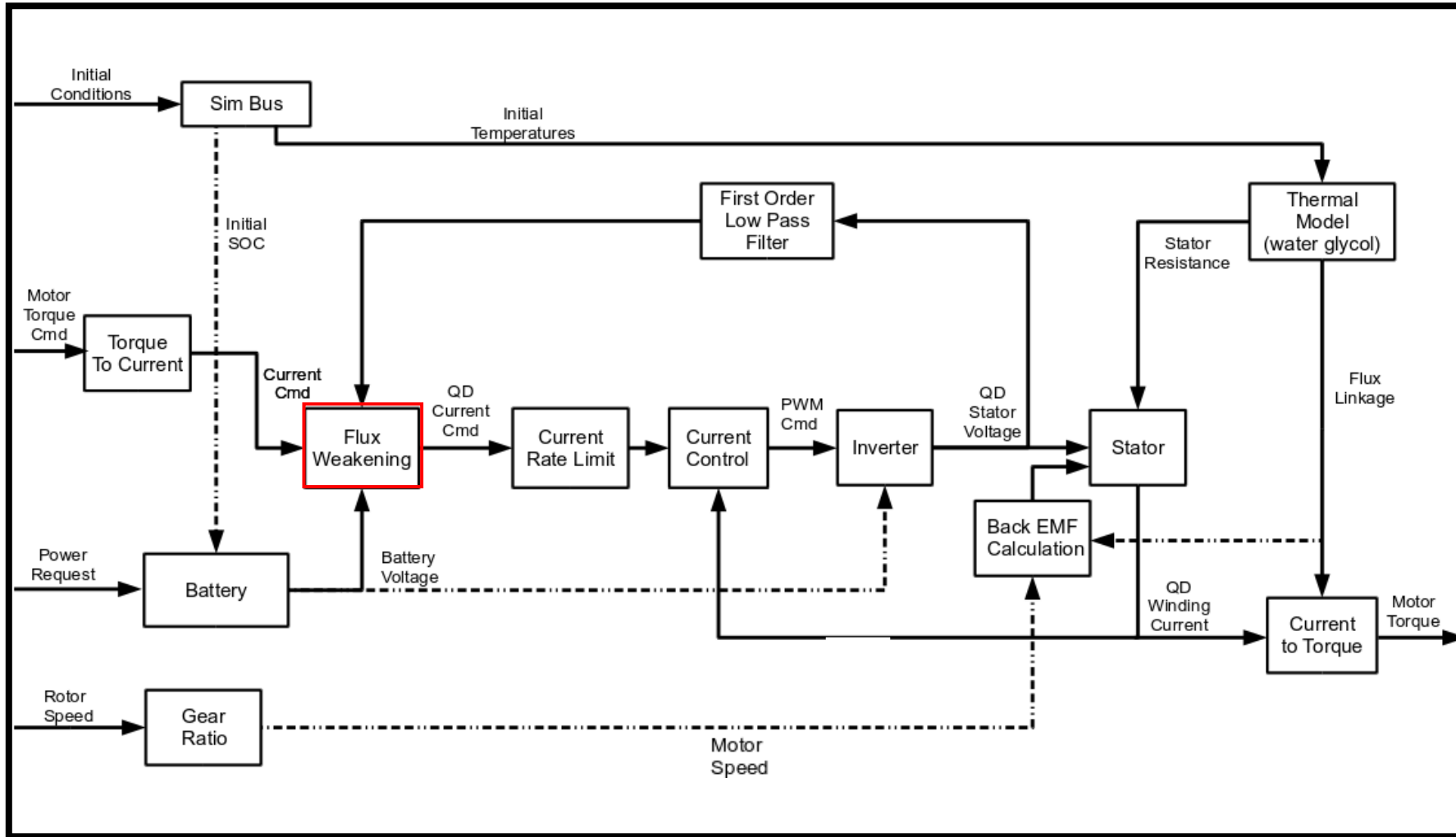


- Voltage Limit

$$\frac{\sqrt{V_{q_stator}^2 + V_{d_stator}^2}}{V_{Battery} * \frac{2}{\pi}} * 100 \quad \boxed{\frac{Desired}{Available}}$$

- The stator voltages are being limited by **flux weakening** so that available battery voltage is not surpassed, and so the **inverter is protected from saturation**

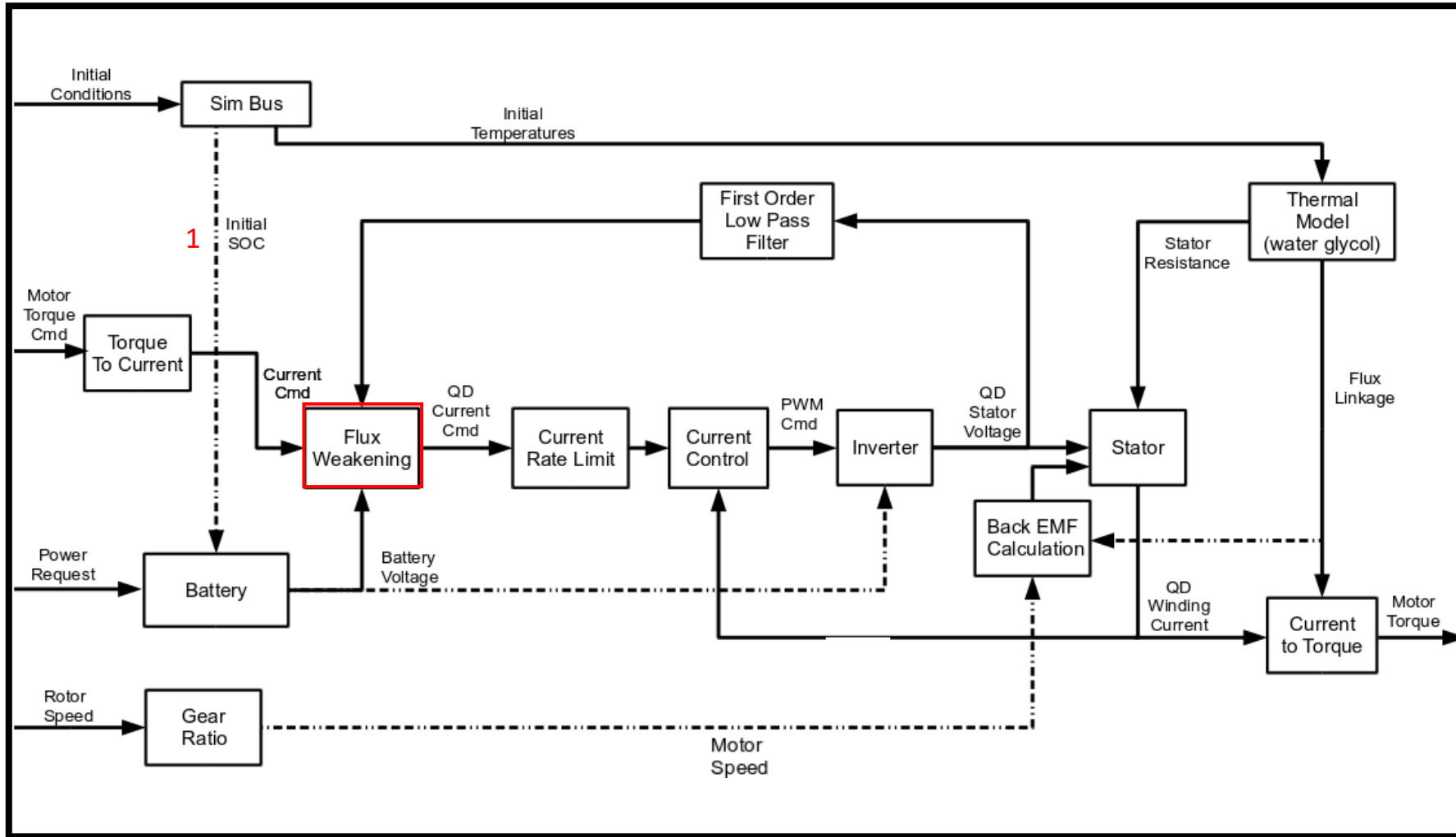
Complex Powertrain Structure: Low SOC



Flux Weakening Impact

1. Decrease the Initial SOC
2. Available battery voltage not able provide the torque that is being commanded.
3. Torque command/current command seeks to compensate by increasing the command.
4. **Flux weakening** protects the inverter from saturating by limiting the current that is provided in point 3

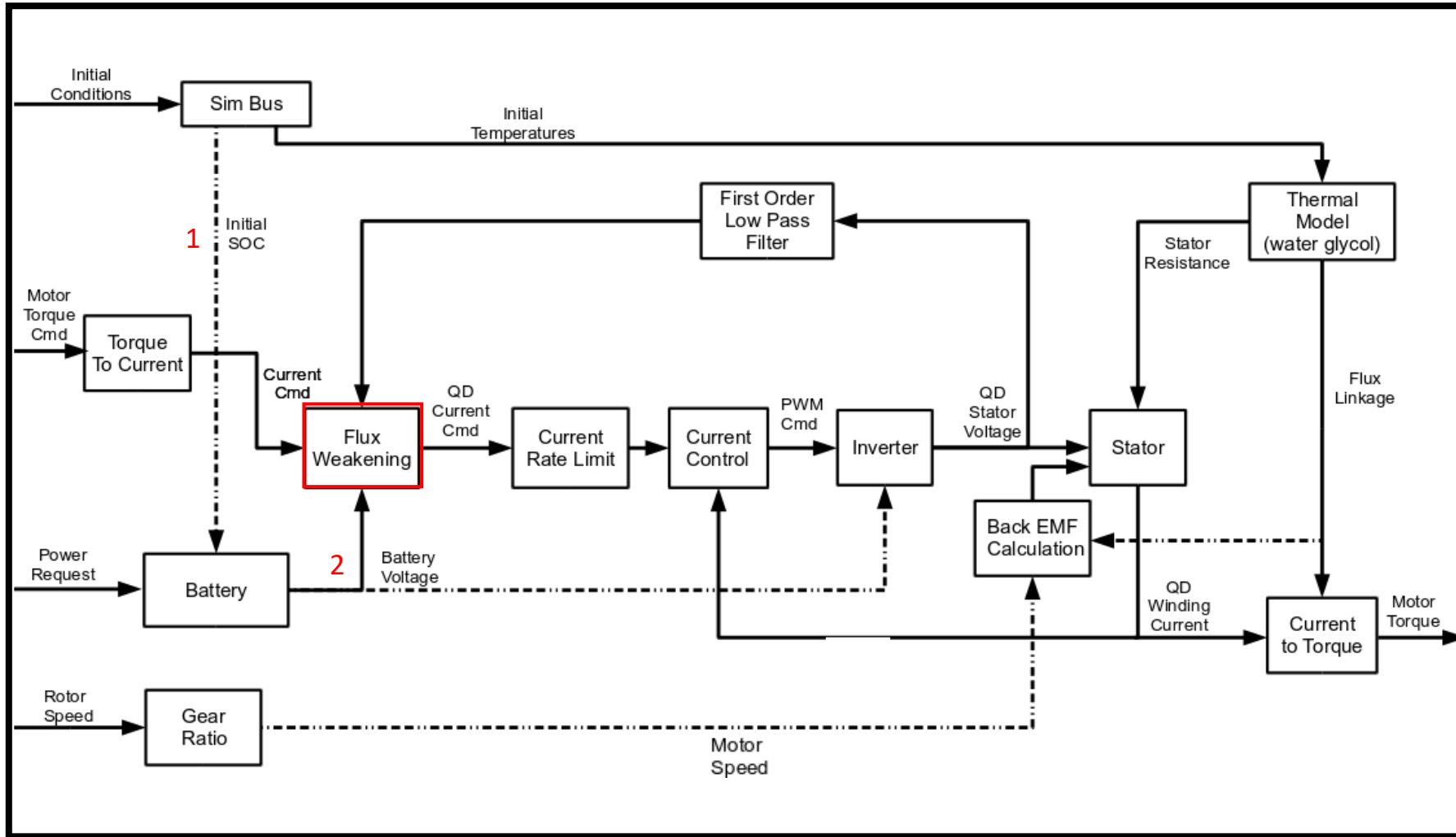
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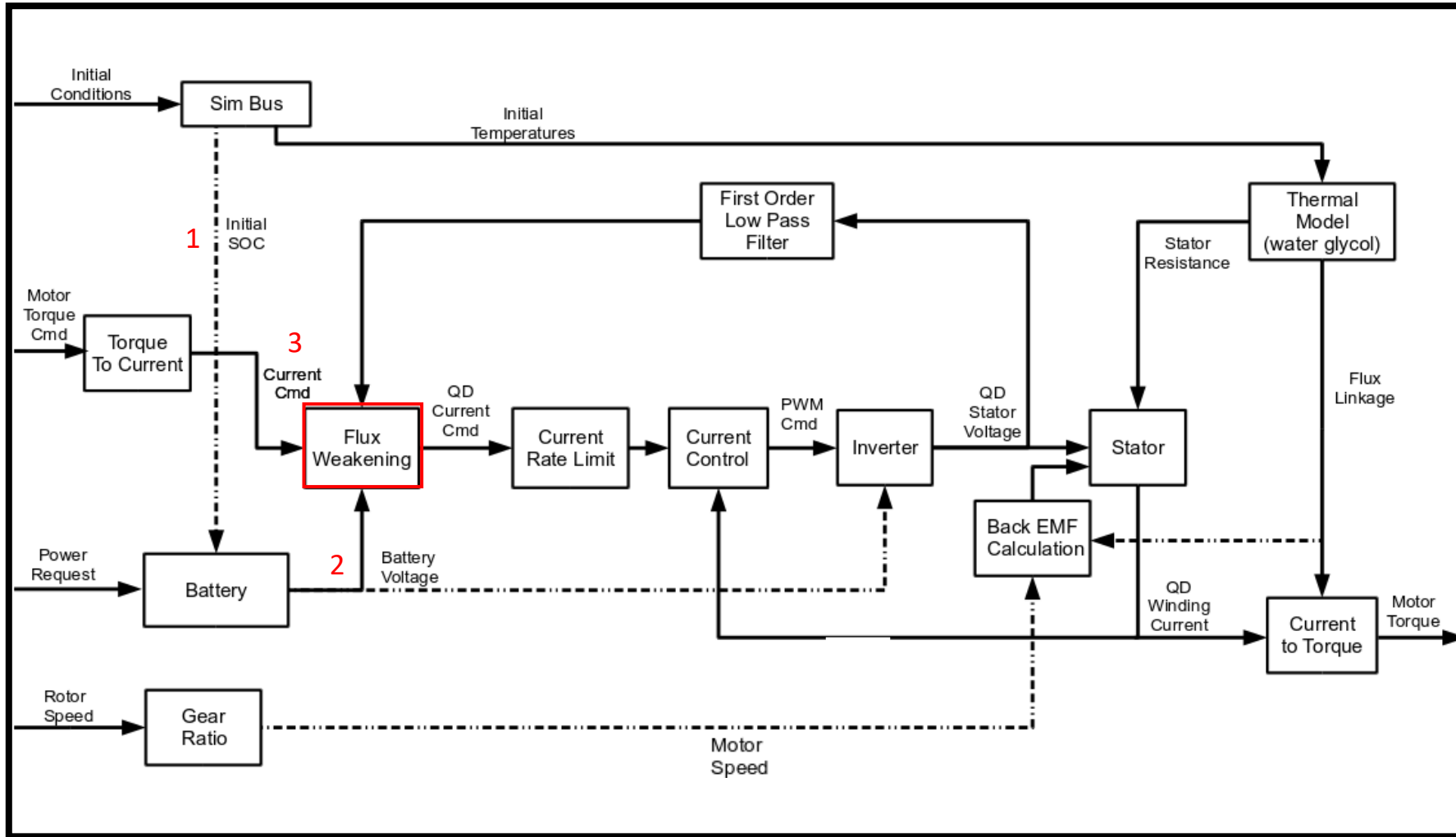
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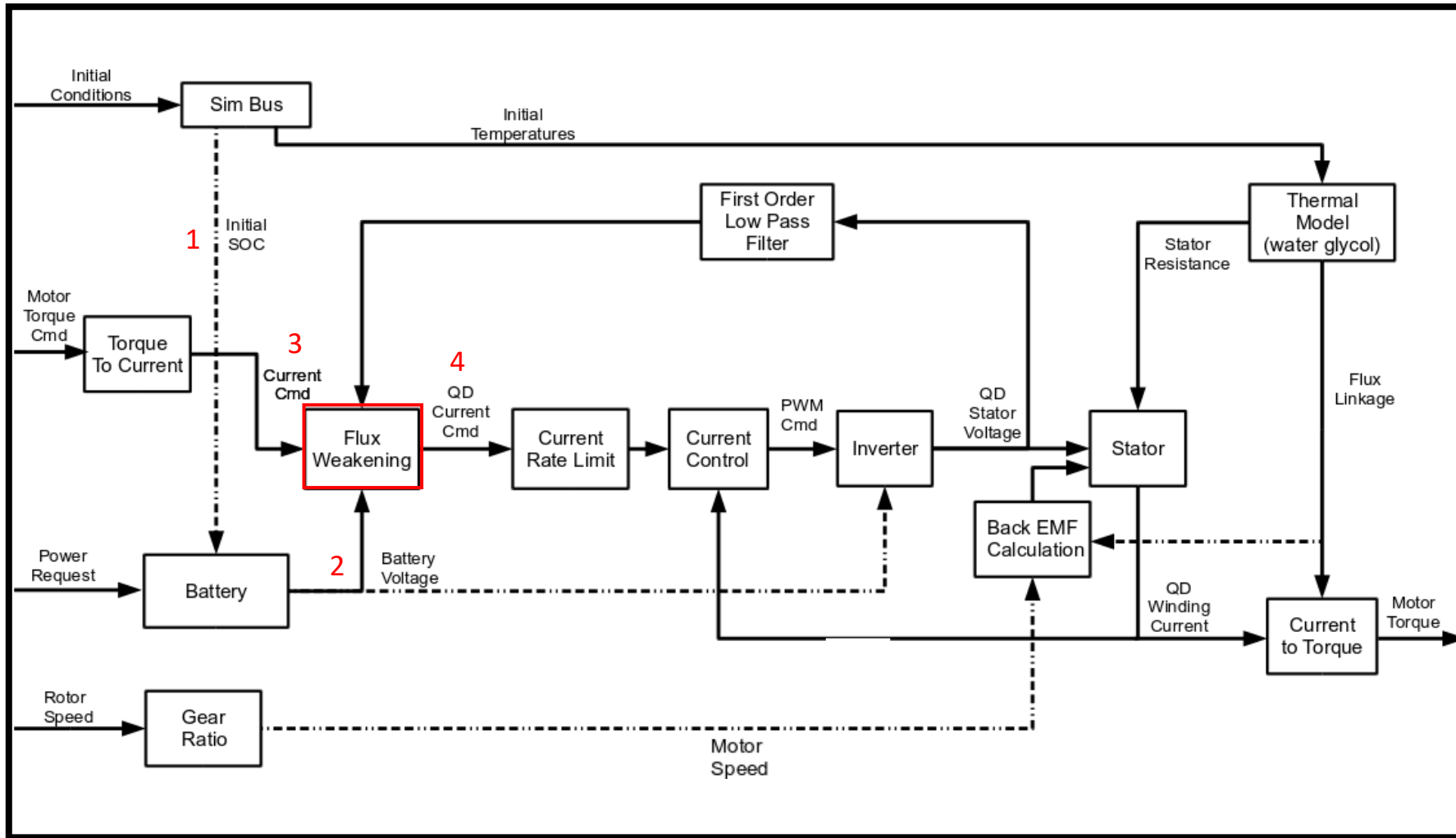
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Data Analysis: Pilot In the Loop

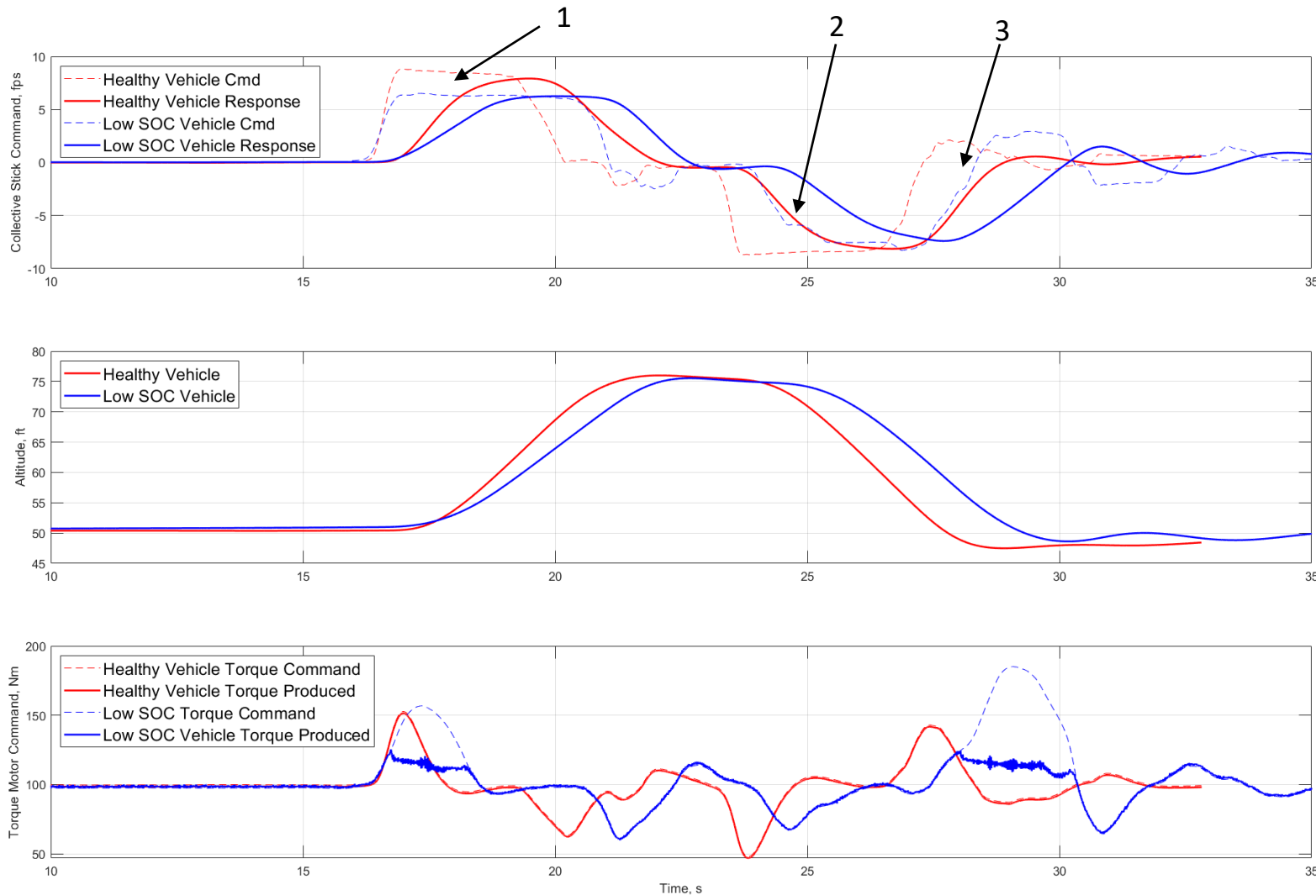
- This comparison will focus on the different pilot techniques implemented for different vehicle conditions during VMS testing
- The observed pilot techniques will have a direct affect on Handling Quality (HQ) ratings

Vertical Maneuver Videos

Pilot A / ADS-33E / **Healthy Vehicle**

Pilot A / ADS-33E / **Low SOC Vehicle**

Heave Rate / Altitude / Torque Response



What We See

- Different Cmd. Rates and Magnitudes
 - **1-3:** Command rate and magnitude were generally lower for the low SOC configuration

"I pulled up with what I thought was a reasonable rate to not saturate."

- Pilot A / Low SOC

- Slight Oscillations with Low SOC

- The delayed collective response to pilot input is due to limited torque from the motor

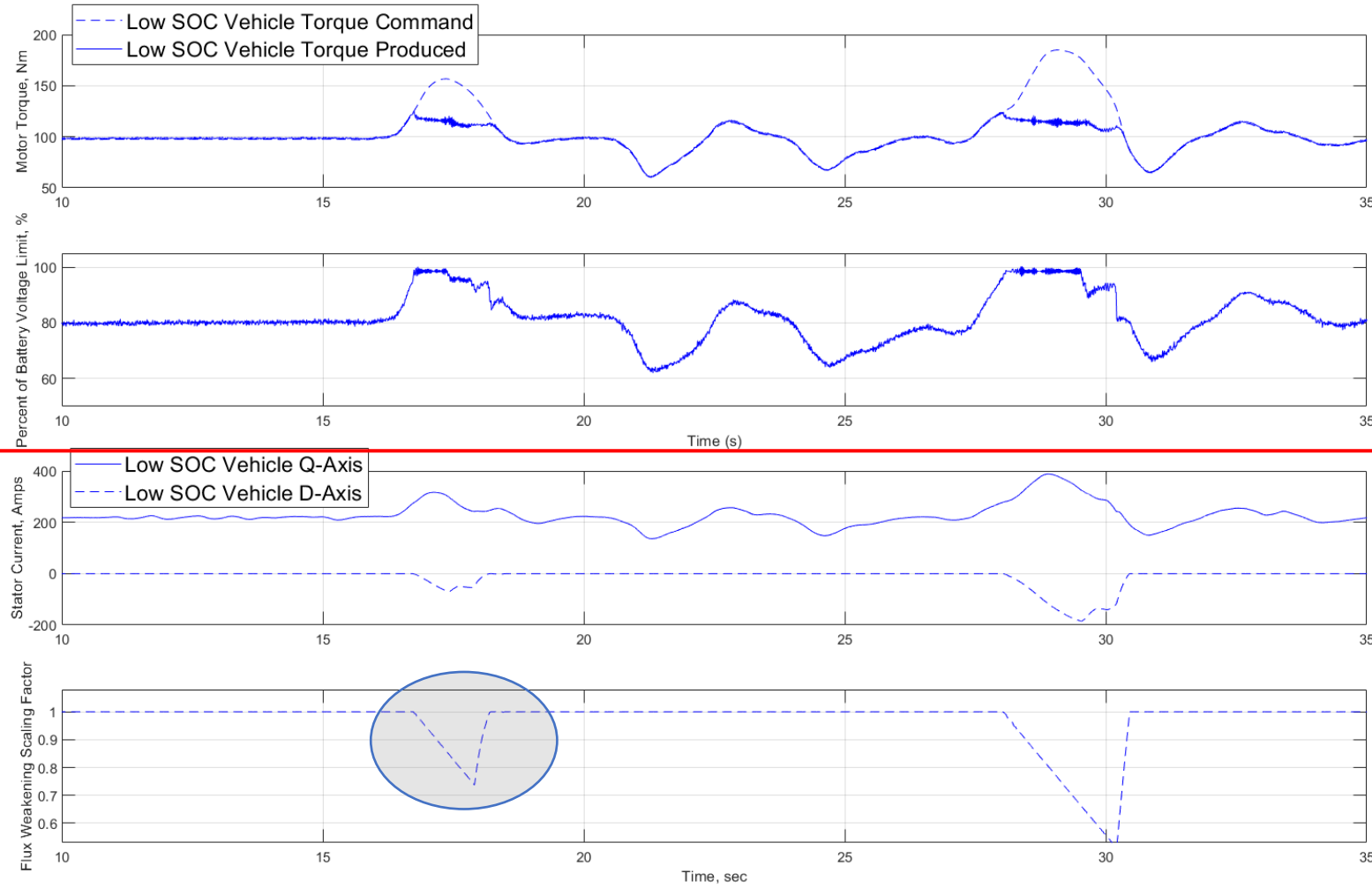
"It was almost like I was getting a low predictability response."

- Pilot A / Low SOC

"That was the fastest I could do it. I almost got into trouble on that one"

- Pilot A / Low SOC

Low SOC: Flux Weakening



- Flux Weakening Impact

- Flux weakening controls the commanded voltage running into the inverter
- Current from torque command distributed between the Q and D axis

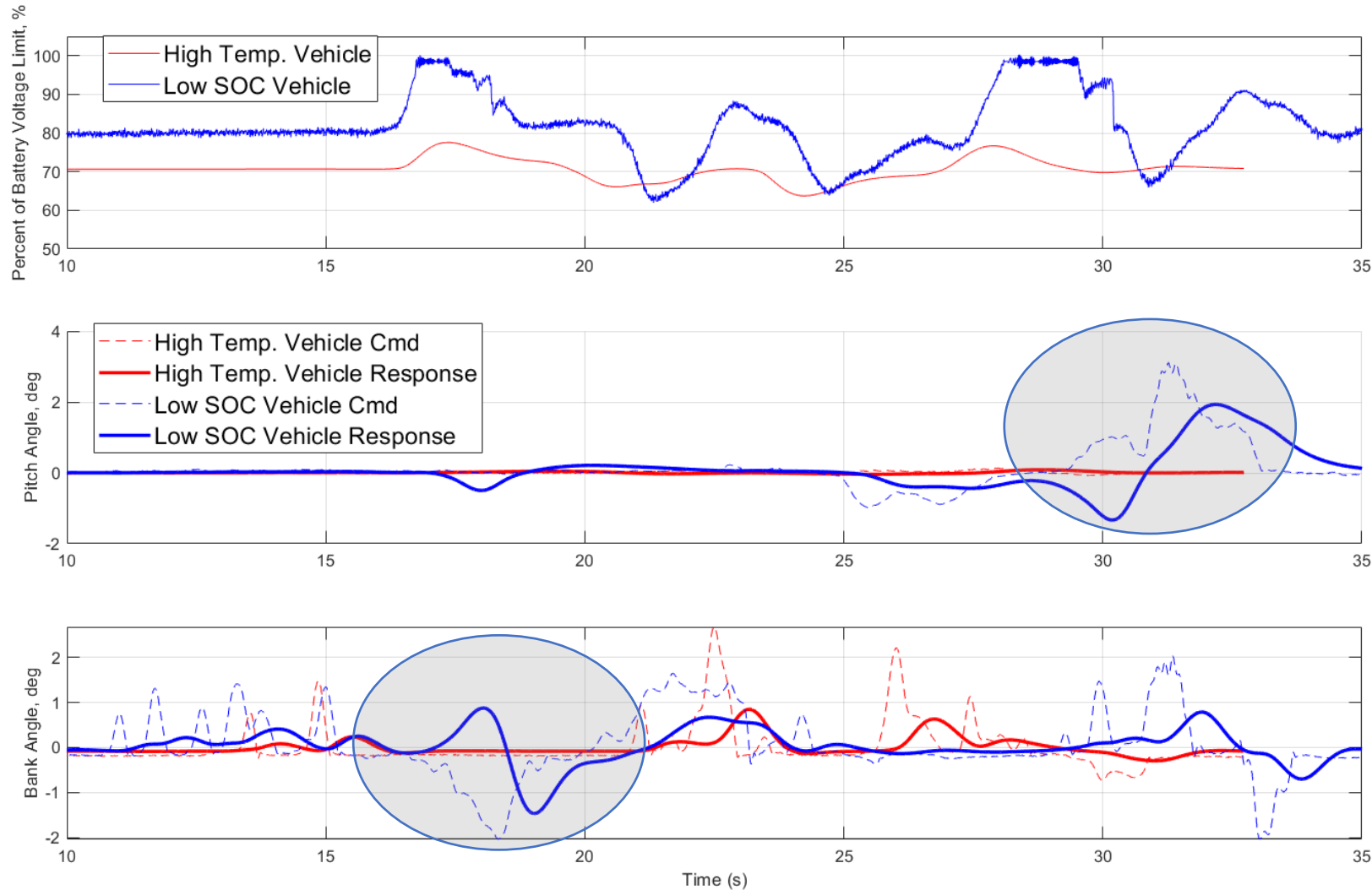
Q-Axis Current

- Current that is used for producing motor torque

D-Axis Current

- Contributes to magnetic losses

Attitude Axis Coupling



- Unwanted Pitch and Bank Attitude
 - Vehicle pitch and bank angle do not follow pilot commands
- Coupling Due to Motor Saturation
 - Motors don't saturate all at once, even during a heave maneuver
 - Motors trim at different torques/RPM due to weight distribution and other factors
 - Small attitude corrections from the pilot cause saturation in certain motors

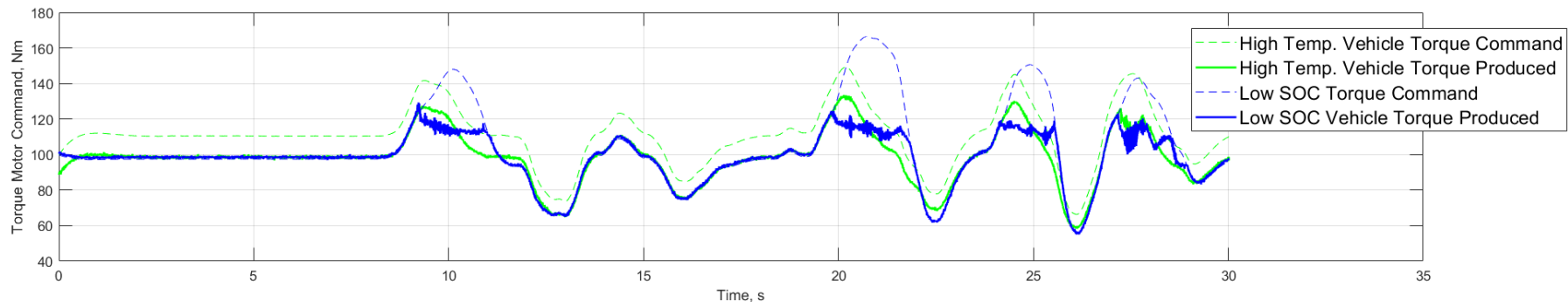
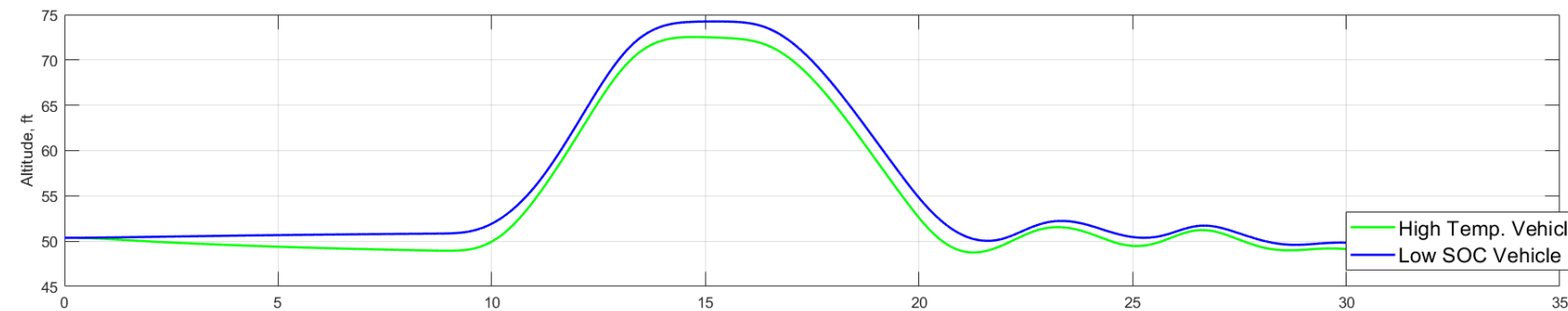
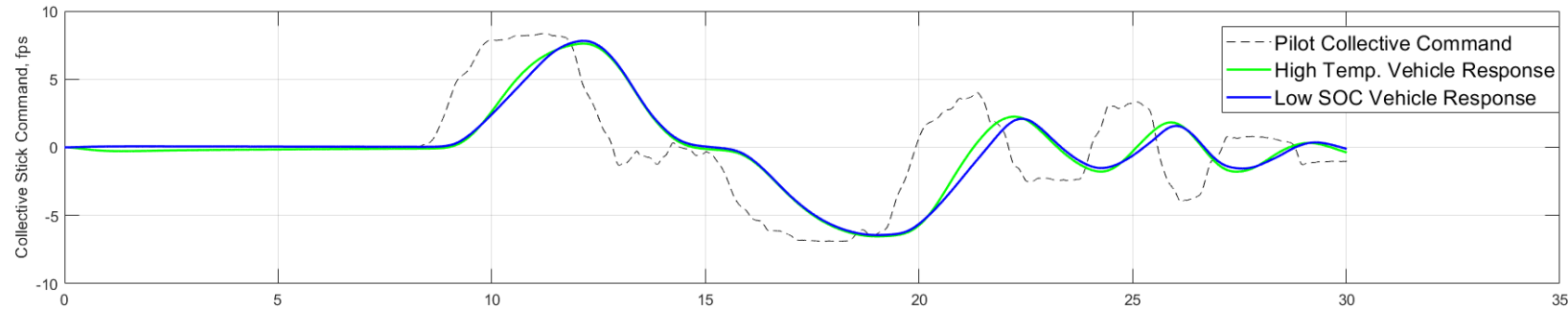
Vertical Maneuver / ADS-33E MTE / High Temp. vs. Low SOC



Data Analysis: Impact of Temperature

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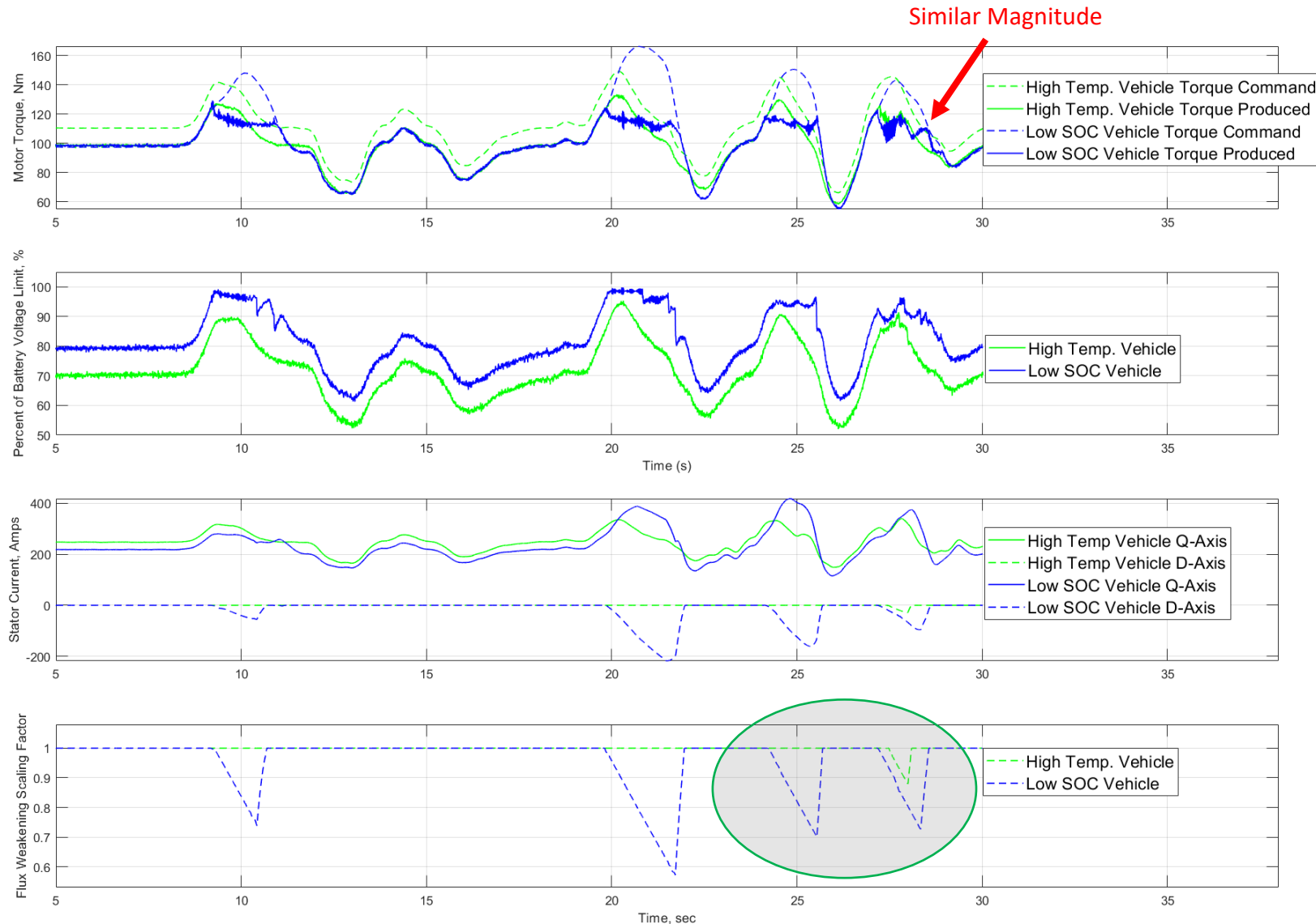
Heave Rate / Altitude / Torque Response



What We See

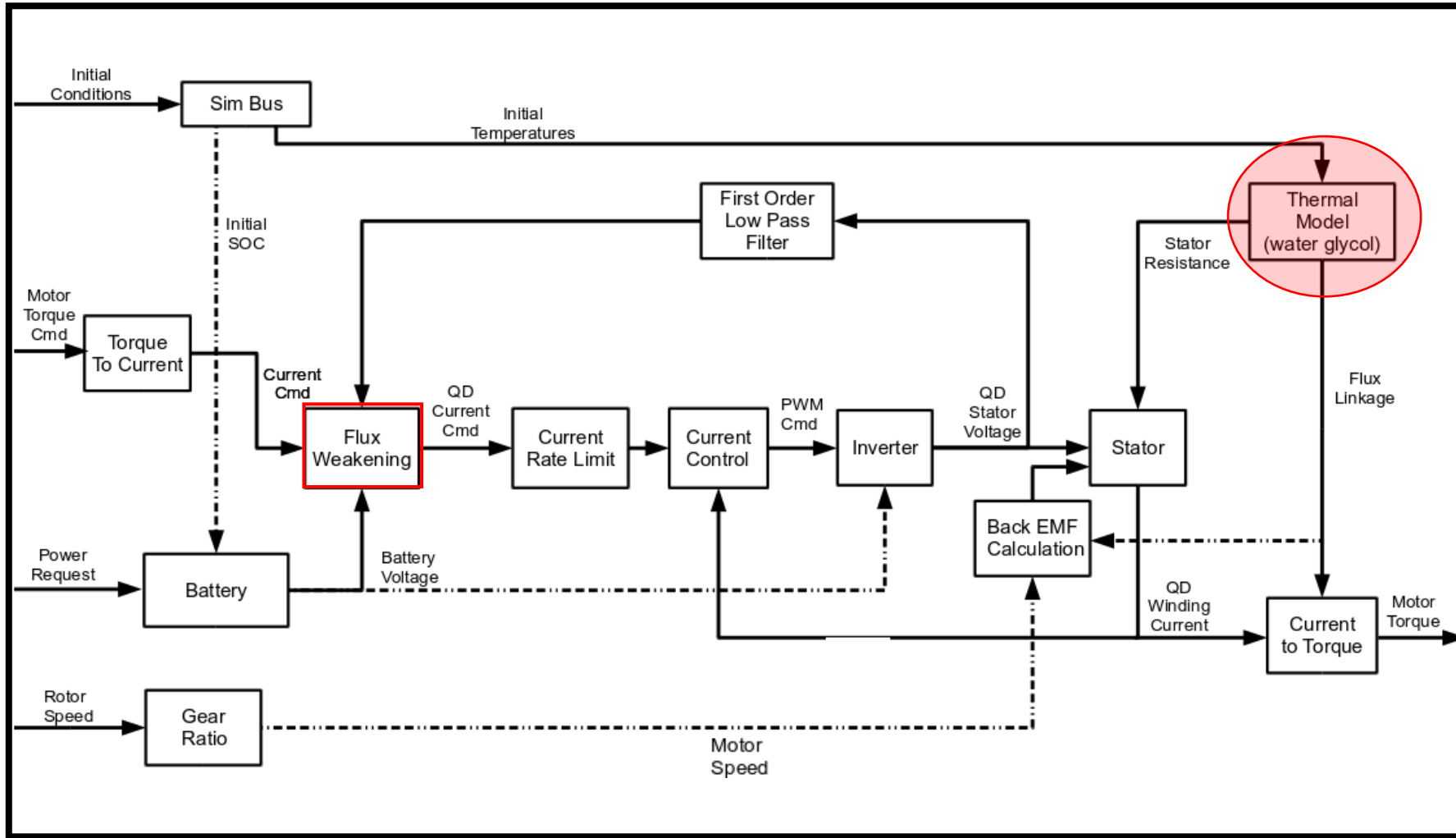
- Different Response Speed
 - High temperature response is quicker to pilot command
- Altitude is higher for low SOC
 - Slight bias in data, due to trimming error
- Increased Torque Command
 - High temperature case has a consistently higher torque command

Flux Weakening Comparison



- **Produced Motor Torque**
 - Motor Torques are a similar magnitude during motor saturation
- **Stator Current During High Temp.**
 - Less stator current is available during motor saturation
- **Flux Weakening Scaling Factor**
 - The scaling factor for flux weakening is generally higher for a high temp. case

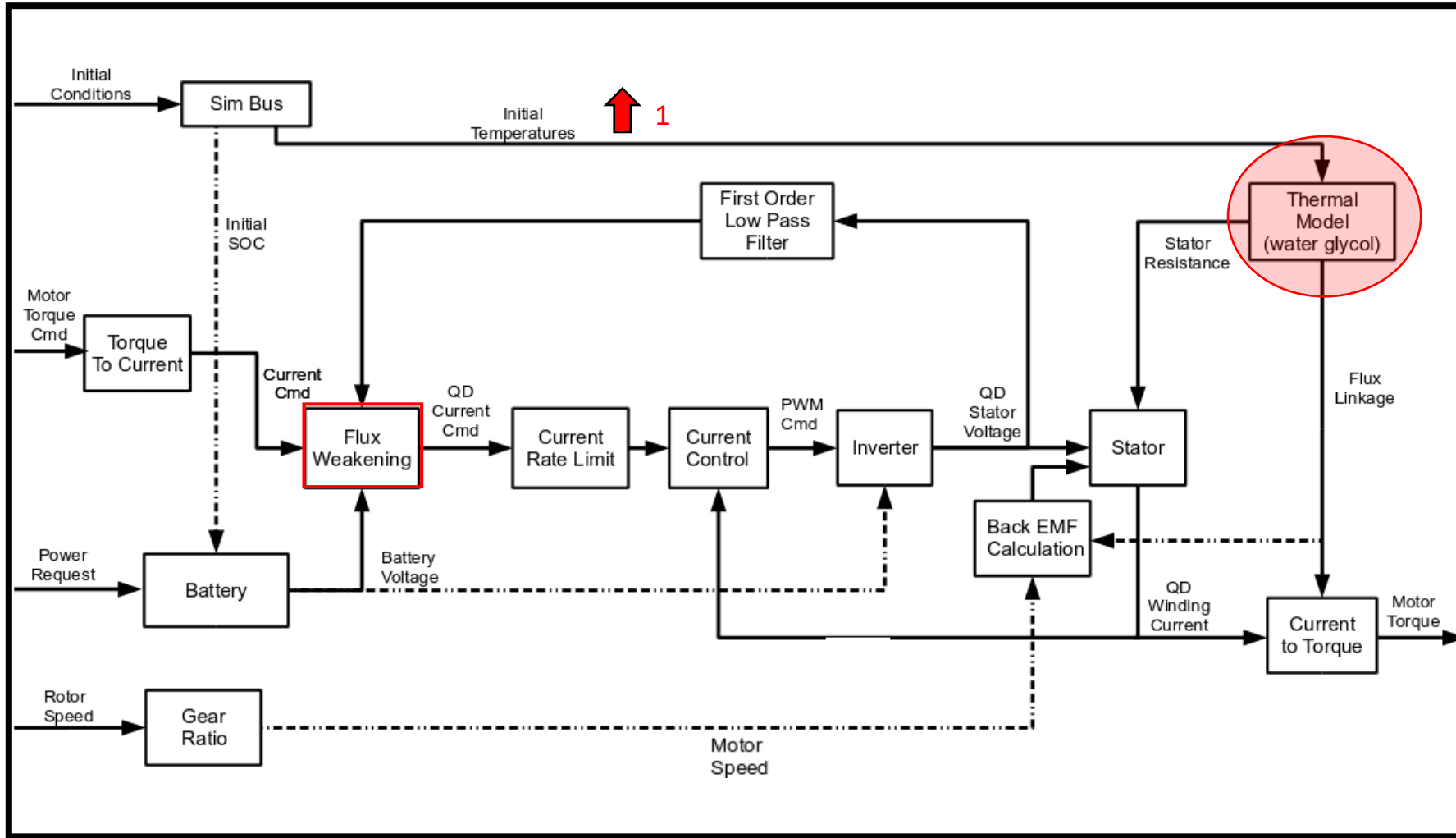
Complex Powertrain Structure: Low SOC



Flux Weakening Impact

1. Increase initial Temperature
2. Flux Linkage Decreases
3. Stator Resistance Increases
4. Decreased Motor Torque
5. Ultimately Motor Torque Command is increased which leads to **Flux Weakening** engaging

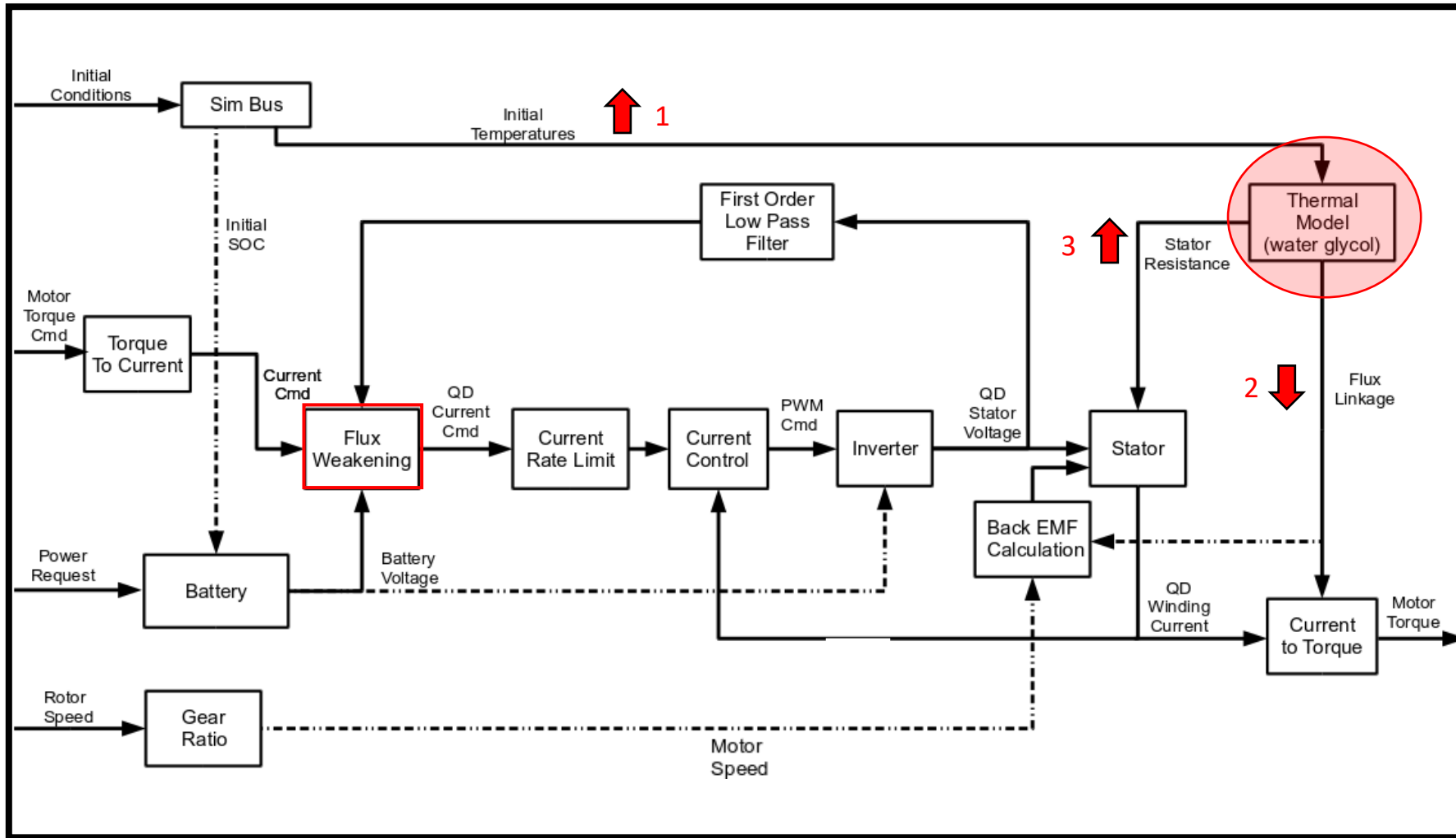
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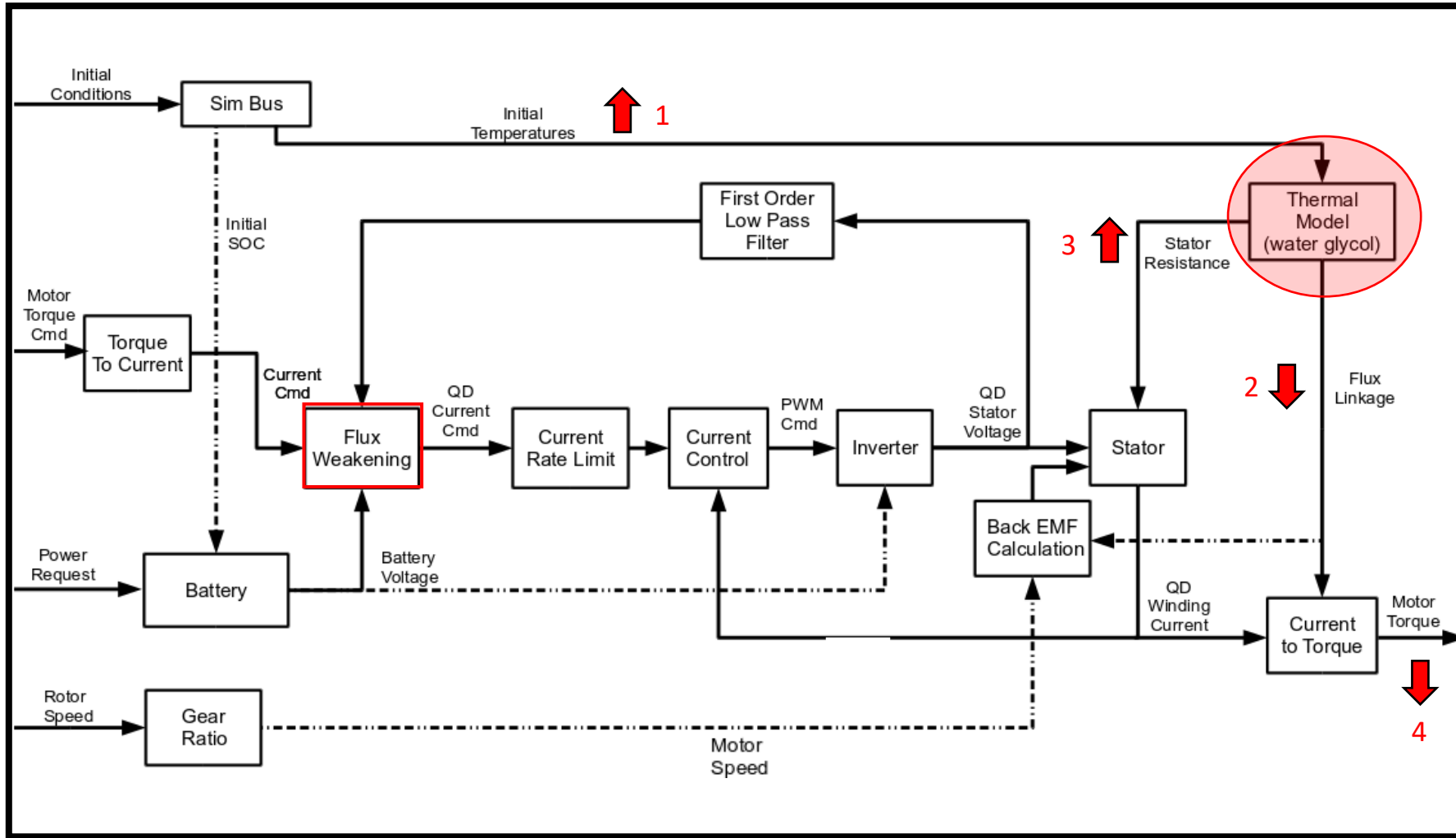
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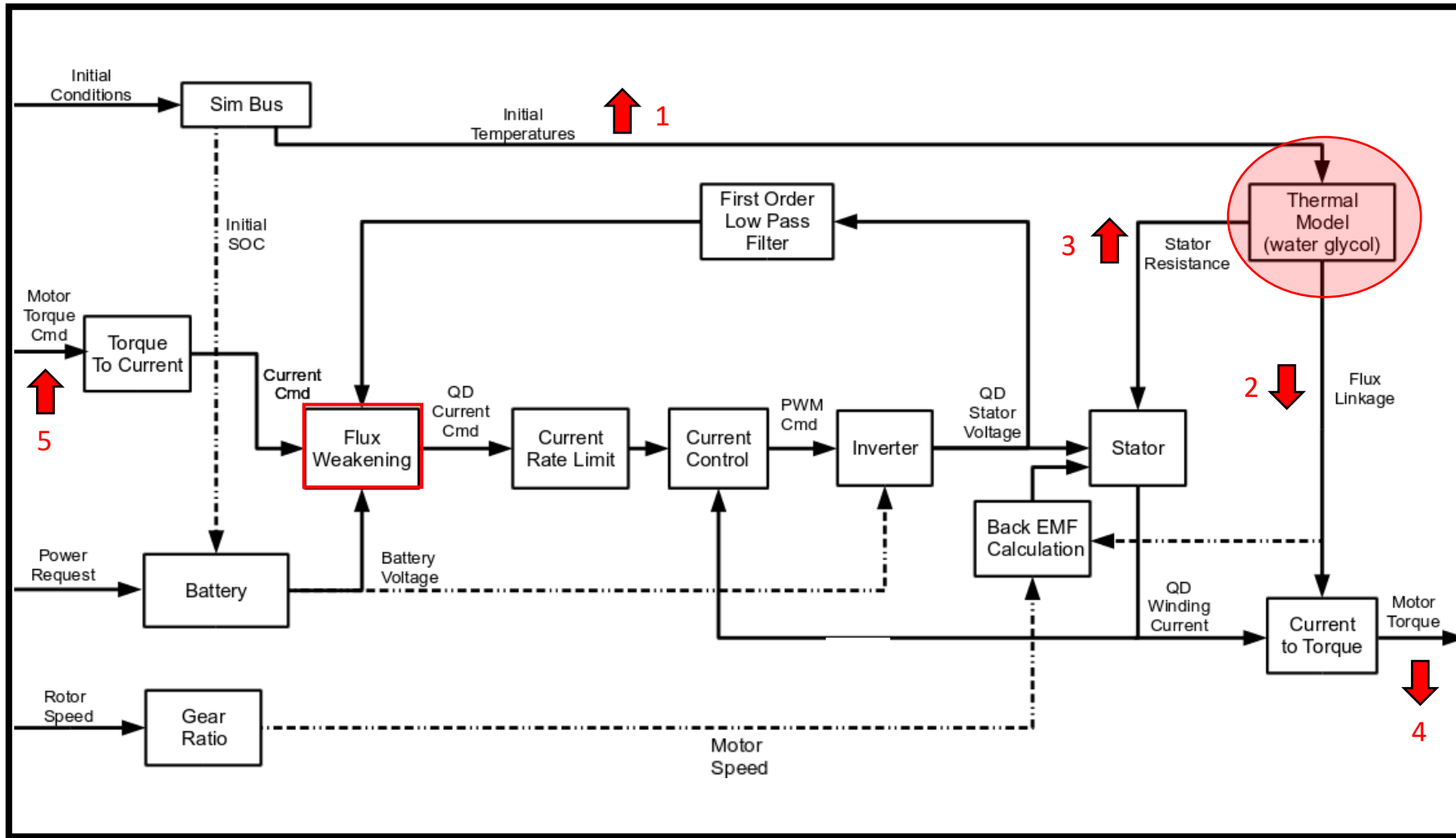
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Motor Configuration Parameters

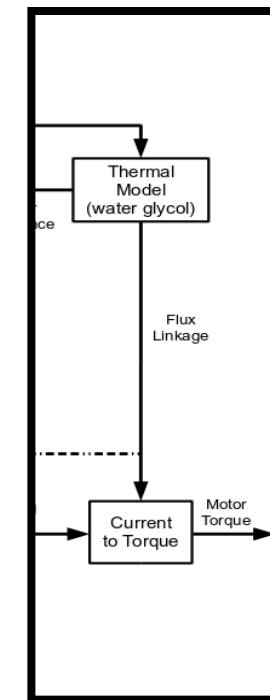
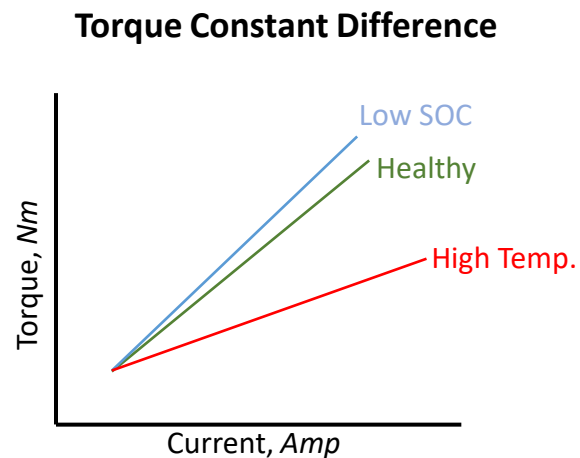


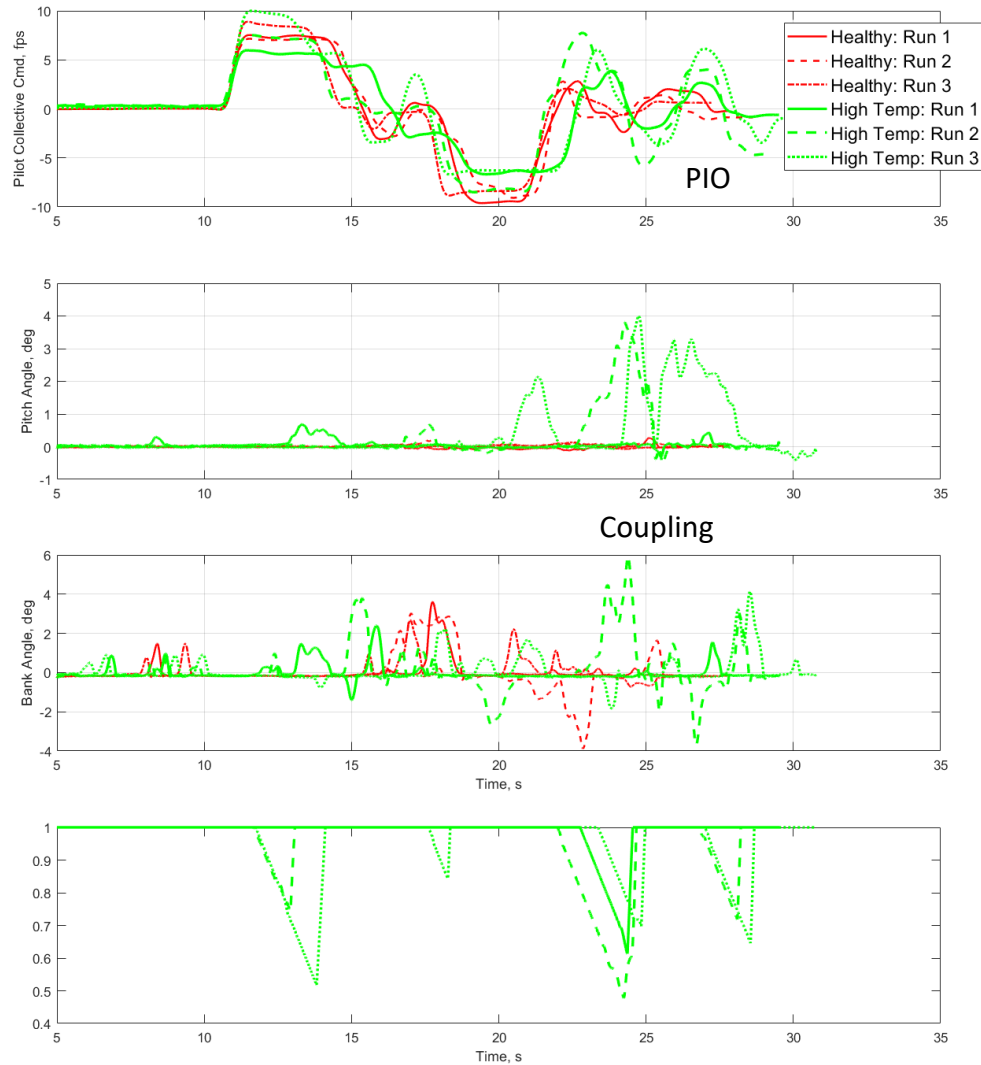
Table 1: Temperature Model Constants and Values

Vehicle State	Torque Constant, $\frac{Nm}{Amp}$	Stator Resistance, $ohms$	Flux Linkage, $\frac{V}{rad/s}$
Healthy/Nominal	0.445	0.0196	0.0495
Low Battery SOC	0.456	0.0182	0.0507
High Temp. Motors	0.402	0.0243	0.0447

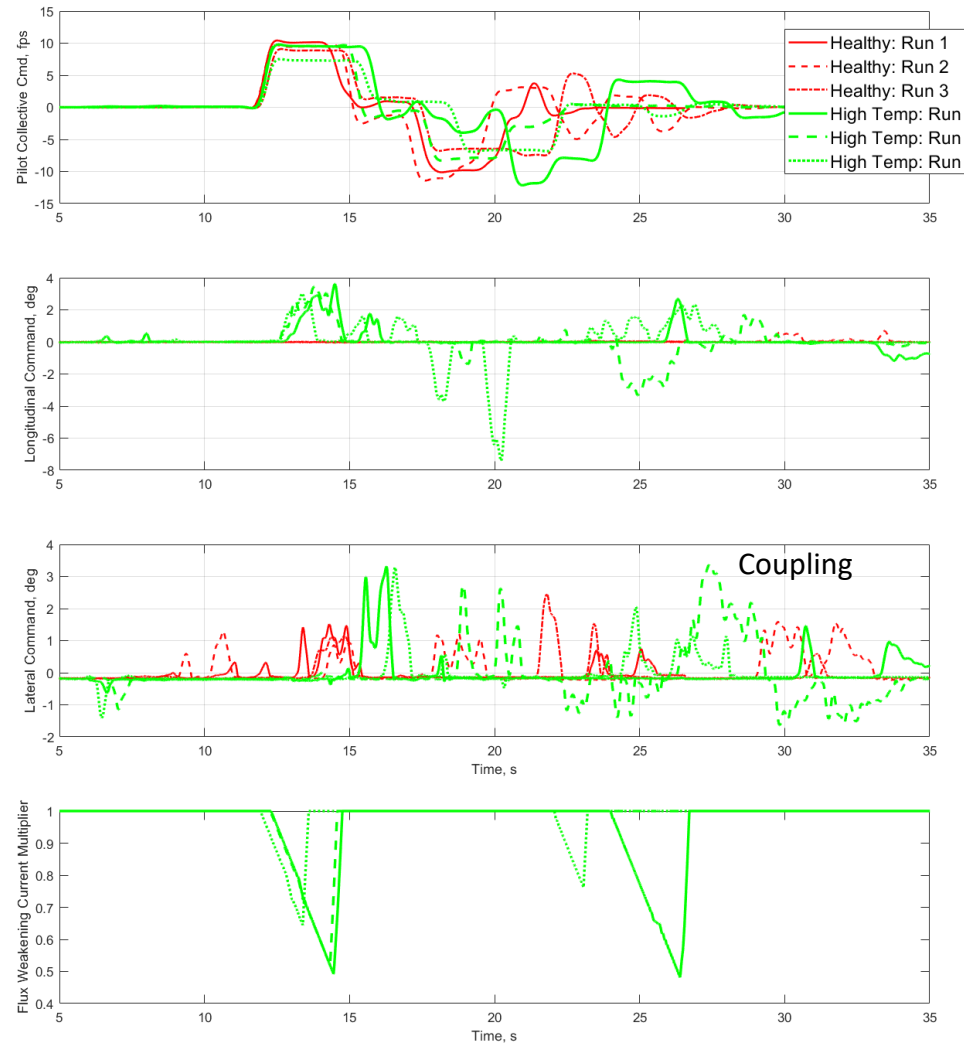
- 12% decrease in **Torque Constant** and **Flux Linkage** in Healthy/High Temp.
- 24% increase in **Stator Resistance** in Healthy/High Temp. Vehicle comparison
- Ultimately decreases the motor torque output

More Pilot Data: High Temp.

Pilot A / Healthy vs. High Temp.



Pilot D / Healthy vs. High Temp.



What We See:

- Pilot A not able to stabilize during high temperature case
 - PIO in the heave axis
 - High Workload in the lat/lon axis due to coupling
- Pilot D hits adequate criteria for temperature case
 - Does not oscillate collective inputs
 - Lower magnitude correction inputs during coupling



Handling Qualities



Other Pilot Comments

Low SOC:

“Had to be as smooth as I could with power and try to anticipate power changes for the reversals”

- Pilot C / Low SOC

“Slowly ramp inputs. Large power inputs were coupled with attitude and that was a little difficult to control.”

- Pilot C / Low SOC

High Temp:

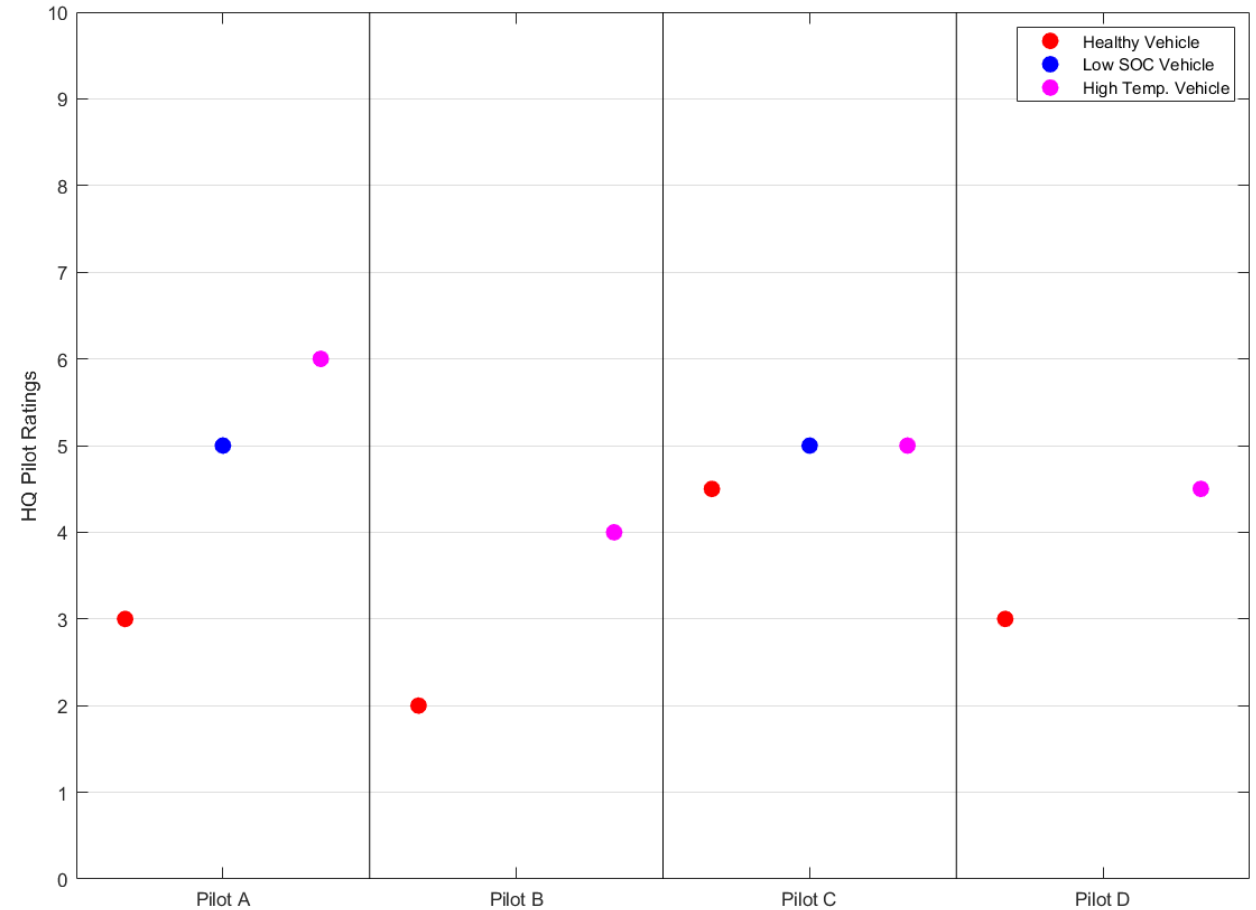
“Mushy at the bottom, had to be careful with the rate of the power application.”

- Pilot A / High Temp.

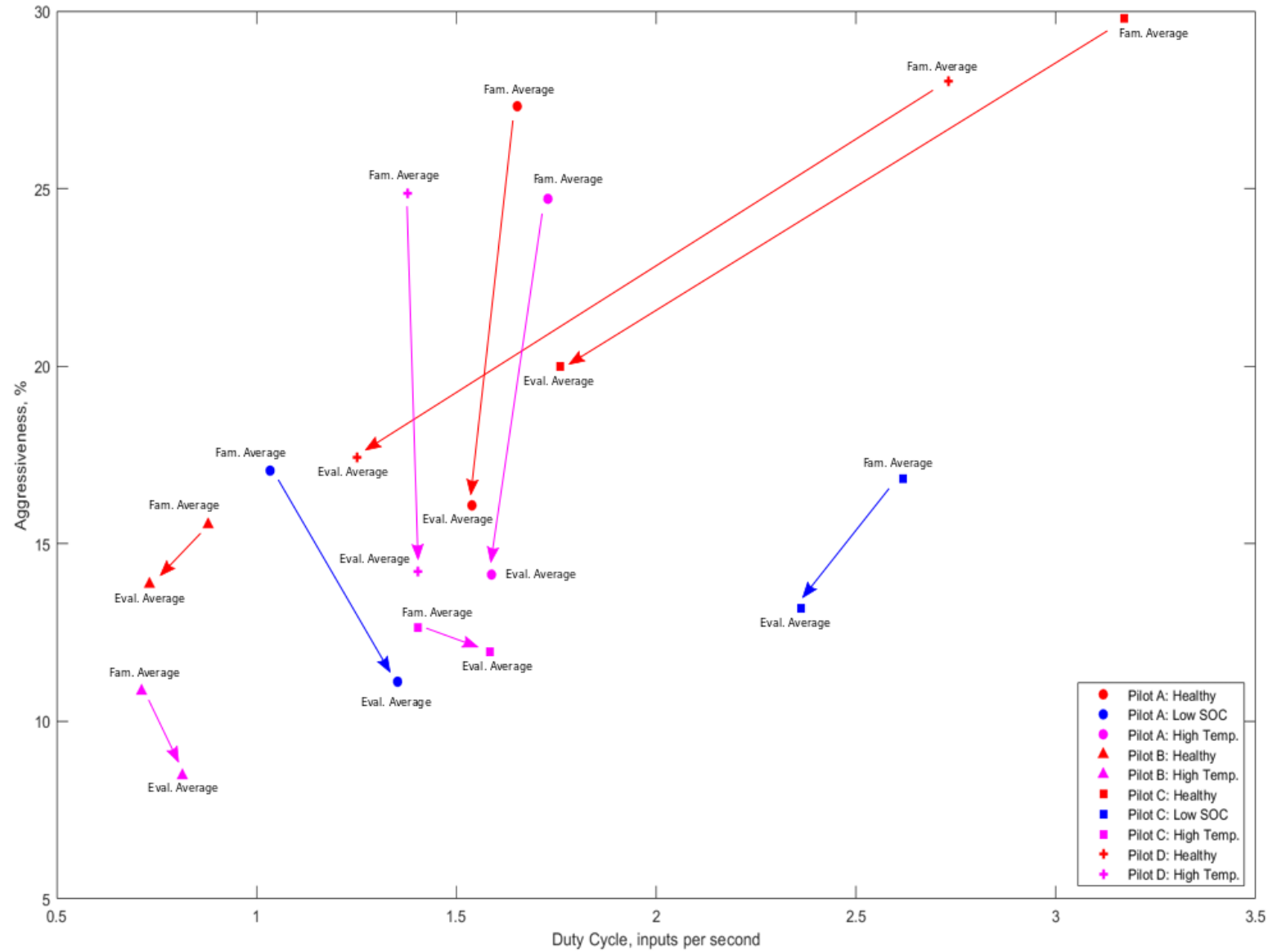
“If you started getting aggressive with the TCL, the attitude would start breaking free”

- Pilot B / High Temp.

Handling Quality Pilot Ratings: Vertical Maneuver



Average Familiarization vs. Average Evaluation



Summary

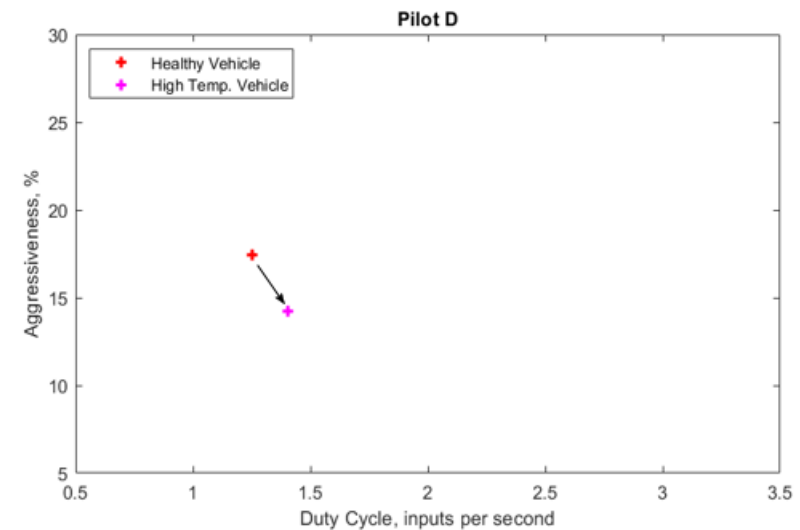
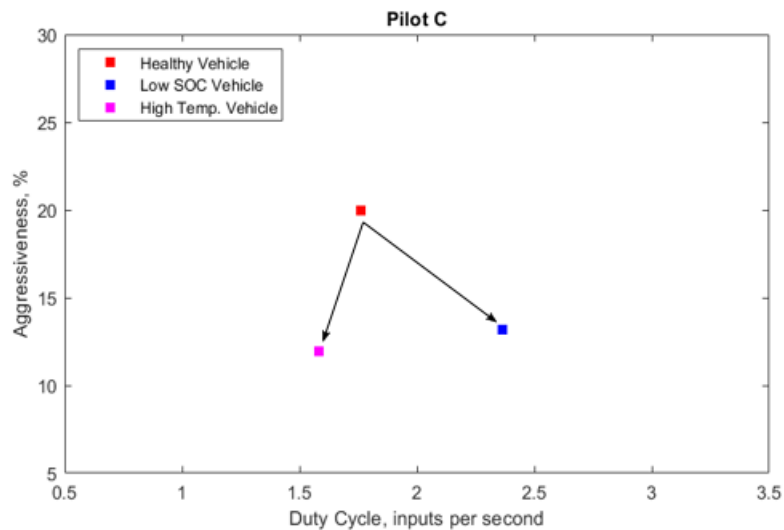
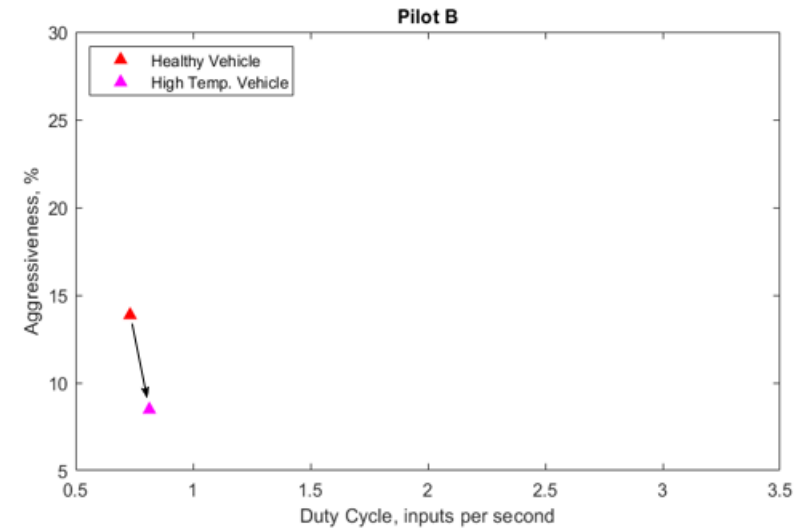
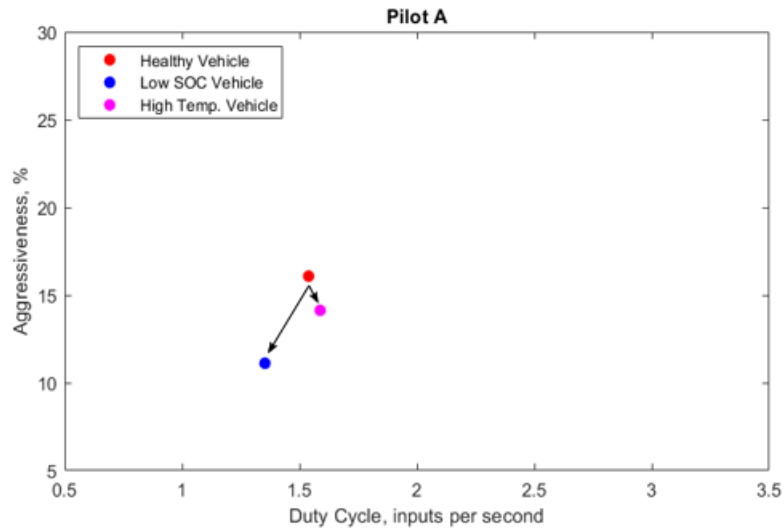
- Complex powertrain degradations introduce insight into flux weakening effects on the vehicle
 - Both low SOC and high temperature engage flux weakening
 - Controller torque command is decreased for both degradations, but for different reasons
 - Motor saturation limits are hit when flux weakening is engaged
 - Saturation can lead to insufficient torque output and off-axis coupling
 - Motor torques don't follow torque commands when saturation limits are hit
 - Vehicle doesn't respond predictably to pilot stick commands
 - Vehicle did not match the preferred aggressiveness of the pilots because of motor saturation
 - Pilot task execution was difficult because desired vehicle response was not obtainable
 - Off-axis coupling introduced unsuspecting workload in the pitch and bank axes

Questions?

Backup Slides



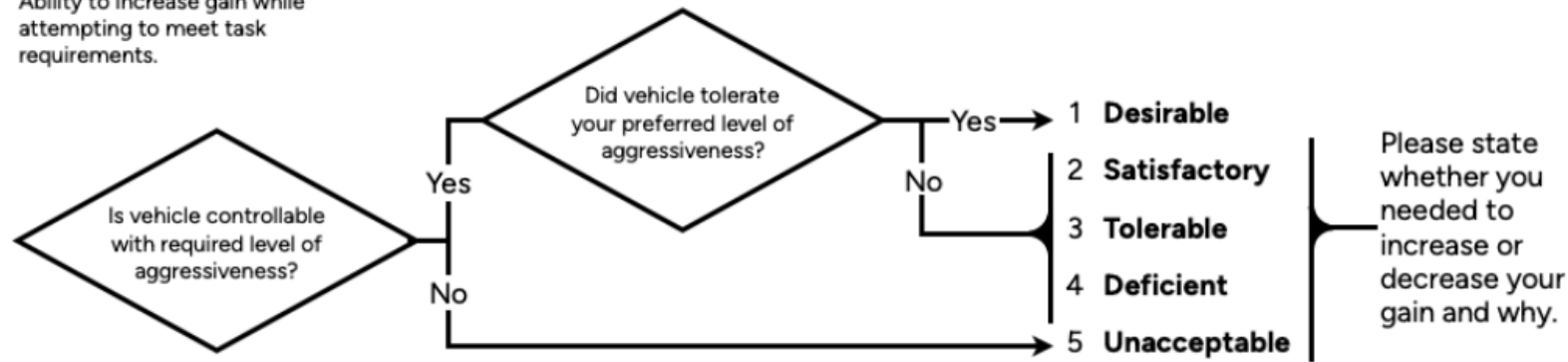
Evaluation Run Average for Each Vehicle Mode



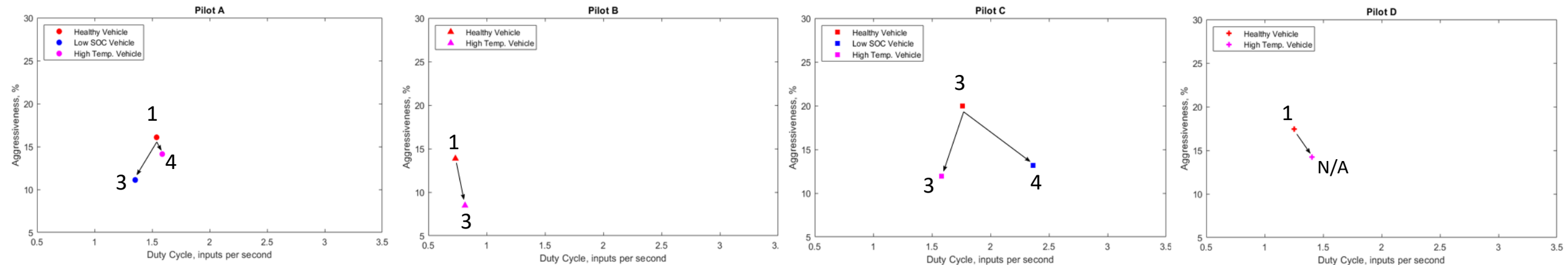
VMS Aggressiveness Scale

Aggressiveness

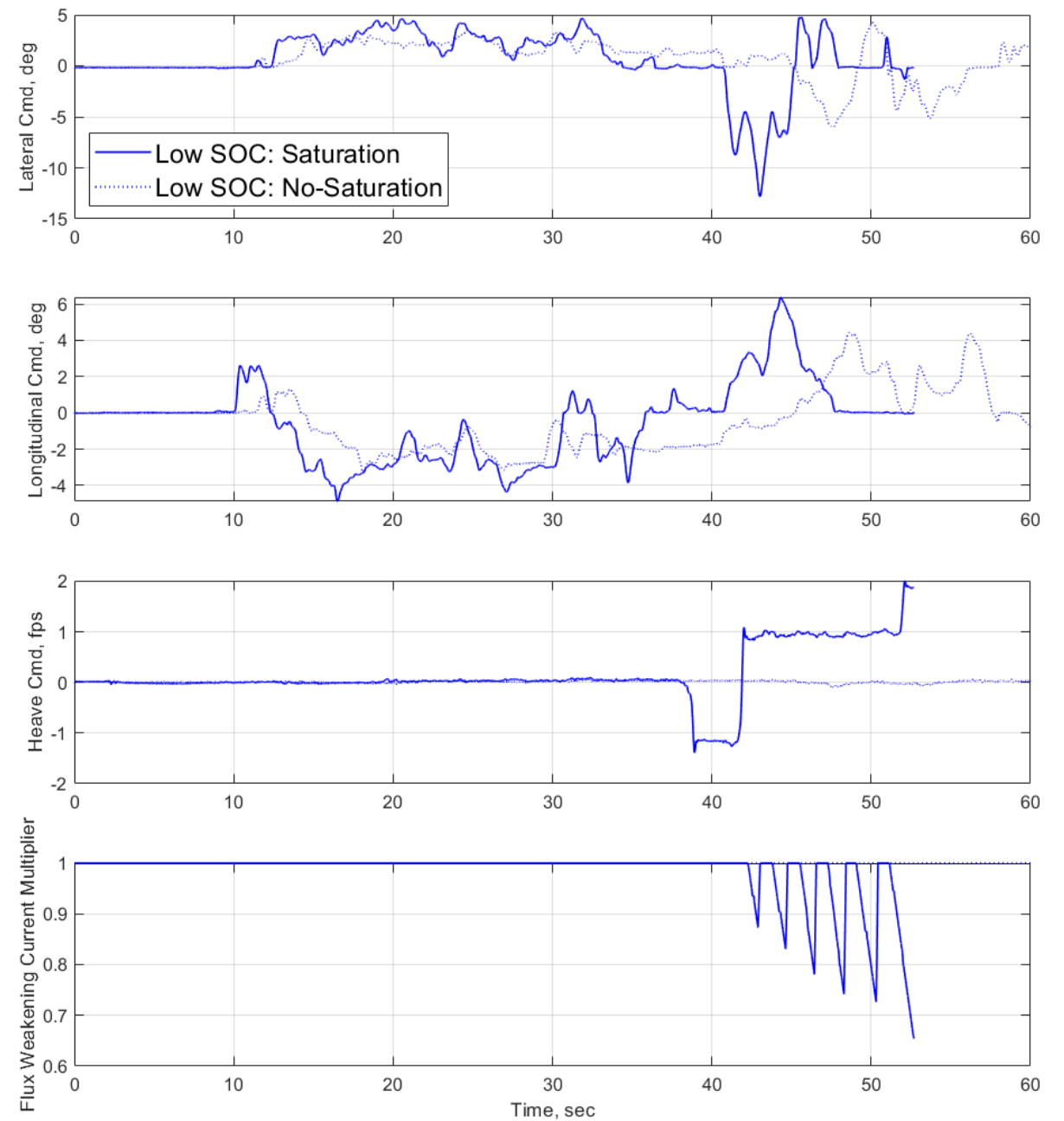
Ability to increase gain while attempting to meet task requirements.



- Desirable Aggressiveness was obtained generally when operating a **Healthy** aircraft
- Higher aggressiveness was generally desired during task execution



Bonus: Hover Task/ Turbulence



Vertical Maneuver Video: High Temp

Pilot C / ADS-33E / **High Temp. Vehicle**

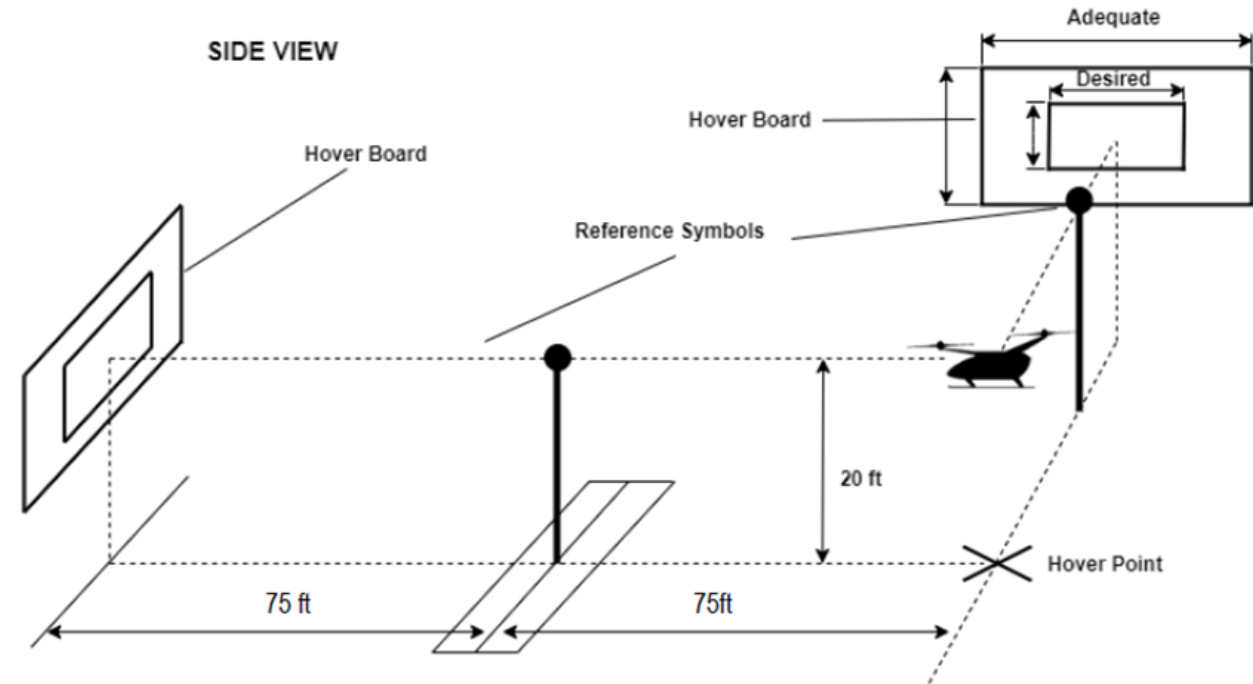
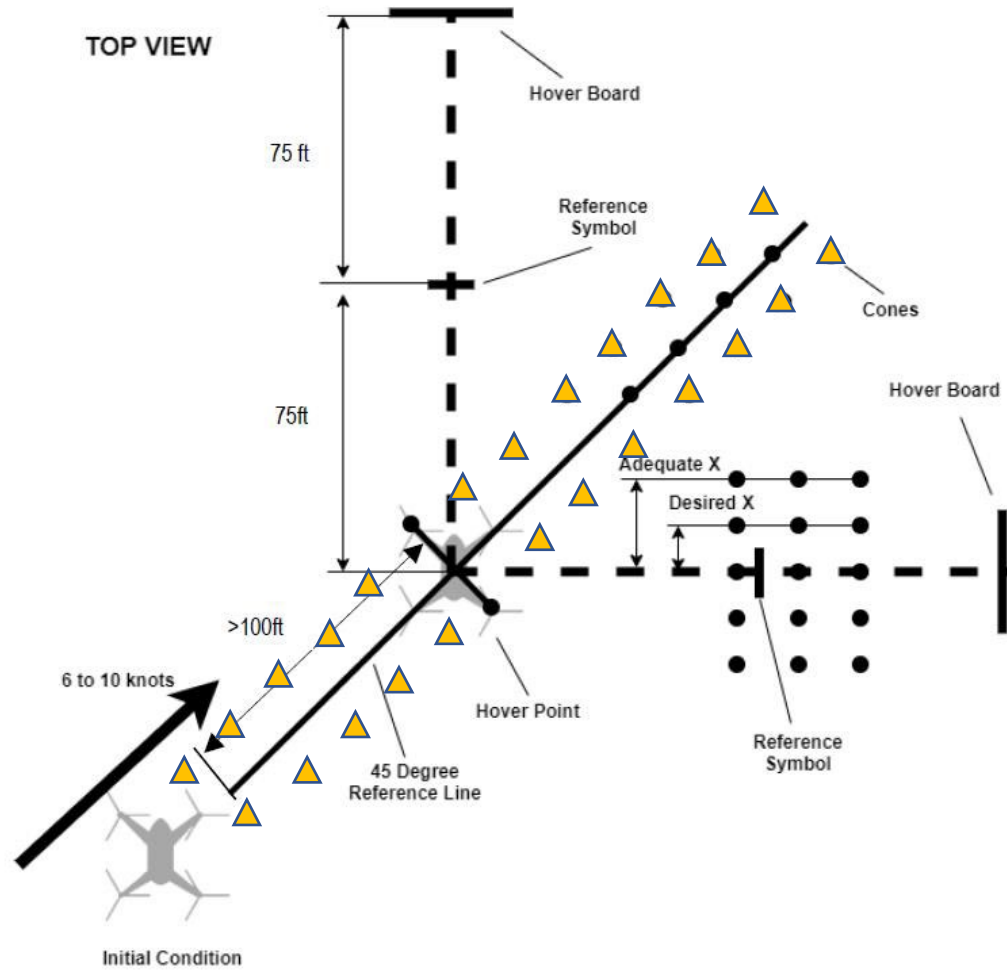
“The more aggressive I got, the more divergent the thrust control went.”

- Pilot C / High Temp.

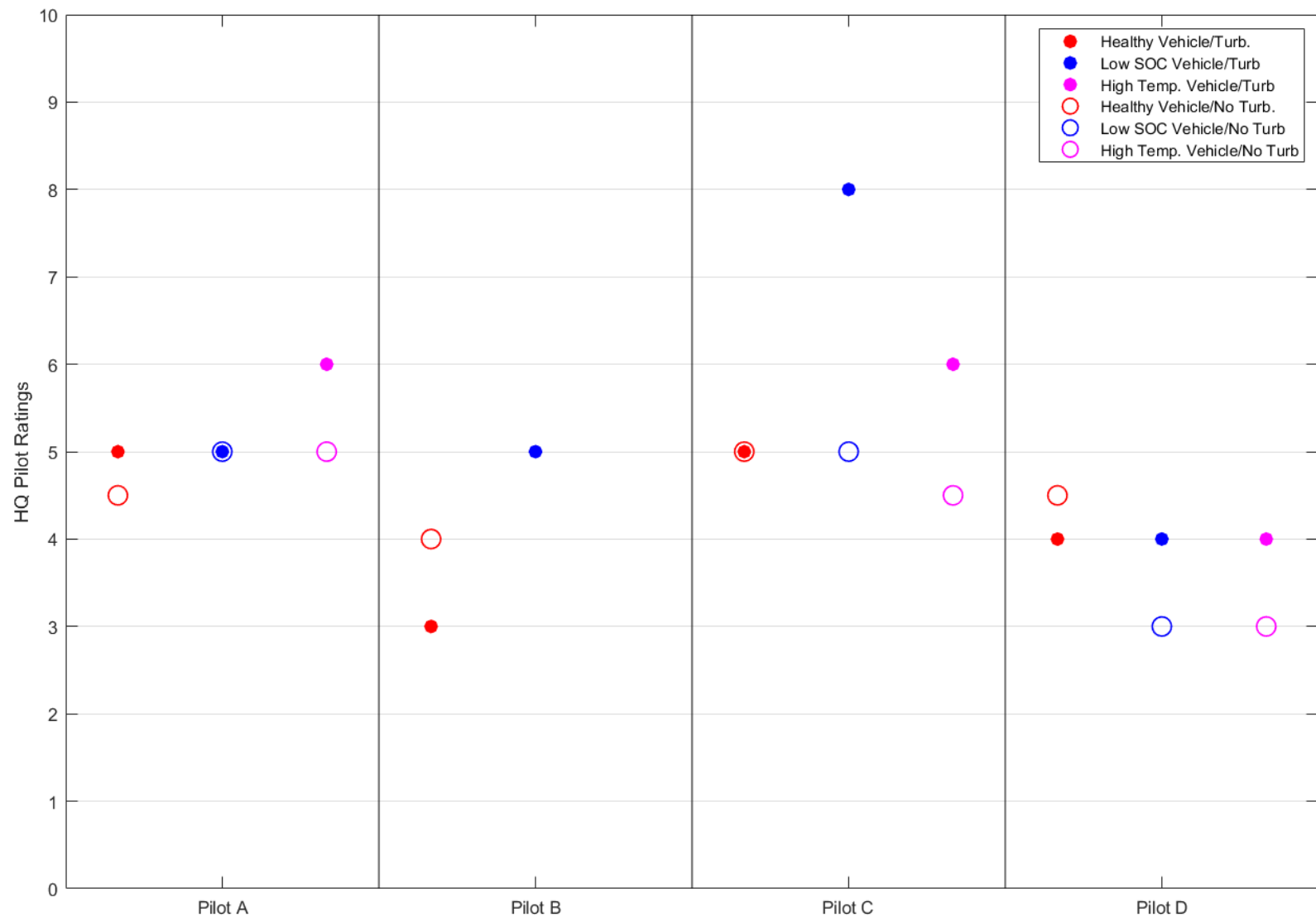
“I could not stay out of the loop, I had to correct perturbations.”

- Pilot C / High Temp.

Hover Maneuver

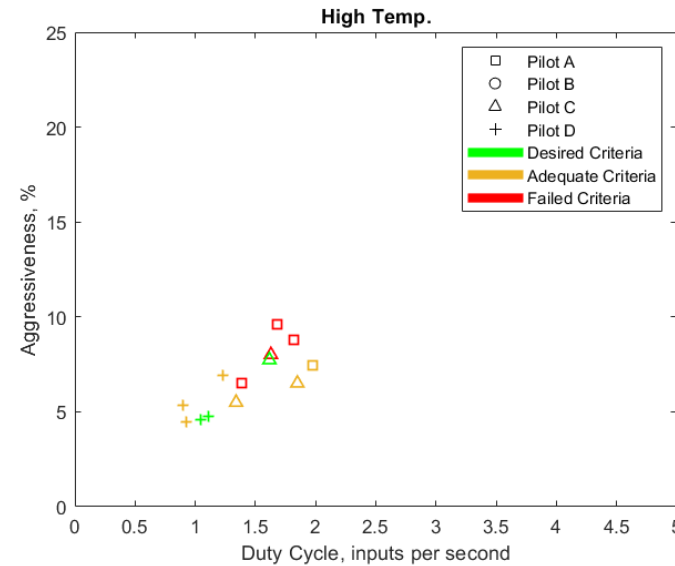
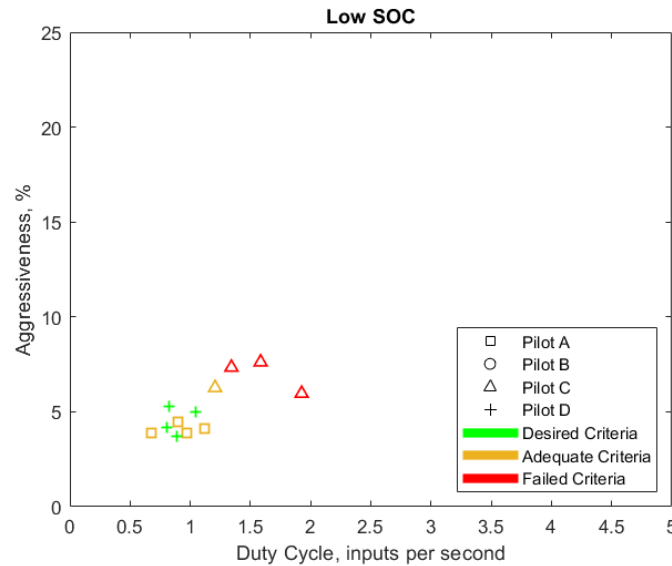


Hover HQ Ratings: Turbulence vs. No Turbulence



Hover: No Turbulence Verses. Turbulence

No Turbulence



Pilot A & Pilot C:

- Attempts to increase duty cycle in response to turbulence. This results in neither desired nor adequate criteria generally.
- Pilot A doesn't like giving up too much control to the controller based on comments.

Pilot D

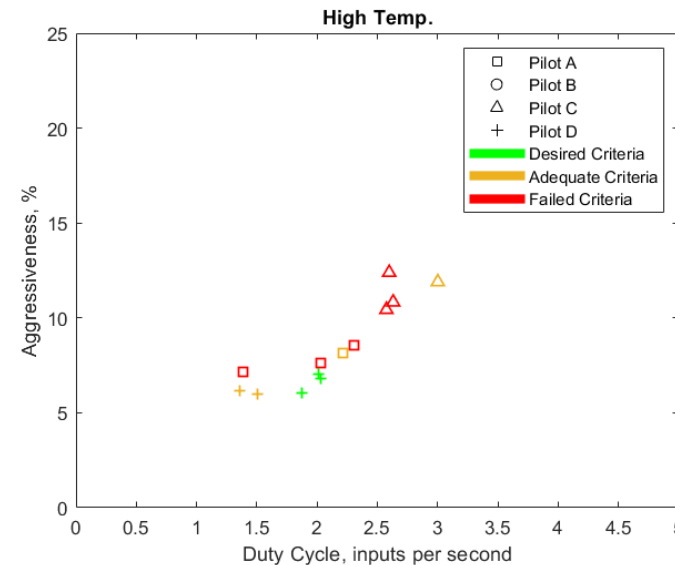
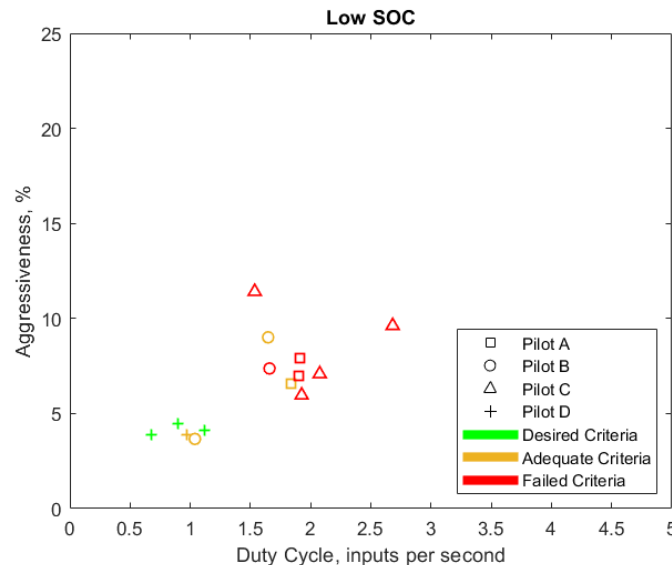
- Kept a similar aggressiveness and duty cycle between turbulence and no turbulence cases, indicating that he/she is **letting the vehicle controller make adjustments to turbulence.**

Conclusions:

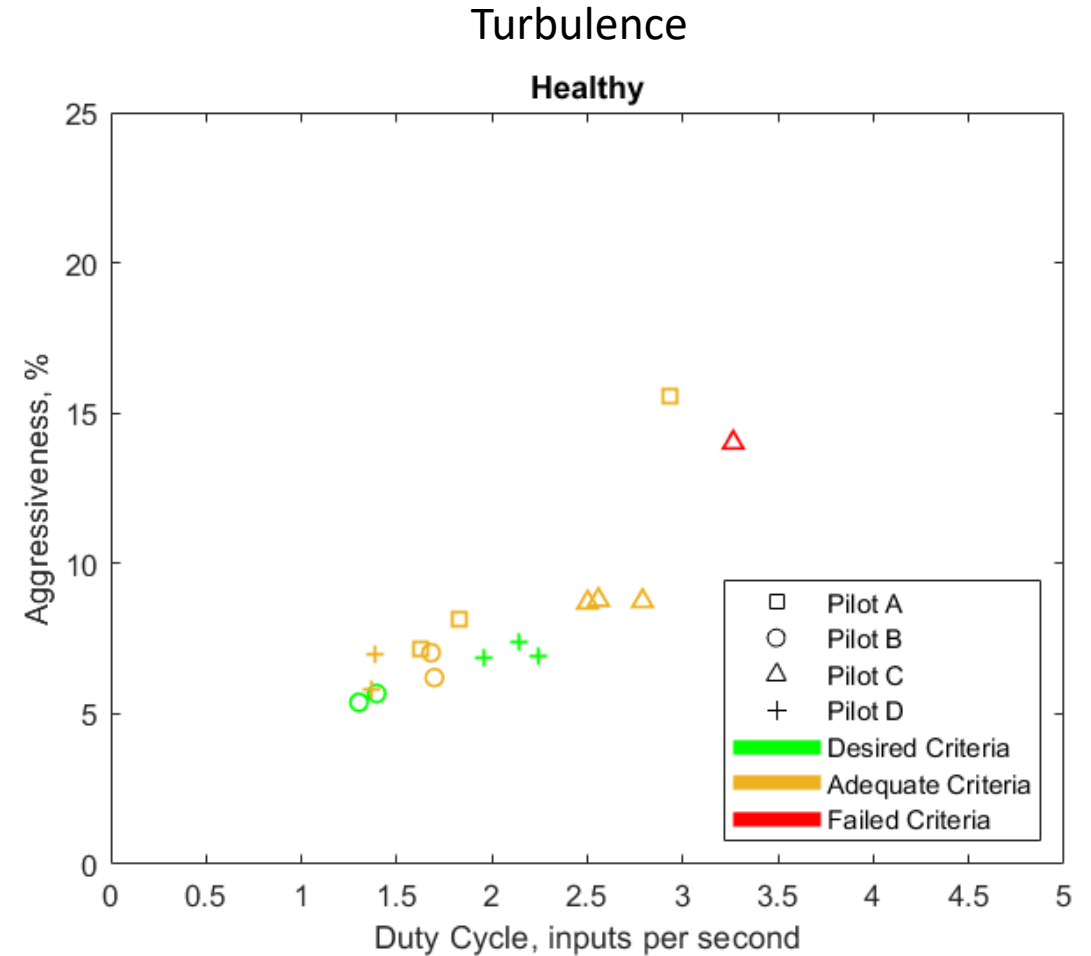
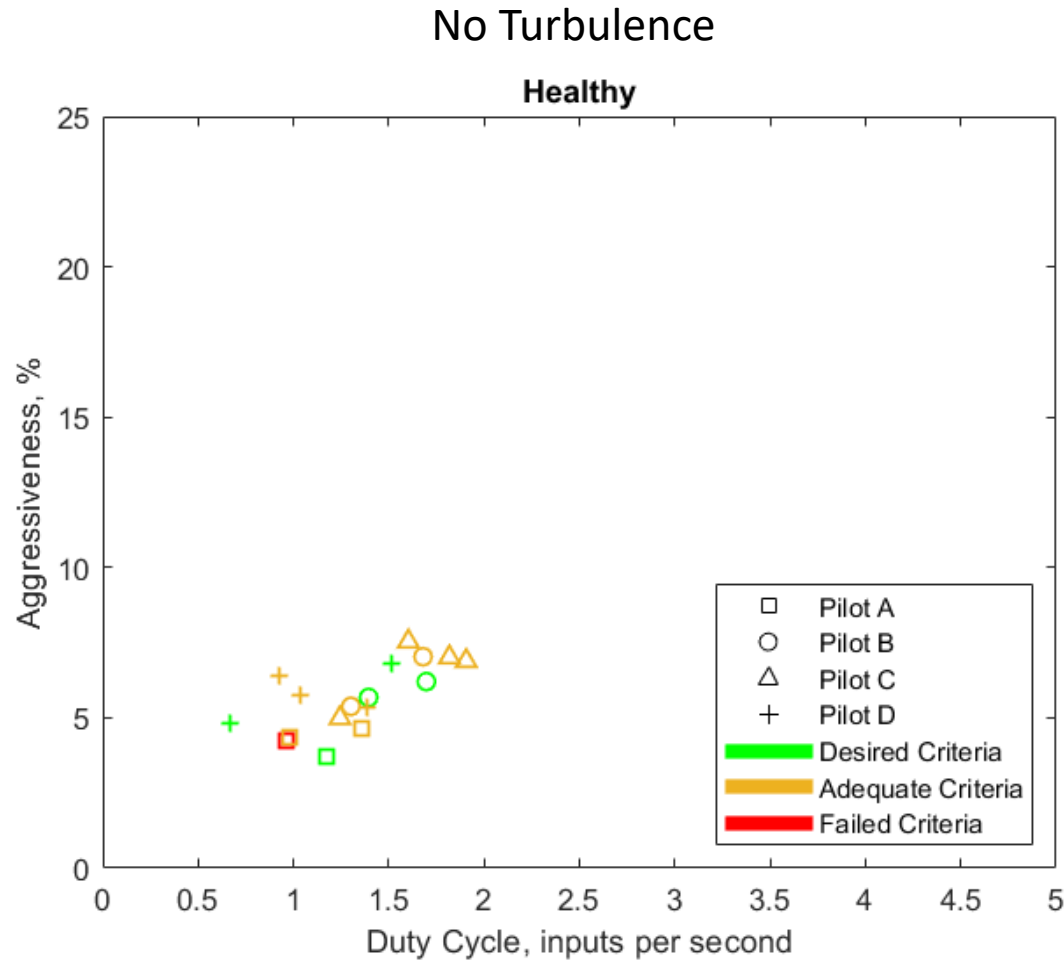
- Generally higher Duty Cycle for High Temp.
- Pilots who did not increase workload to compensate for turbulence achieved better criteria.**

Turbulence

Generally a slightly higher Duty Cycle than the "No turbulence" run (not much though)

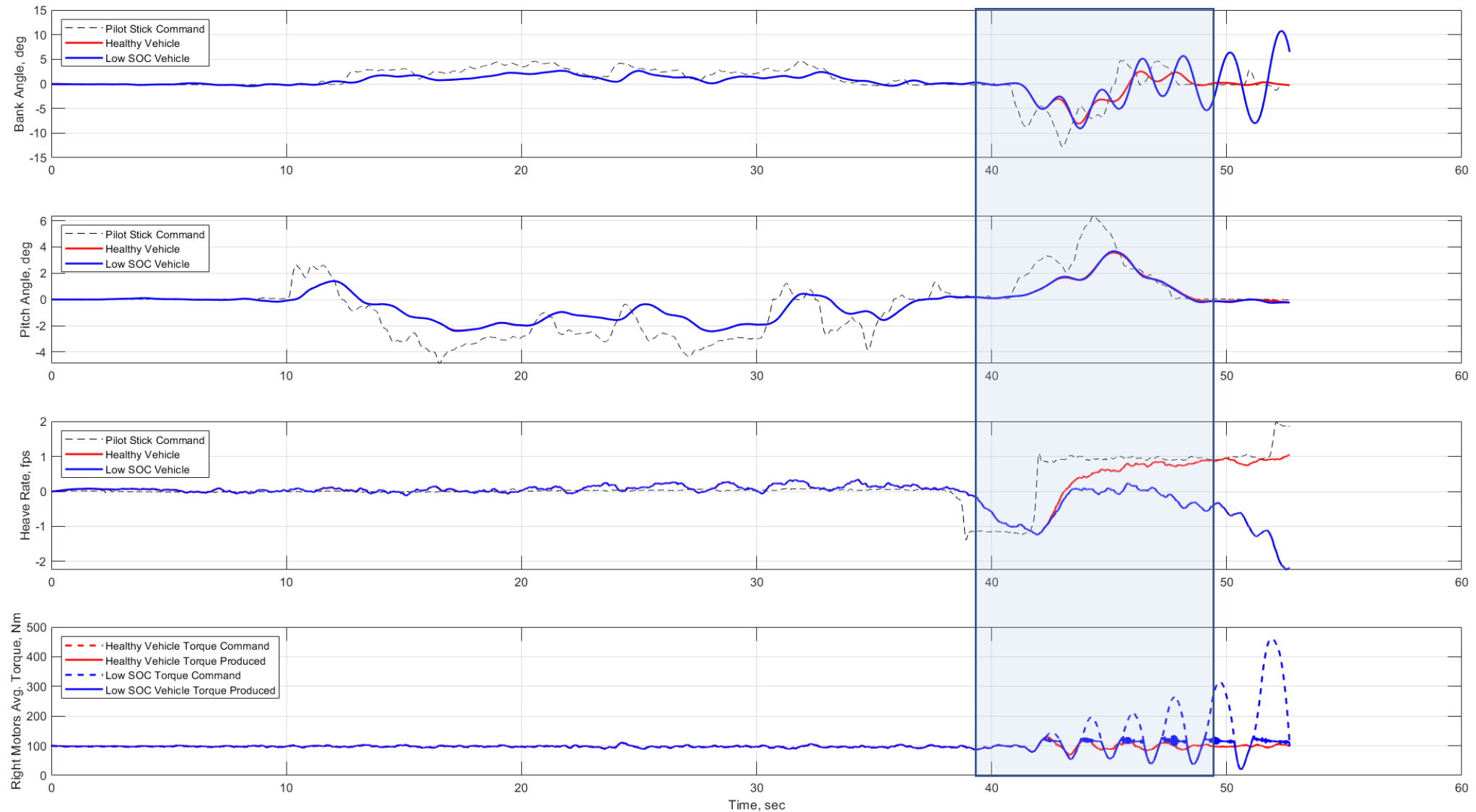


Hover: No Turbulence Verses. Turbulence

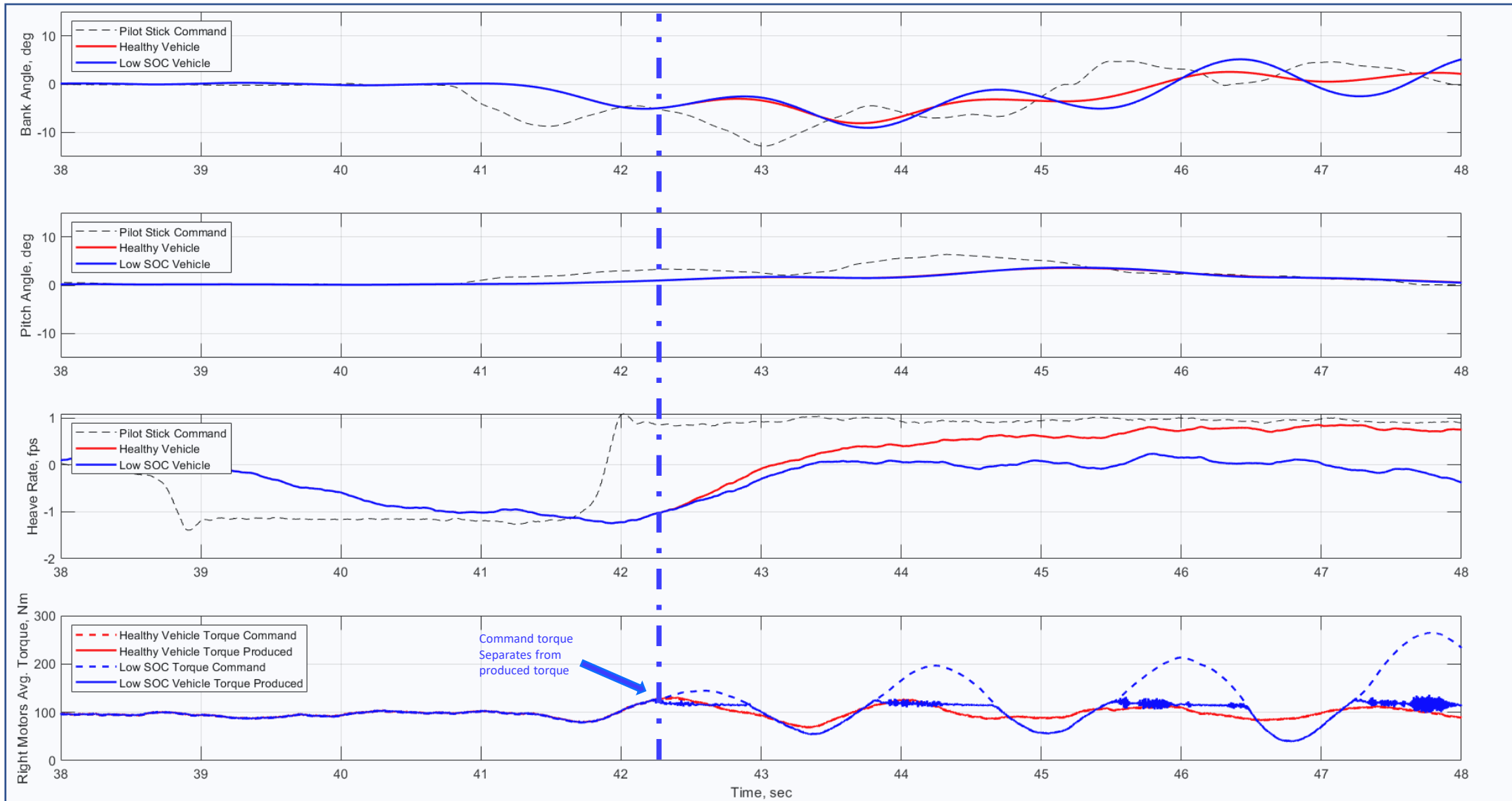


- Generally higher duty cycle for turbulence case. **Didn't have to let controller take over due to healthy configuration having larger margins before hitting limits**

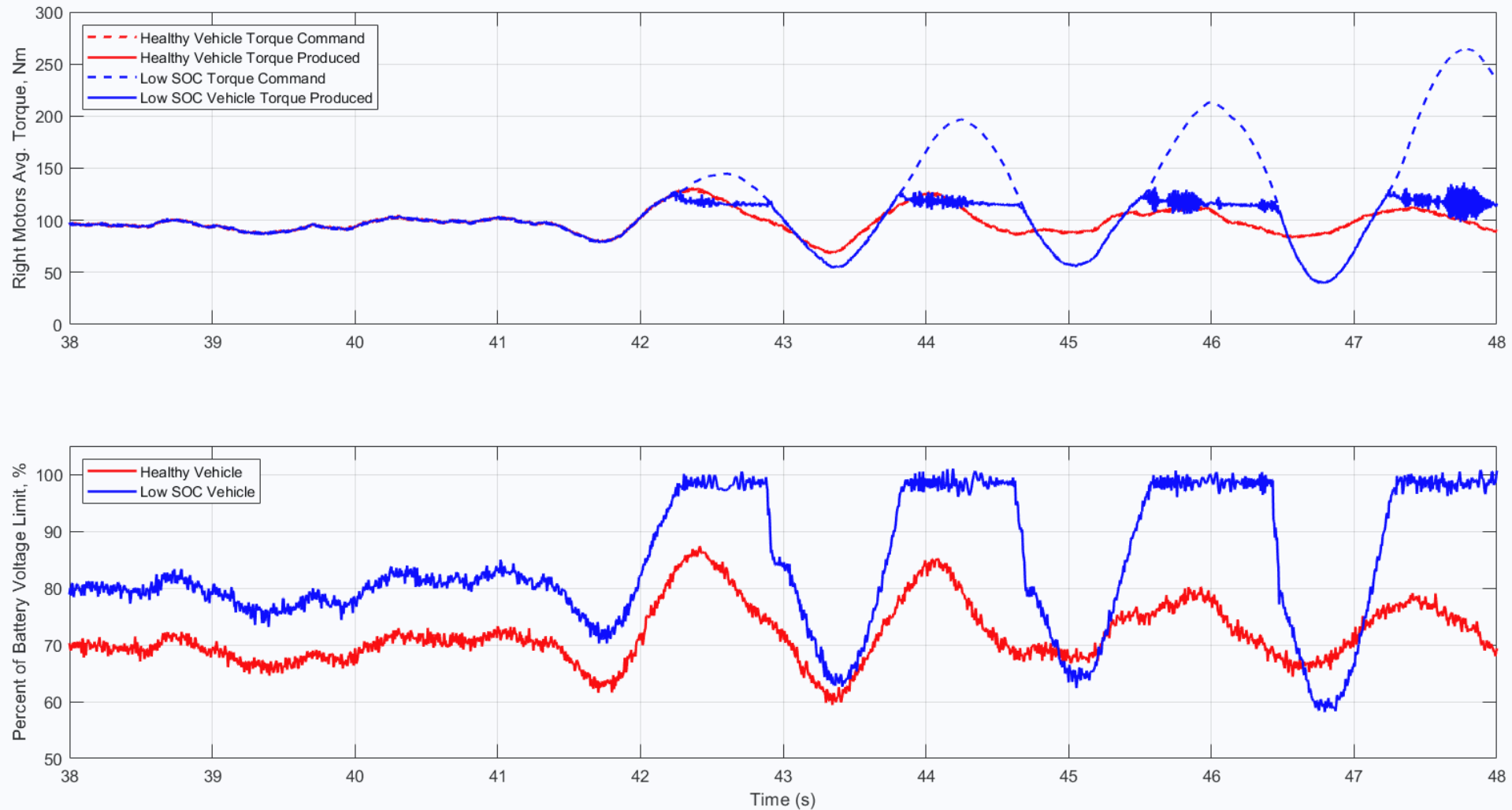
Pilot Inputs and Torque Response



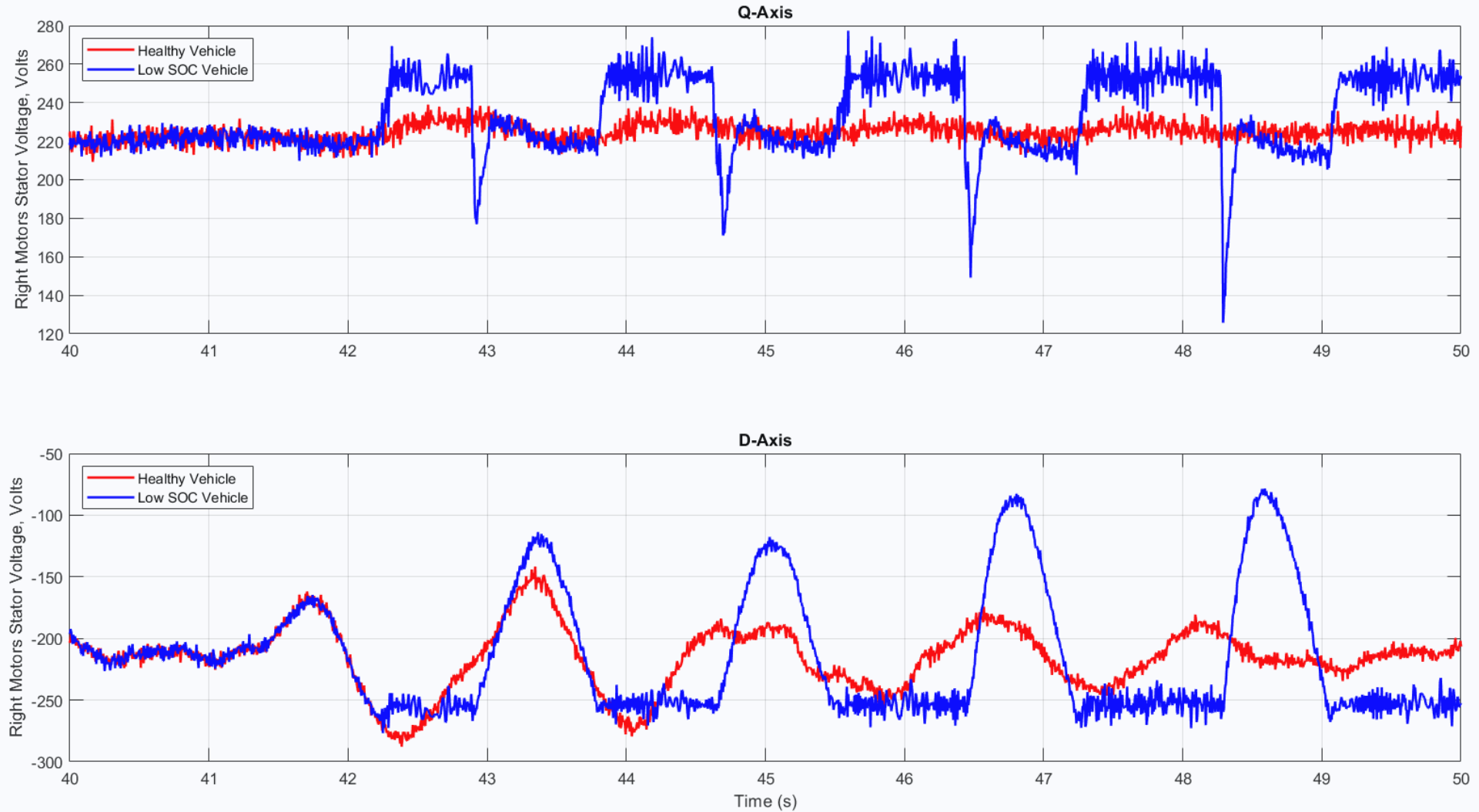
Pilot Inputs and Torque Response: Zoomed In



Torque Response and Voltage Limit

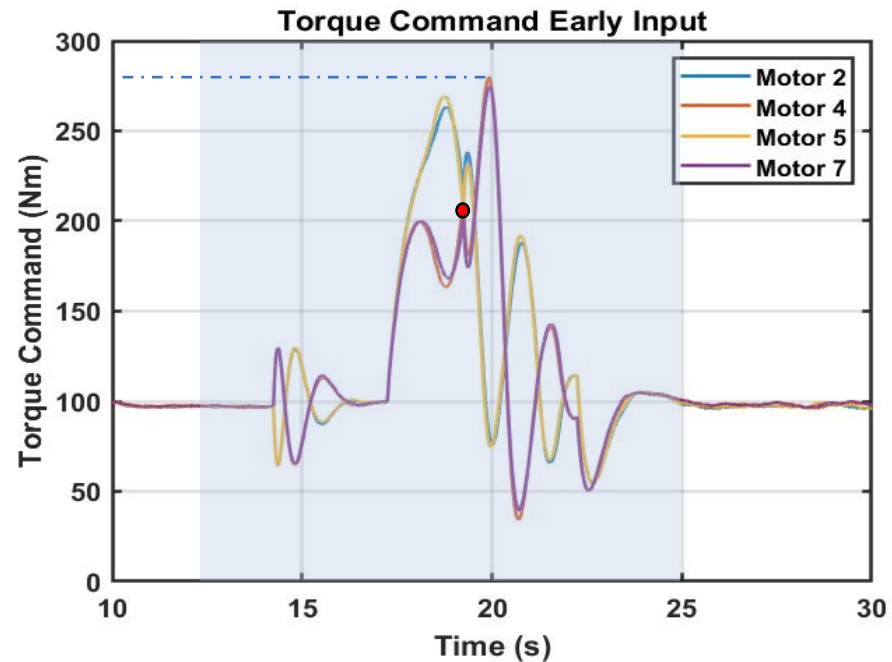
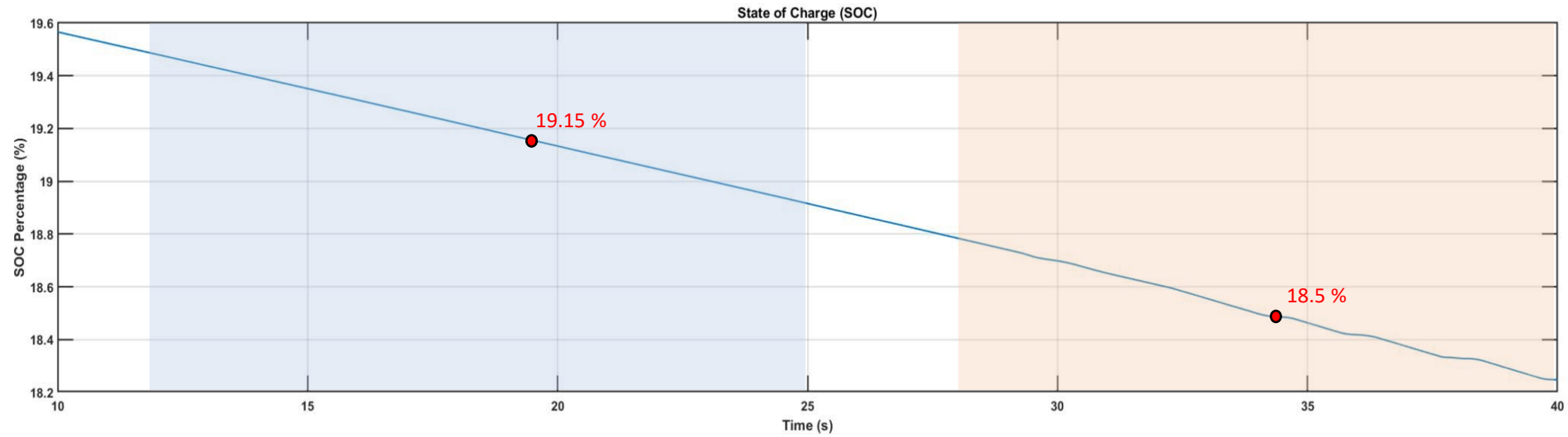


Stator Voltage

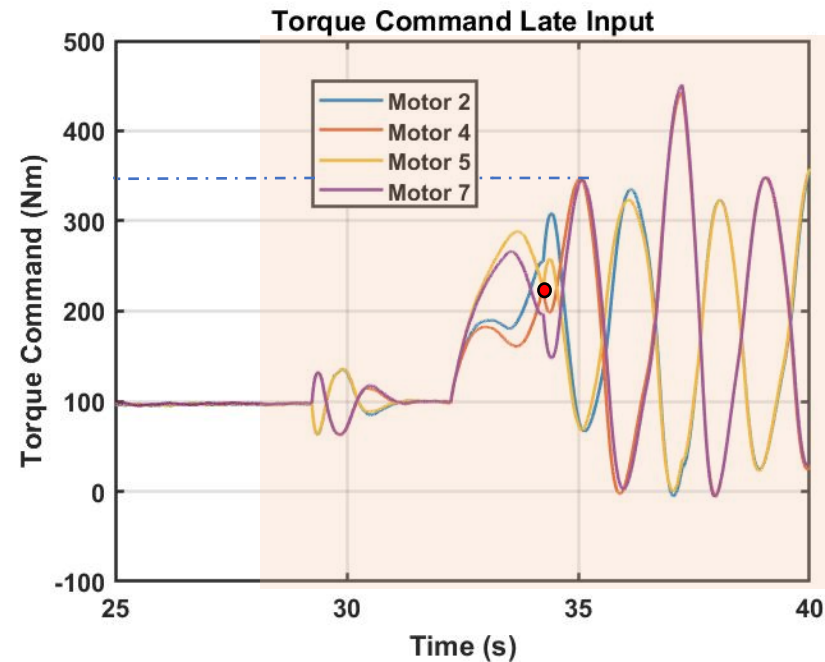




SOC Draining Effect on Stability



- When command is input earlier rather than later, vehicle converges back to hover after command execution



- When command is input later rather than earlier, SOC reduction by $\approx 0.65\%$ causes instability