



Vertical Motion Simulator Handling Qualities Testing of a Piloted eVTOL Vehicle Having a Degraded Powertrain

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Overview

1. Vertical Motion Simulator (VMS) Testing Setup

- a. VMS Test Setup (2022)
- b. Test Objective

2. Vehicle Response to Powertrain Degradation

- a. Low SOC Effect On Vehicle
- b. High Temp. Effect On Vehicle

3. Handling Qualities Ratings and Metrics

- a. Rating Scales
- b. Measurements and Calculations

Vertical Motion Simulator (VMS) Testing Setup

- VMS Test Setup (2022)

- Facility

- 6-degree of freedom motion simulation
 - 60-ft (vertical) by 40-ft (horizontal) actuation system
 - Interchangeable pilot cab

- Test Plan

- Lift-Plus-Cruise (LPC) reference aircraft
 - 4 rotorcraft test pilots
 - Numerous test points:
 - ☐ Mission Task Elements (MTE)
 - ☐ Powertrain health
 - ☐ Disturbances on/off

- Test Objective

- Verify handling quality predictions for RPM-controlled eVTOL aircraft with off-nominal powertrain conditions

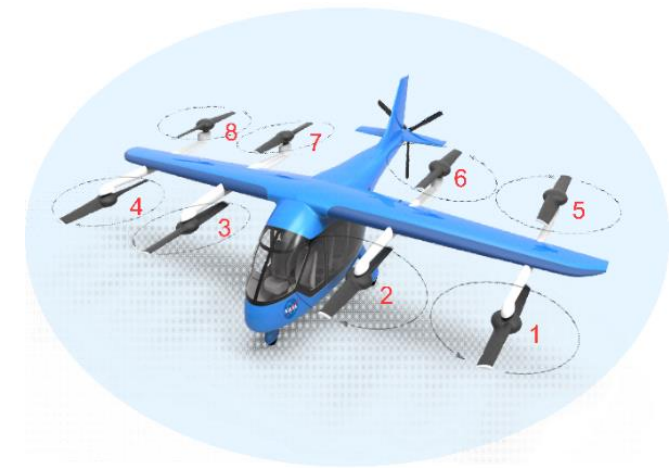


a)



b)

NASA Ames VMS: (a) Cab and Actuation System; and
(b) Internal Cab Configuration

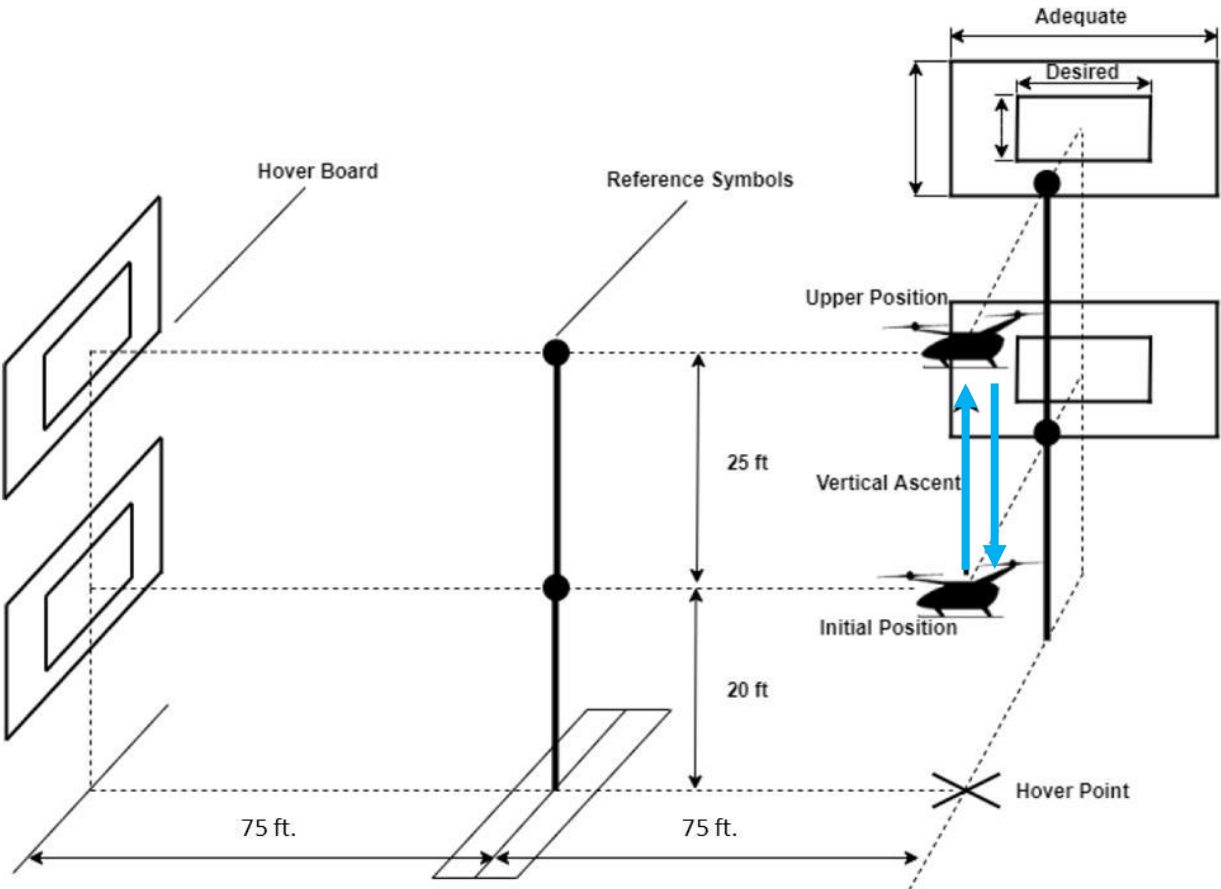


NASA Lift-Plus-Cruise Reference Aircraft

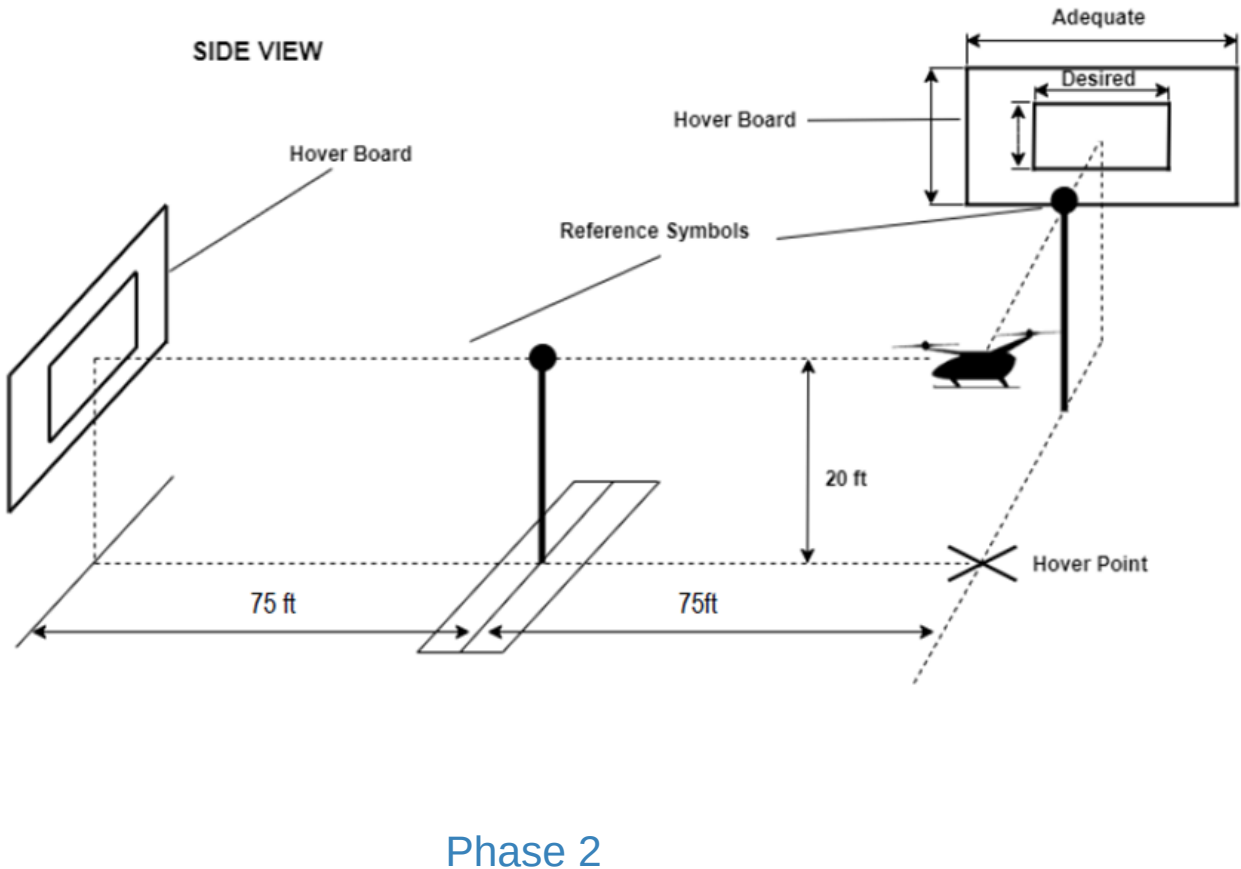
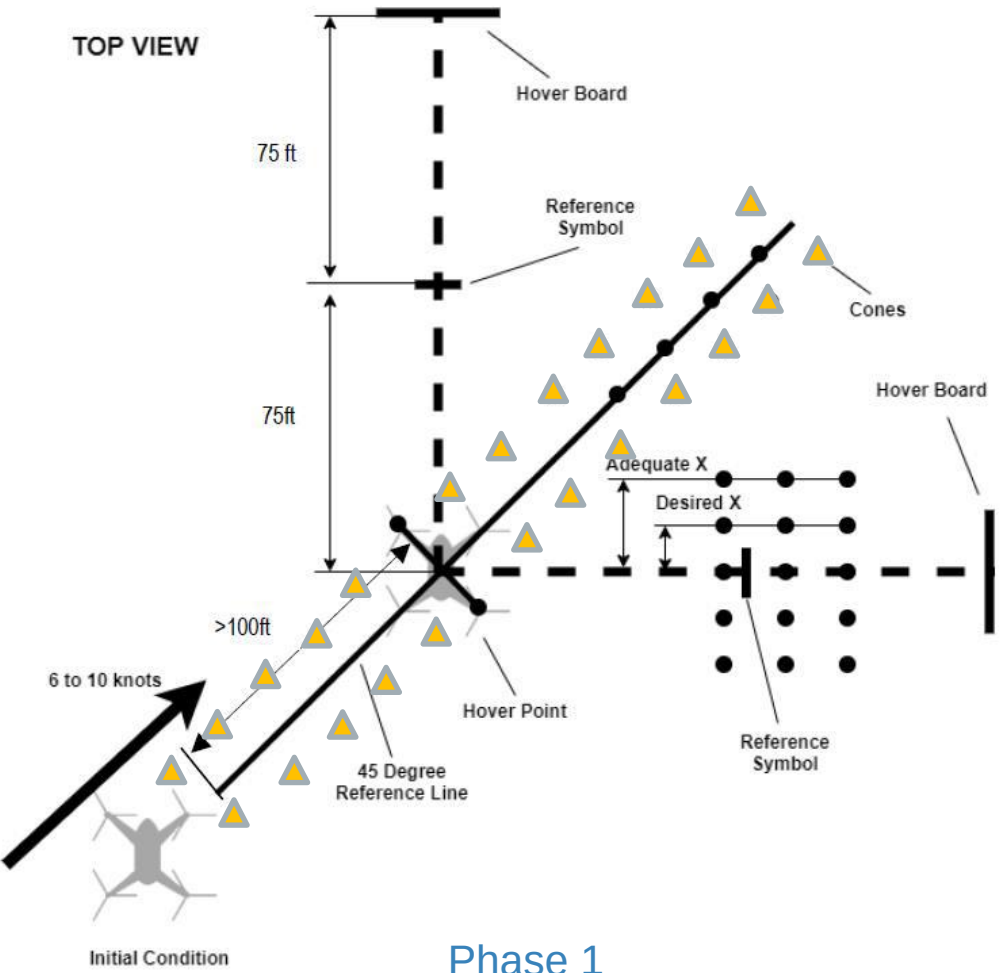


Vertical Maneuver MTE: Task Description

		RVLT-HQ2 ADS-33E MTE	RVLT-HQ2 FAA HQTE	Changes from the published tasks to support RVLT HQ2
Criteria	Horizontal	3 / 6 ft.	3 / 6 ft.	The lower criteria of 20 and 25 sec. were removed from the FAA HQTE definition
	Altitude	3 / 6 ft.	3 / 6 ft.	
	Heading	5 / 10 deg.	5 / 10 deg.	
	Timing	13 / 18 sec.	24 / 29 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	



Hover Maneuver MTE: Task Description

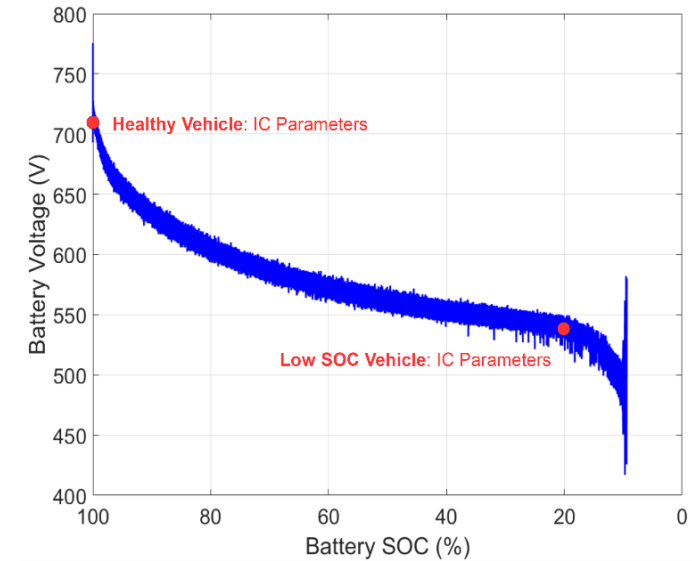


Vehicle Response to Powertrain Degradation: Low Battery State of Charge (SOC)

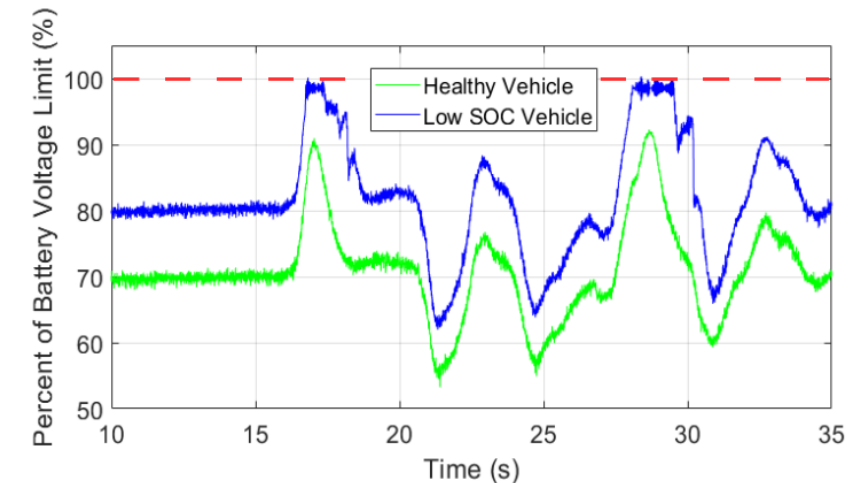
- Initial Condition
 - 20% Battery SOC
 - 150 Volt battery reduction

$$\text{Voltage Constraint [1]} \quad \frac{\sqrt{V_{q_stator}^2 + V_{d_stator}^2}}{\underbrace{V_{Battery}}_{\text{circled}} * \frac{2}{\pi}} < 1$$

- Voltage Saturation
 - Susceptible to depleting 100% available voltage
 - Pushes voltage request up to available voltage limit
 - Results:
 - limited torque during pilot task execution



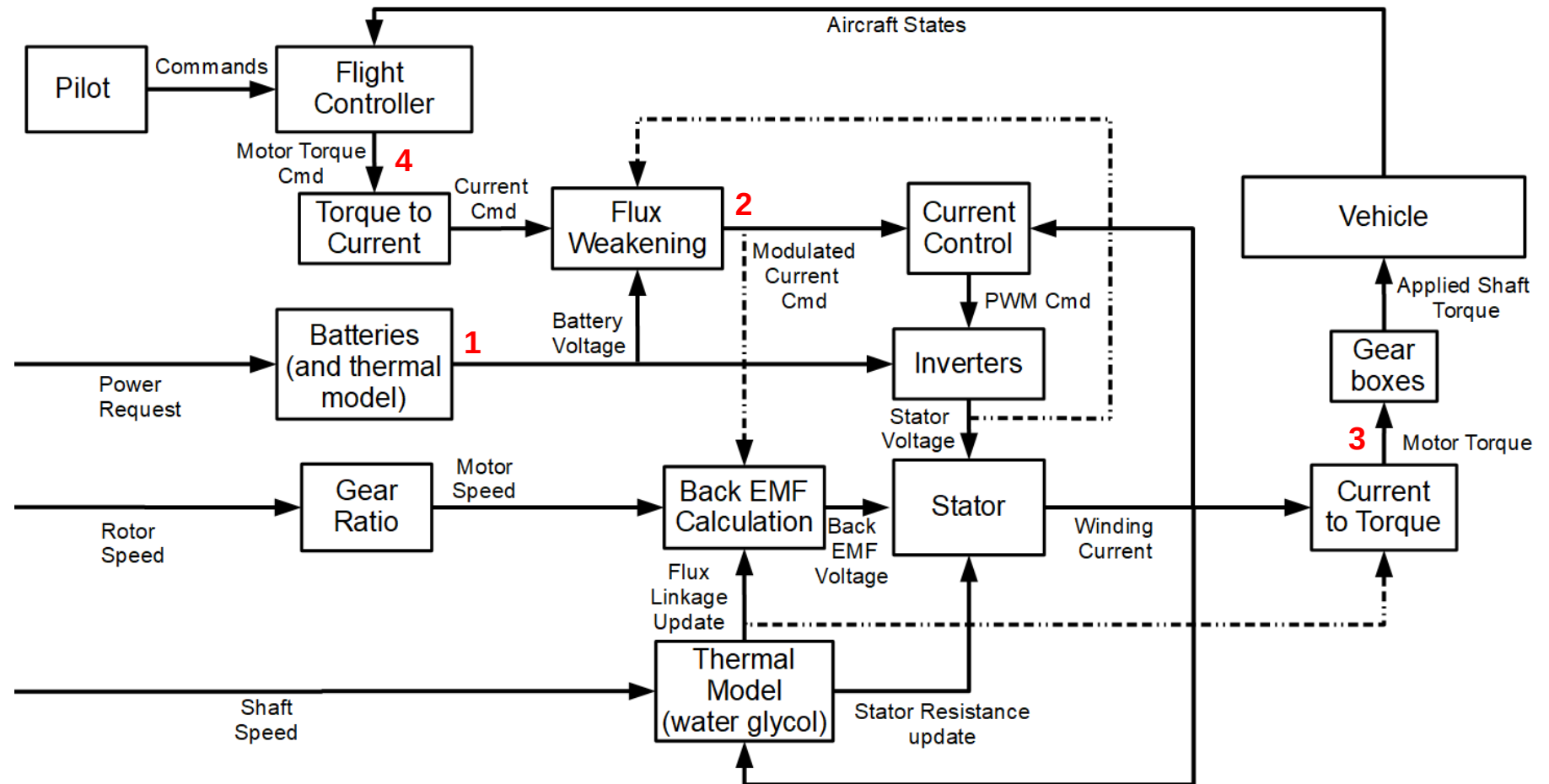
Battery Voltage Curve at Hover Condition



Healthy and Low SOC Vehicle Voltage Limit Comparison

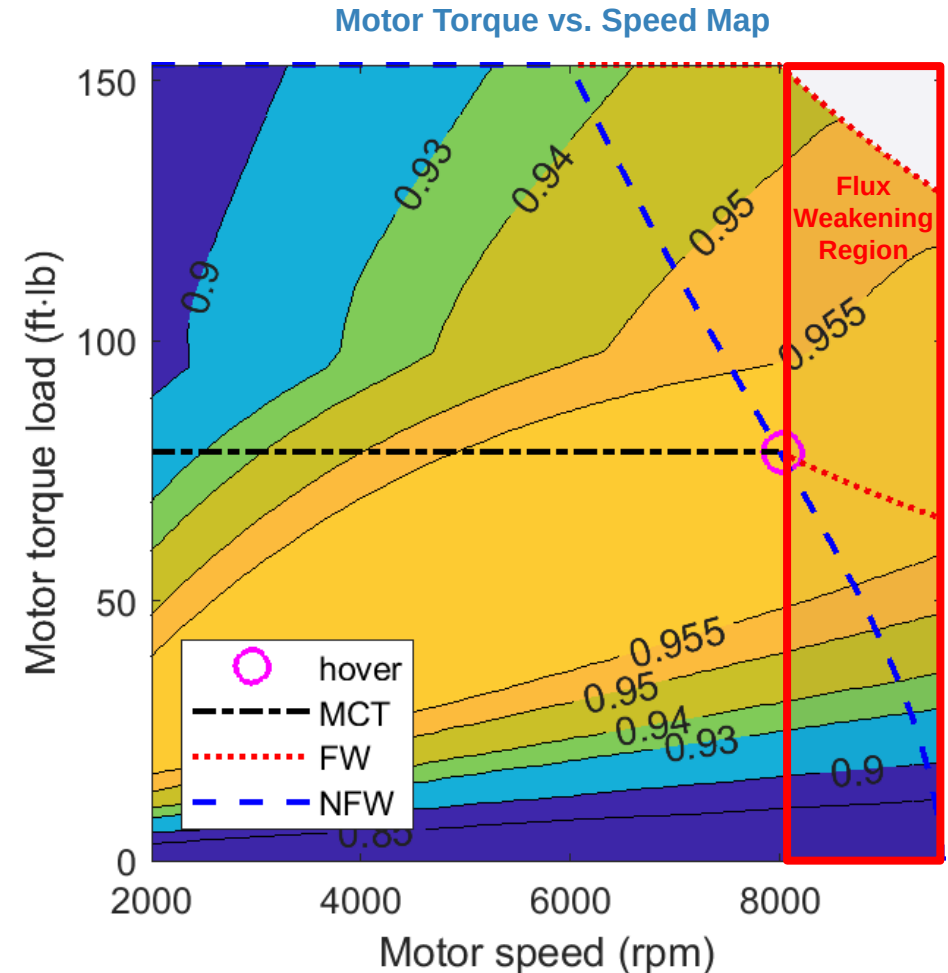
Powertrain Model Structure: Low SOC

1. Available battery voltage is decreased due to low SOC
2. Flux weakening control mitigates voltage saturating by adjusting current
3. Motor torque is decreased
4. Flight controller attempts to compensate for low torque by increasing torque command



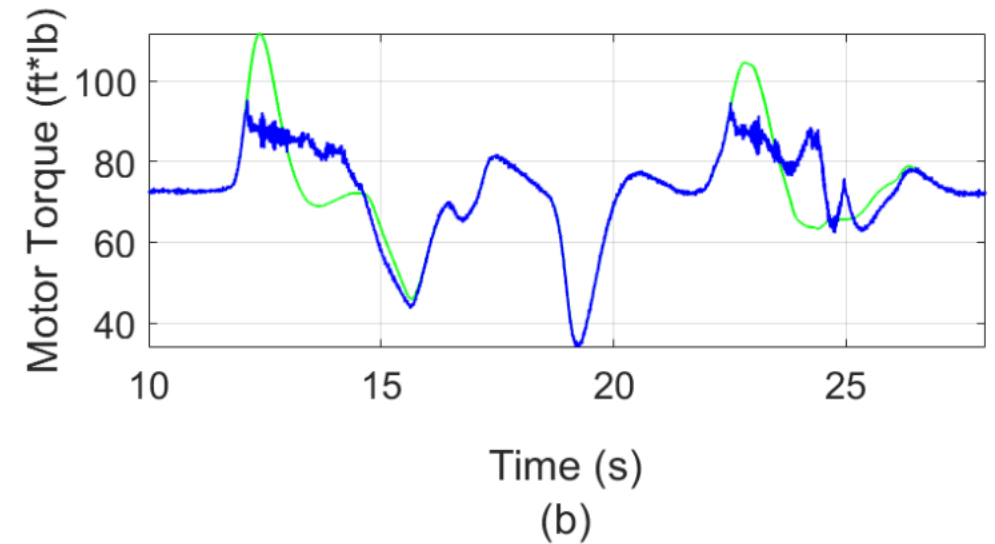
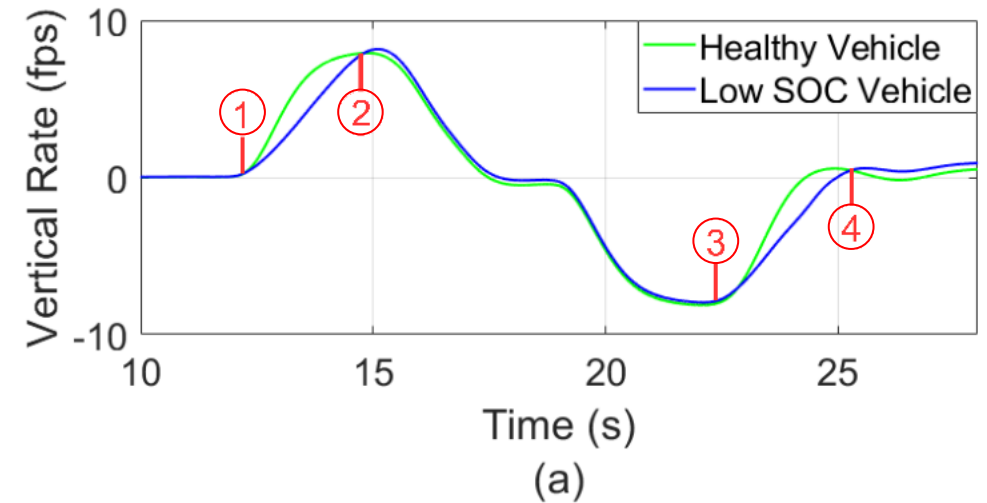
Motor Torque vs. Speed Map

- Back-EMF
 - Increased back-EMF at high motor speeds
 - Torque loss
 - Flux weakening control mitigation
- Flux Weakening (FW) Control
 - VMS test assumed larger battery voltage
 - Reduces effect of back-EMF by reducing magnetic field
 - **Flux weakening region**: Gradual torque reduction
- No Flux Weakening (NFW) Control
 - Baseline motors at rated voltage
 - Increased back-EMF prevents current flow
 - Sudden loss in motor torque



Offline Simulation Data: Low SOC

- Vertical Rate Response
 - Single injected Pilot Command
 - Sluggish Low SOC Vehicle Rate of Response
 - 2-3 sec delay from healthy profile
 - Diverges during motor torque loss
- Motor Torque Saturation
 - Torque saturation for low SOC vehicle
 - Due to motor voltage saturation
 - No longer increases with healthy profile
 - Torque gradually decreases until no longer voltage limited



Healthy and Low SOC Vehicle Response (Single Vertical Rate Command): (a) Vertical Rate Response; and (b) Motor Torque

VMS Vertical Maneuver MTE: Low SOC

- Cross-Axis Coupling
 - Corresponds to voltage saturation
 - High magnitude/rate of vertical commands taxing the motors

1. Uncommanded Roll Angle

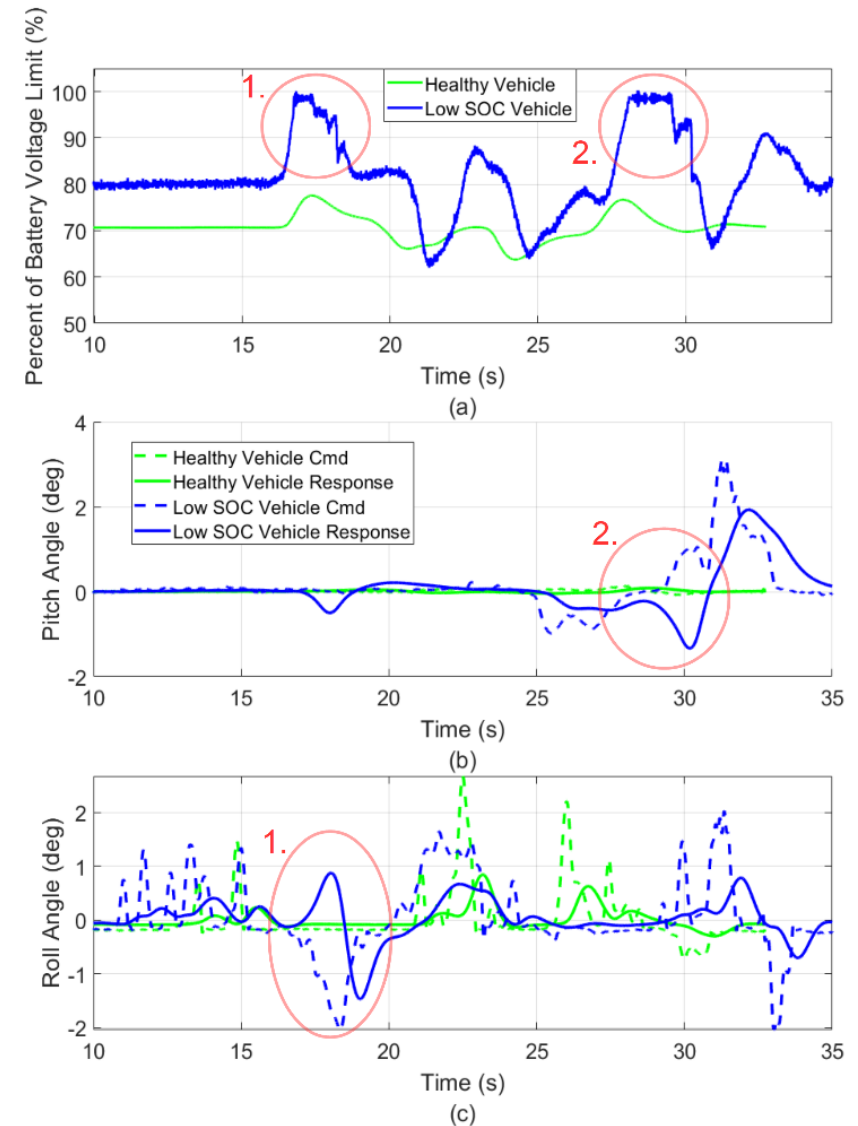
- Saturating right motors
- Roll “right” when commanding “left”

2. Uncommanded Pitch Angle

- Saturating front motors
- Pitch “down” when commanding “up”

- “It was almost like I was getting a low predictability response.”

Pilot A / Vertical MTE / Low SOC

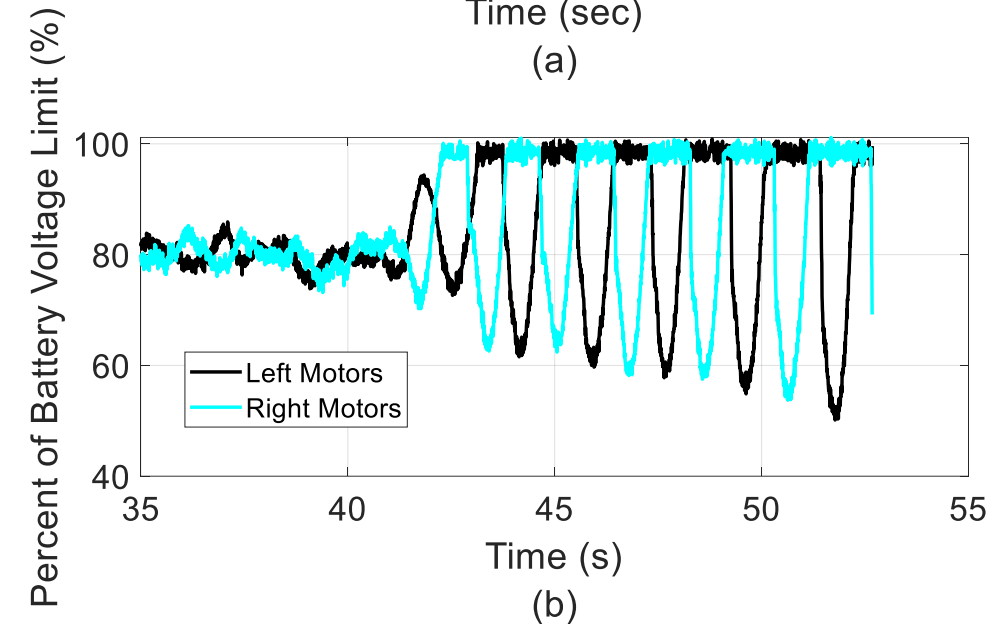
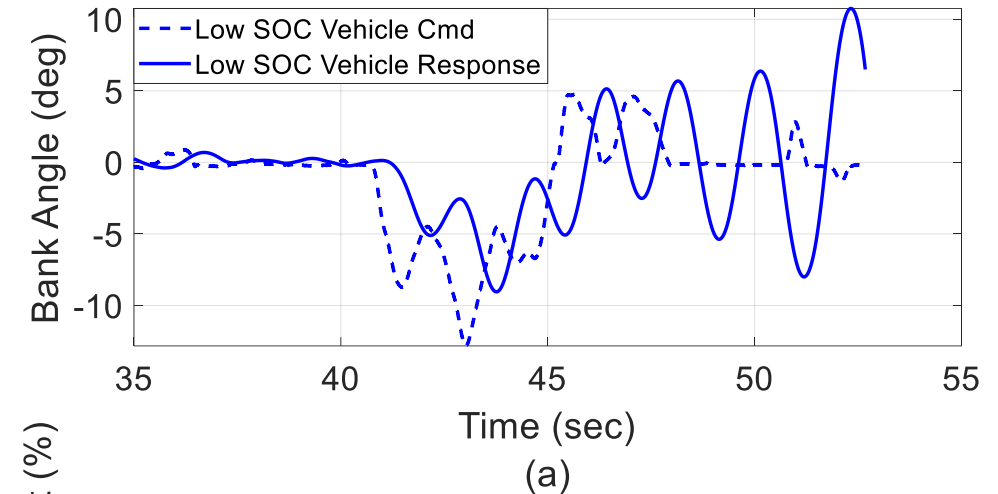


Cross-Axis Coupling Indicated by Red Circles : (a) Battery Voltage Limit Percentage; (b) Pitch Angle; and (c) Roll Angle.

VMS Hover Maneuver w/ Turb. MTE: Low SOC

- Bank Angle Oscillations
 - Pilot Induced Oscillations (PIO)
 - Vehicle response out of phase with command
 - Pilot eventually out of loop
 - Too late, Loss of Control (LOC)
 - Alternating Motor Voltage Saturation
 - Pilot inputs dictate sequence of saturation
 - Alternating between right and left motors
 - Required high inceptor workload
- *“You snuck in a battery charge on me, nicely done.”*
- *“Fairly frequent inputs longitudinally and laterally.”*

Pilot B / Hover MTE with Turb. / Low SOC



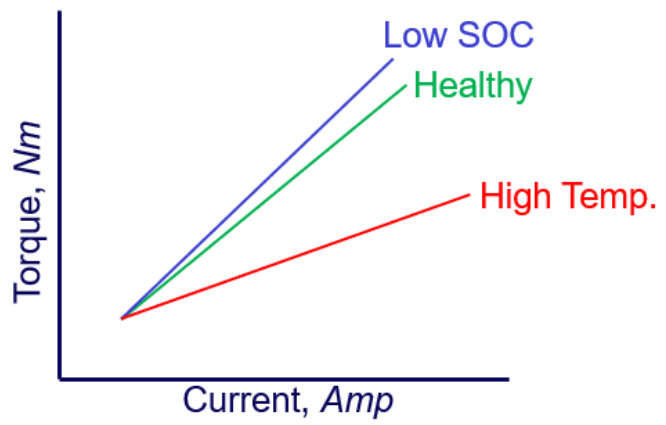
Roll Angle PIO / Pilot B: (a) Roll Angle; and
(b) Battery Voltage Limit Percentage.



Vehicle Response to Powertrain Degradation: **High Motor Temp.**

- Initial Conditions:

- From 60°C (140°F) to **130°C (266°C)**
 - Coolant Temperature
- Elevated motor component temps:
 - Winding Temp.
 - Rotor Temp.
 - Case Temp.



Notional Torque Constant Difference

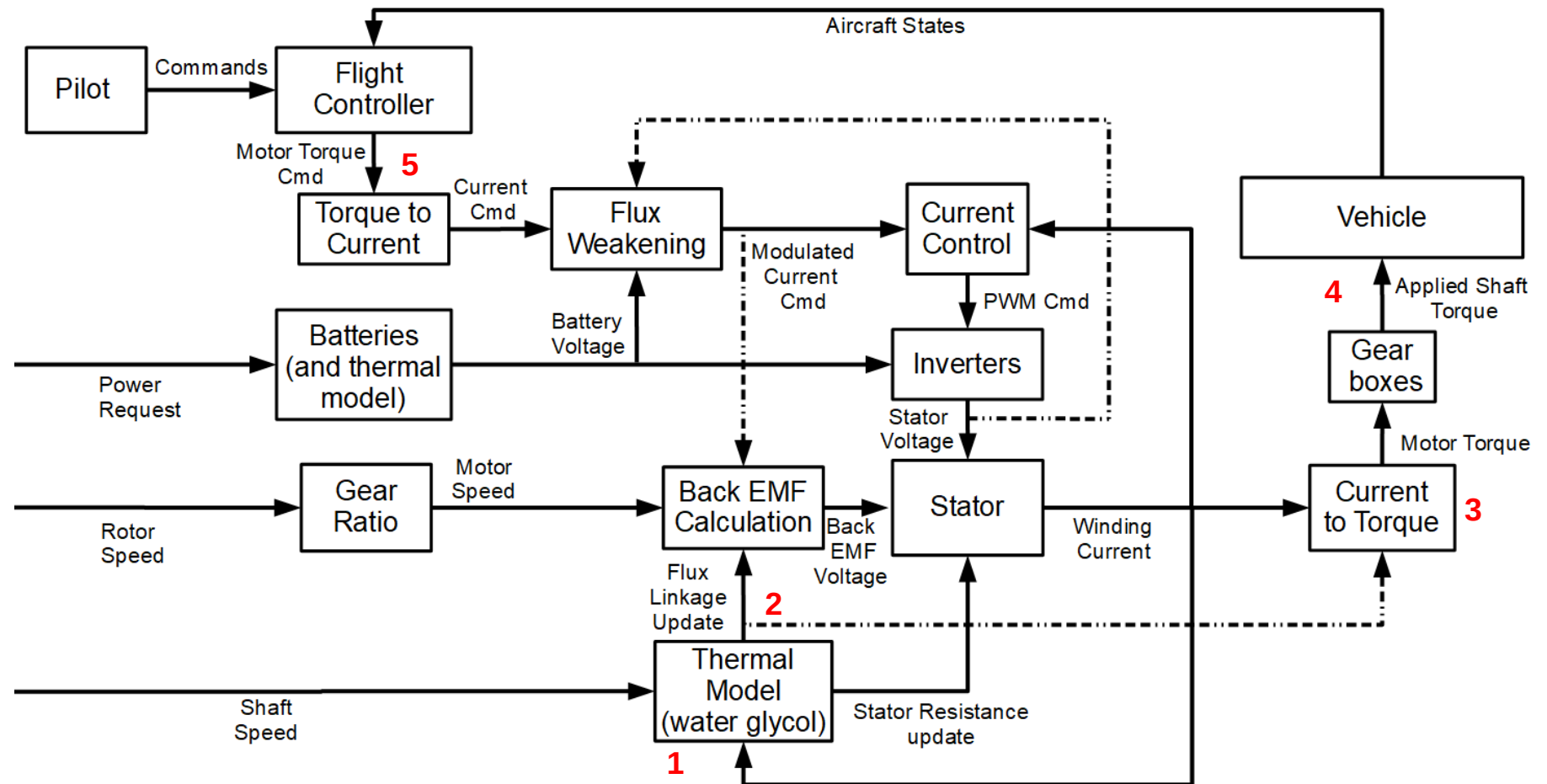
- Temp. Model Constants:

- **12%** Flux linkage decrease
- **12%** Torque constant decrease
- **Results:**
 - limited torque during pilot task execution

Temperature Model Constants and Values.			
Vehicle Condition	Torque Constant $\frac{Nm}{Amp}$	Stator Resistance <i>ohms</i>	Flux Linkage $\frac{V}{rad/s}$
Healthy/Nominal	0.445	0.0196	0.0495
Low SOC	0.456	0.0182	0.0507
High Temp.	0.402	0.0243	0.0447

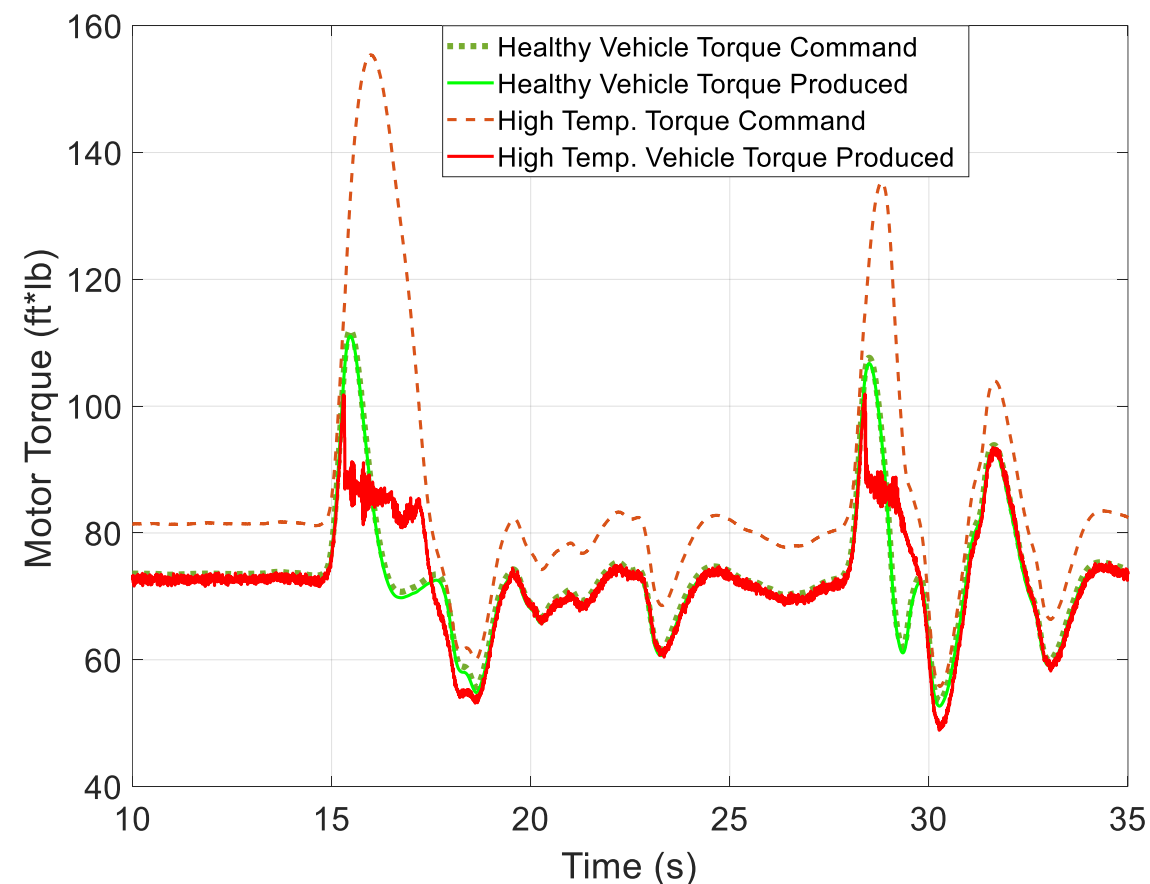
Powertrain Model Structure: High Temp.

1. Increase initial temperature
2. Flux linkage decreases
3. Torque constant decreases
4. Motor torque decreases
5. Motor torque command is increased to compensate for loss in torque



Offline Simulation Data: High Temp

- Motor Torque
 - Single injected Pilot Command
 - High temp. torque command
 - Controller compensation
 - ❑ Low torque constant
 - ❑ Increase regardless of limited torque
 - ❑ Increase regardless of pilot command
 - High temp. torque response
 - Diverges from pilot anticipated torques (healthy configuration)
 - ❑ Pilot commands out of the loop
 - ❑ Sudden recapture of torque command



Healthy and High Temp. Motor Torque (Single Vertical Rate Command)

VMS Vertical Maneuver MTE: High Temp.

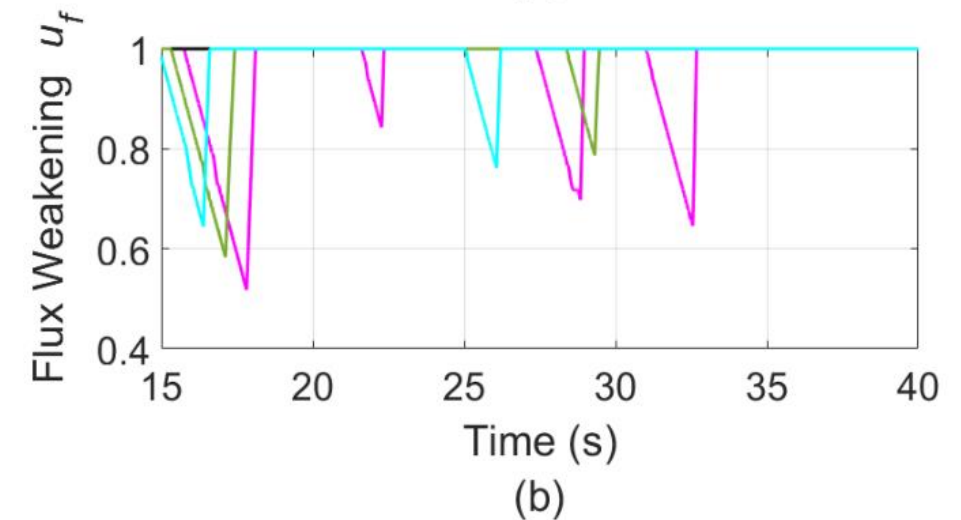
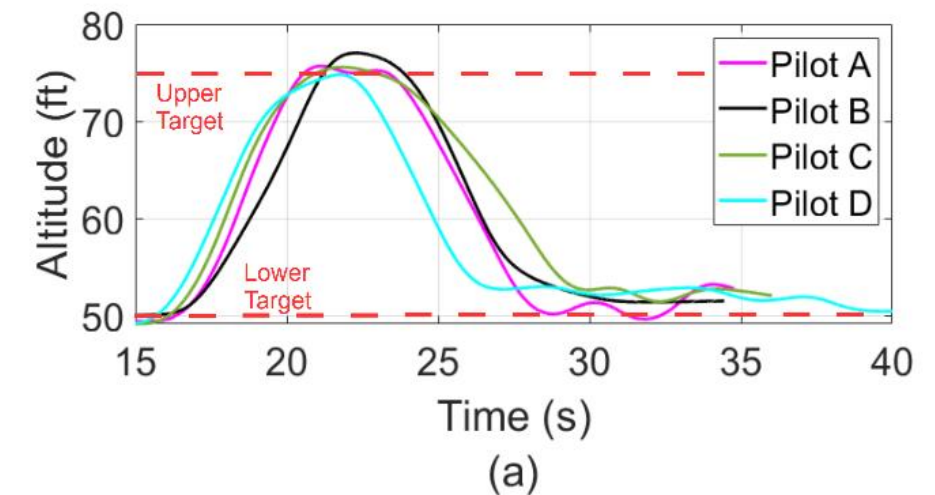
- Flux Weakening Control Mitigation

- Primarily at lower target
 - Critical Subphase: Deceleration at end of task
 - More precision required for end of task (ADS-33-PRF)
 - Lat/Lon excursions

- “Definite heave to pitch coupling... so had to compensate for that. On the recovery (it) was definitely prone to PIO. It was a function of TCL input and rate of decent.”

Pilot D / Vertical MTE / High Temp.

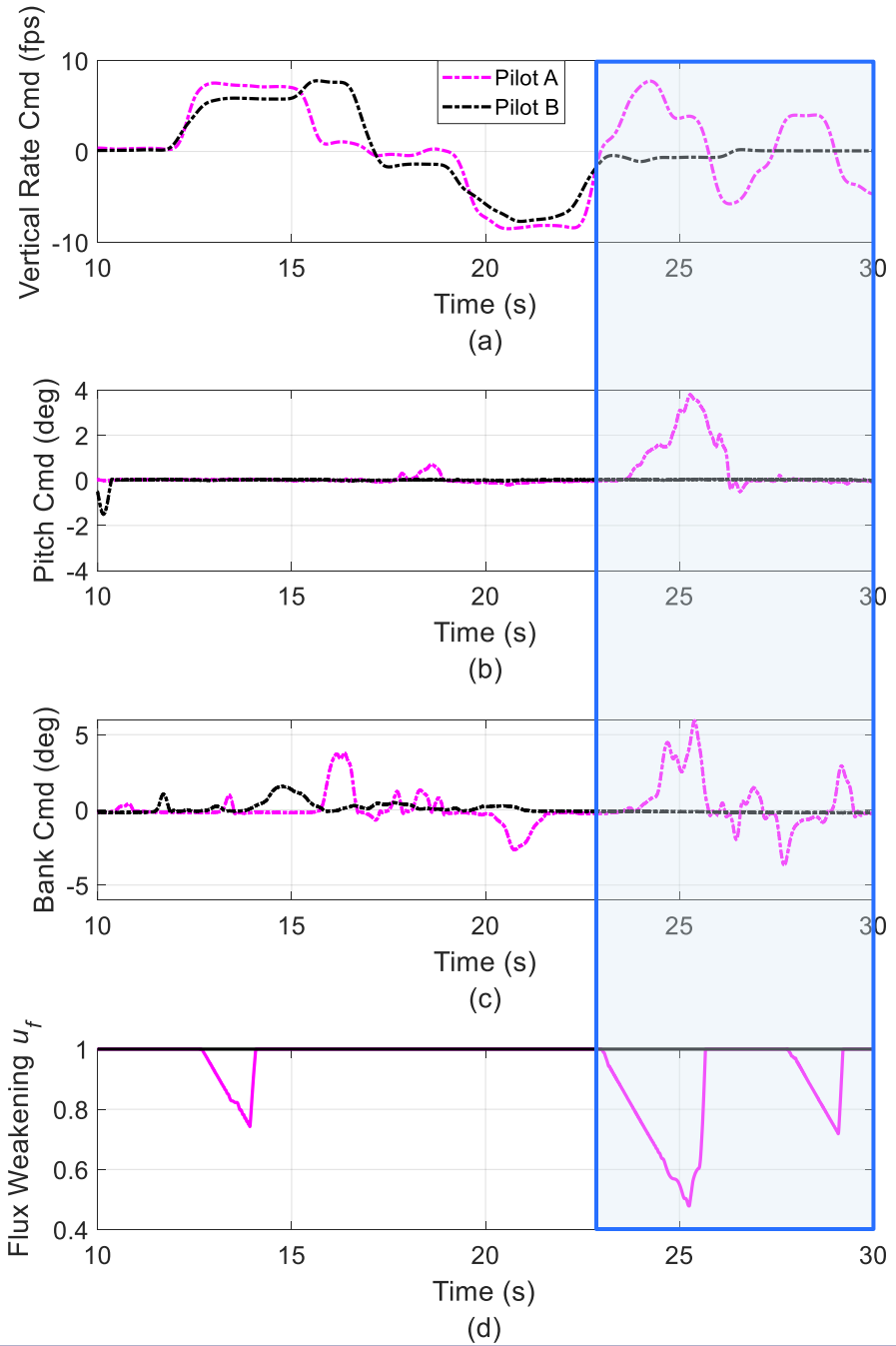
- Altitude Oscillations
 - Experienced by Pilot **A**, **C**, and **D**
 - Not experienced by Pilot **B**
 - Did not engage flux weakening control
 - Slower task execution



Pilot Altitude and Corresponding Flux Weakening Scaling Factor (u_f) / All Pilots: (a) Altitude; and (b) Flux Weakening u_f .



VMS Vertical Maneuver MTE: High Temp.



Handling Qualities Ratings	
Pilot A	6
Pilot B	4

Pilot A and Pilot B Data for: (a) Vertical Rate Command; (b) Pitch Angle Command; (c) Bank Angle Command; and (d) Flux Weakening Scaling Factor

Handling Qualities: Aggressiveness vs. Flux Weakening Engaged

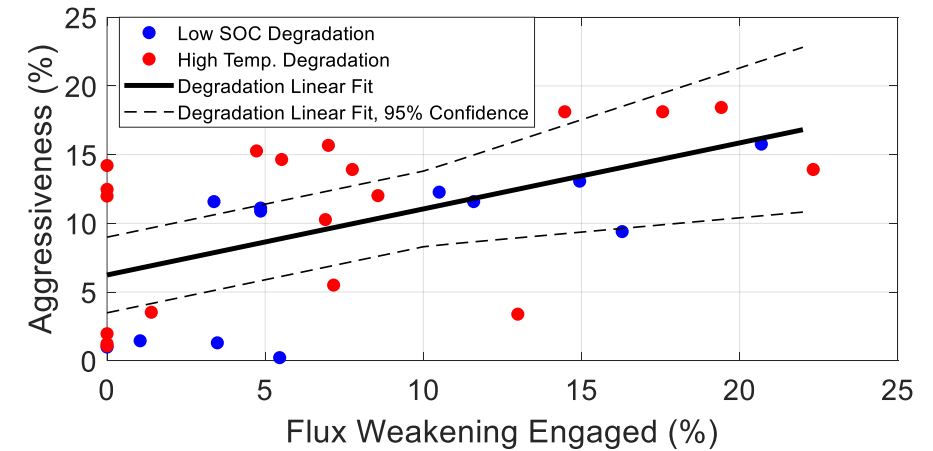
- Flux Weakening = Elevated Aggressiveness

- Definitions

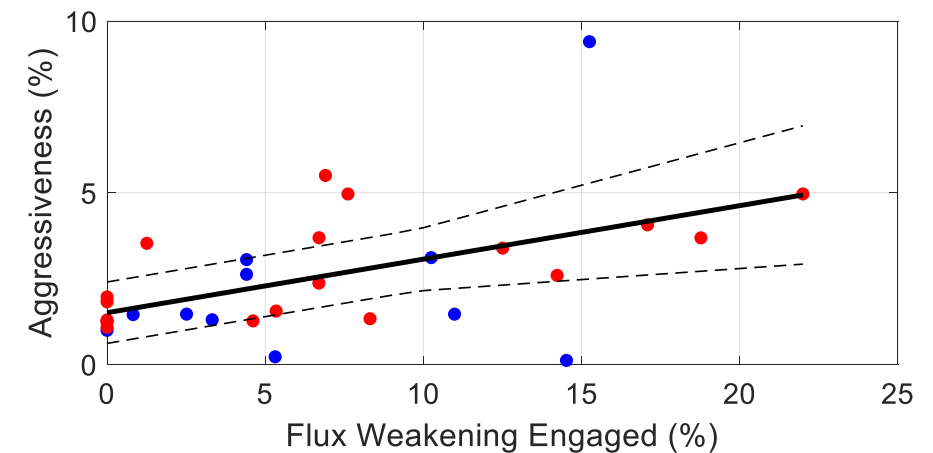
- Aggressiveness: *The measure of dynamic control deflection which is recorded as a time-averaged summation of pilot inceptor inputs during the maneuver*
- Flux Weakening Engaged: *Percentage of MTE that flux weakening control was mitigating voltage limiting*

- Statistical Significance

- Significant correlation if:
 - $p < 0.05$
- Vertical Axis: $p = 0.0015$ ✓
- Lateral/Longitudinal Axes: $p = 0.0028$ ✓



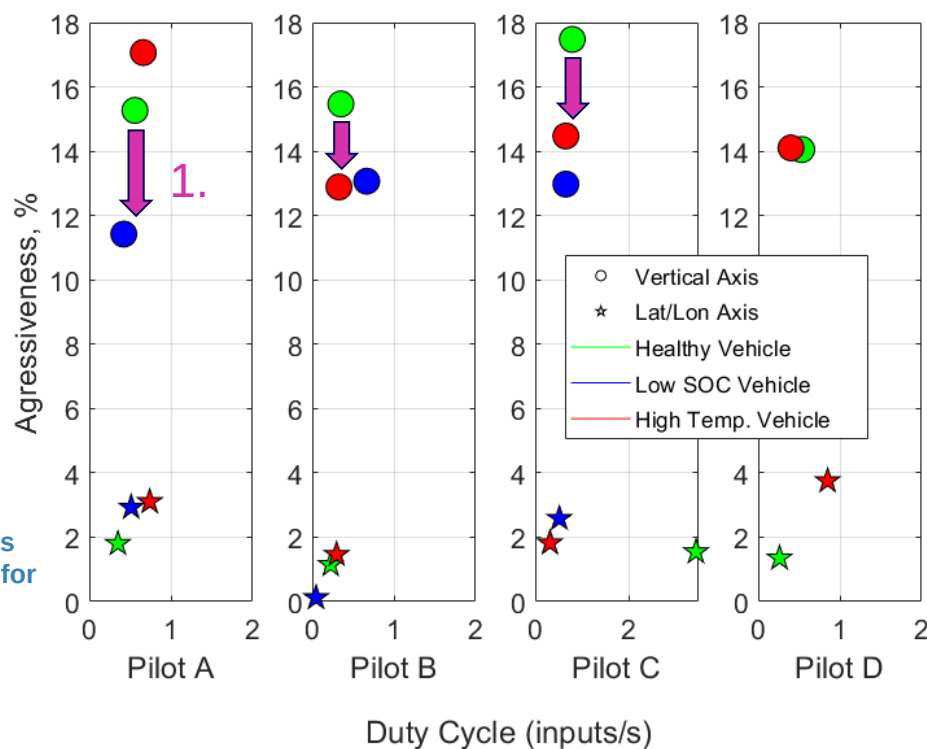
(a)



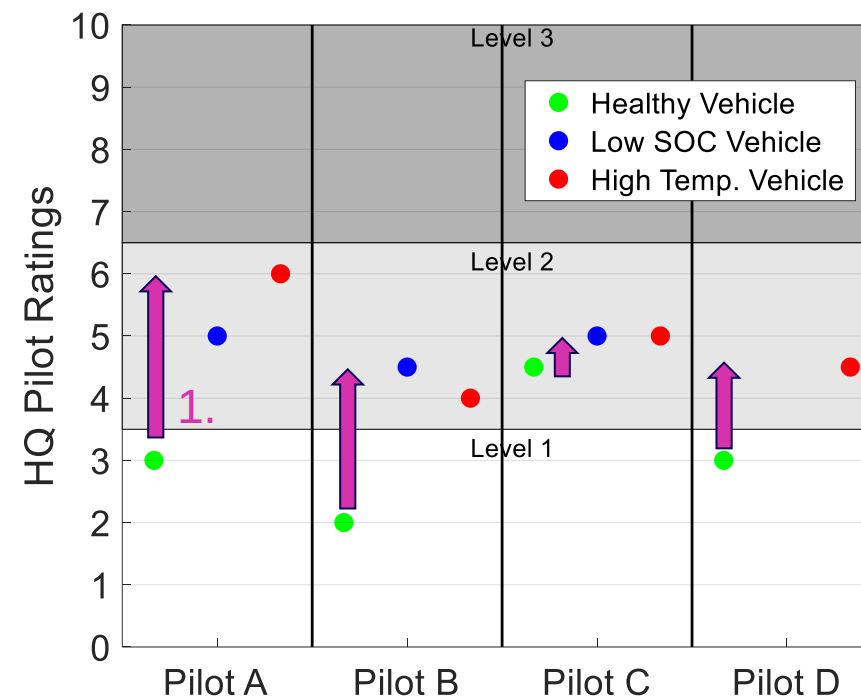
(b)

Aggressiveness vs. Flux Weakening Engaged for all Degradation Test Points: (a) Vertical Axis; and (b) Lat/Lon Axes

Vertical Maneuver MTE: Inceptor Workload and Ratings



Aggressiveness
vs. Duty Cycle for
all Pilots

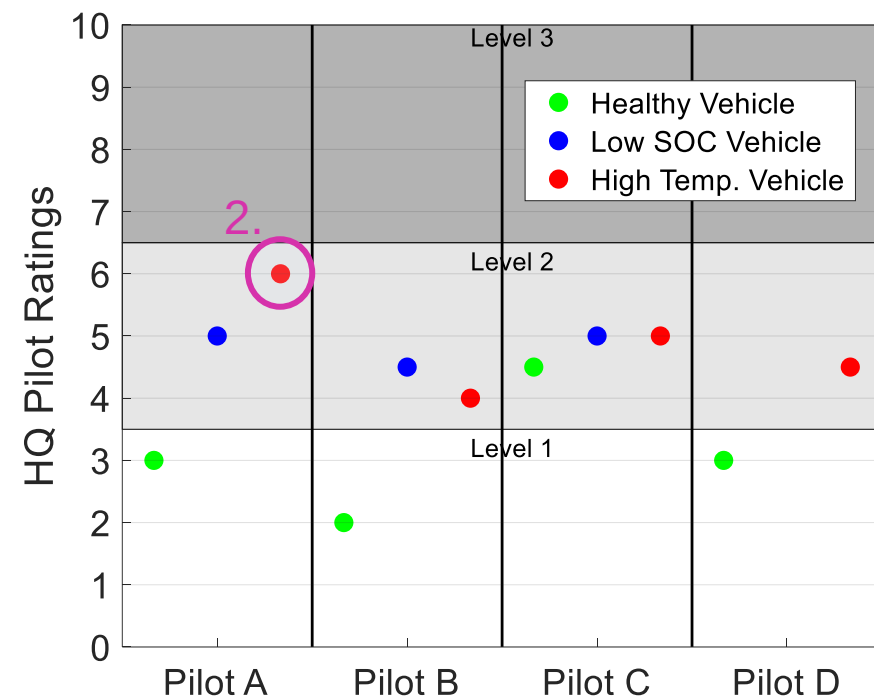
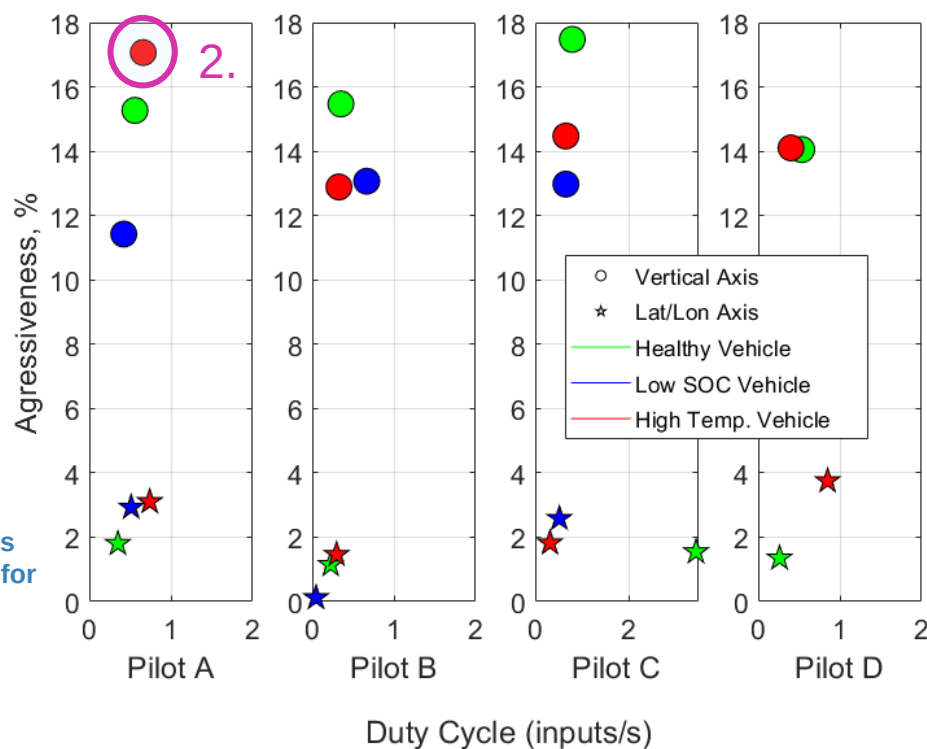


Cooper-Harper
Ratings for all
Pilots

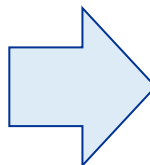
1. Forced to reduce inceptor aggressiveness

1. Increased Handling Quality Ratings (HQRs)

Vertical Maneuver MTE: Inceptor Workload and Ratings

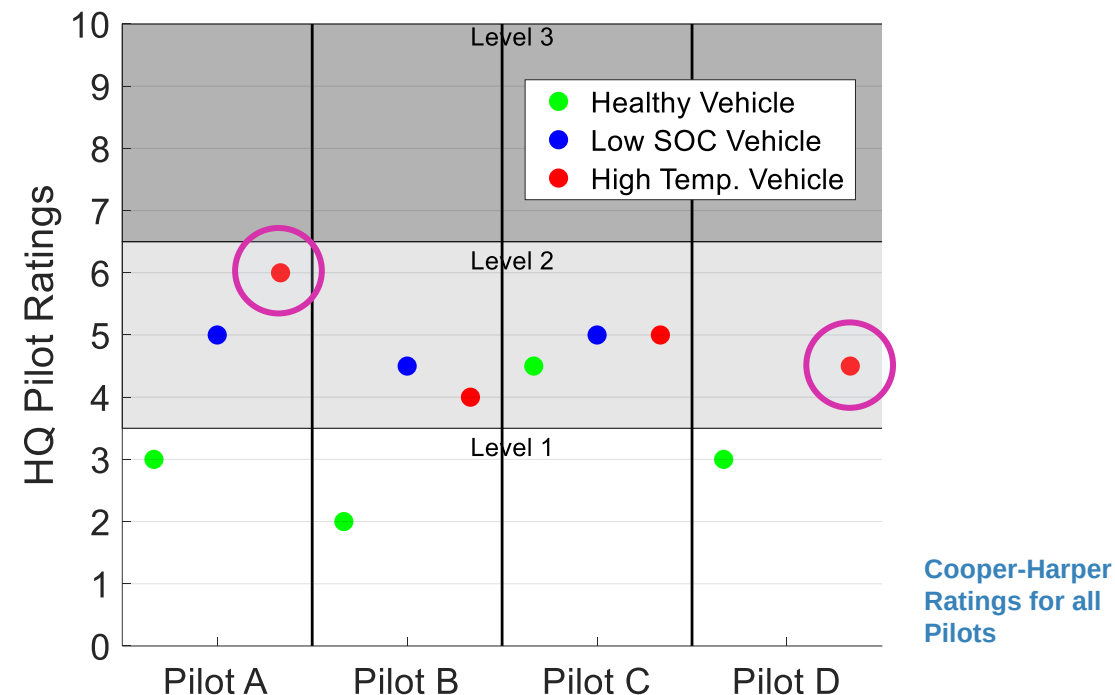
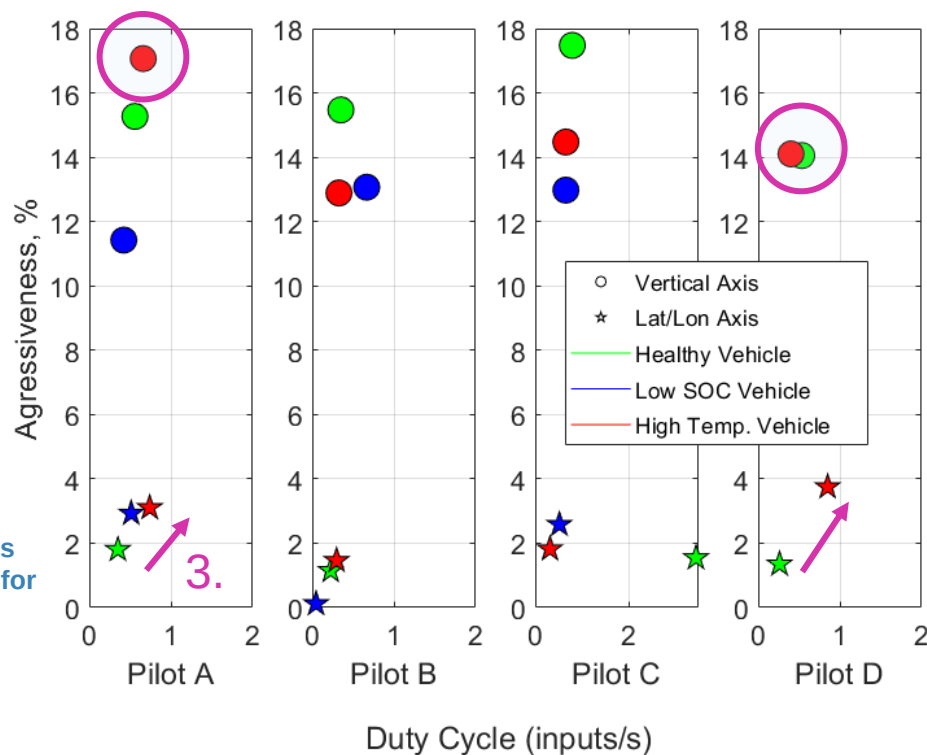


1. Forced to reduce inceptor aggressiveness
2. Attempt to increase aggressiveness (high temp.)

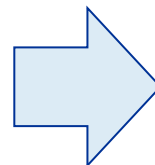


1. Increased Handling Quality Ratings (HQRs)
2. Worst HQR (high temp.)

Vertical Maneuver MTE: Inceptor Workload and Ratings



1. Forced to reduce inceptor aggressiveness
2. Attempt to increase aggressiveness (high temp.)
3. If vertical axis inceptor not reduced, lat/lon inceptor increased (voltage limiting)



1. Increased Handling Quality Ratings (HQRs)
2. Worst HQR (high temp.)
3. Contributed to reduced high temp. HQRs



MTE: Aggressiveness Ratings

* Degraded Vehicles generally did not tolerate preferred level of aggressiveness

Healthy Configuration

Ratings: **1-3** (Pilot A explanation)

Degraded Configurations

Ratings: **3-5**

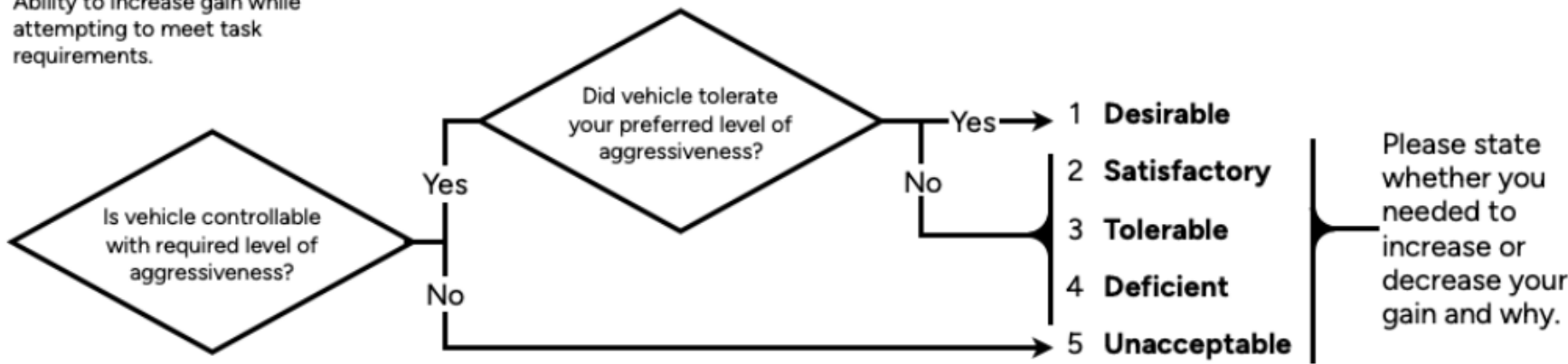
Table 3. Aggressiveness Ratings for MTEs.				
Vehicle Configuration	MTE Ratings: (Vertical/Hover with Turb.)			
	Pilot A	Pilot B	Pilot C	Pilot D
Healthy/Nominal	(1/4)	(1/2)	(3/3)	(x/x)
Low SOC	(3/4)	(x/4)	(3/5)	(x/x)
High Temp.	(4/4)	(3/x)	(3/4)	(x/x)

Note: x indicates that no rating was collected

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Aggressiveness

Ability to increase gain while attempting to meet task requirements.

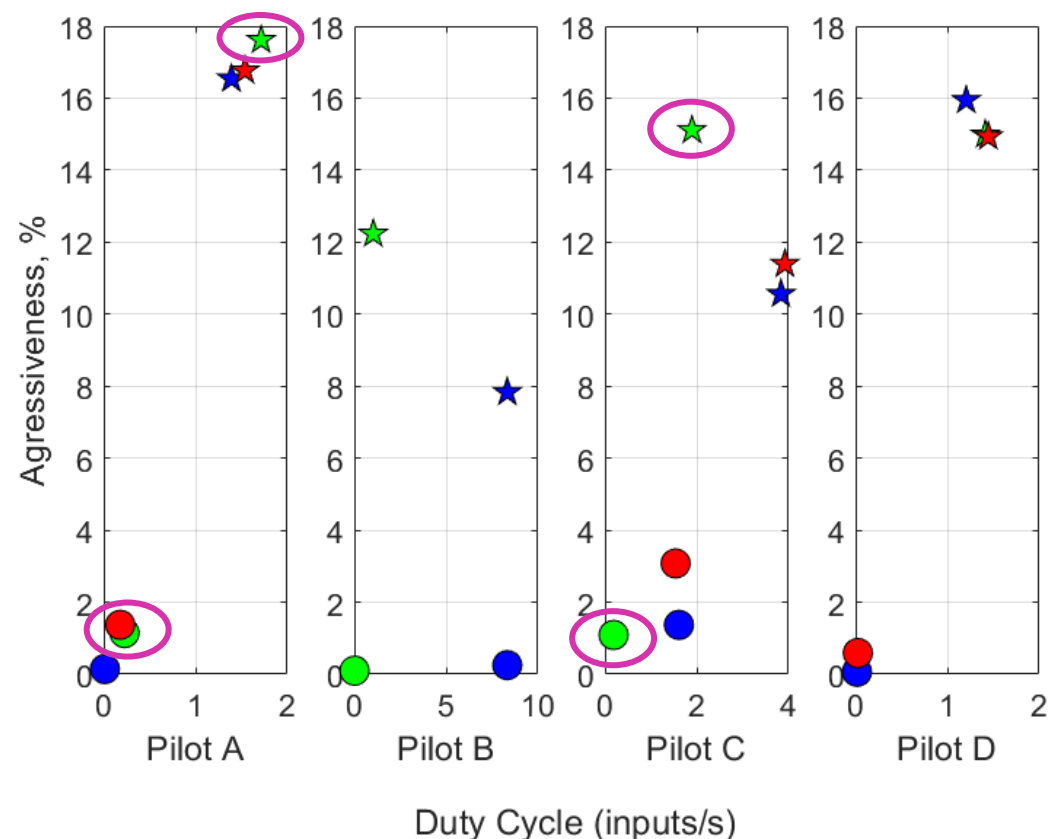


Hover Maneuver w/ Turb. MTE: Aggressiveness

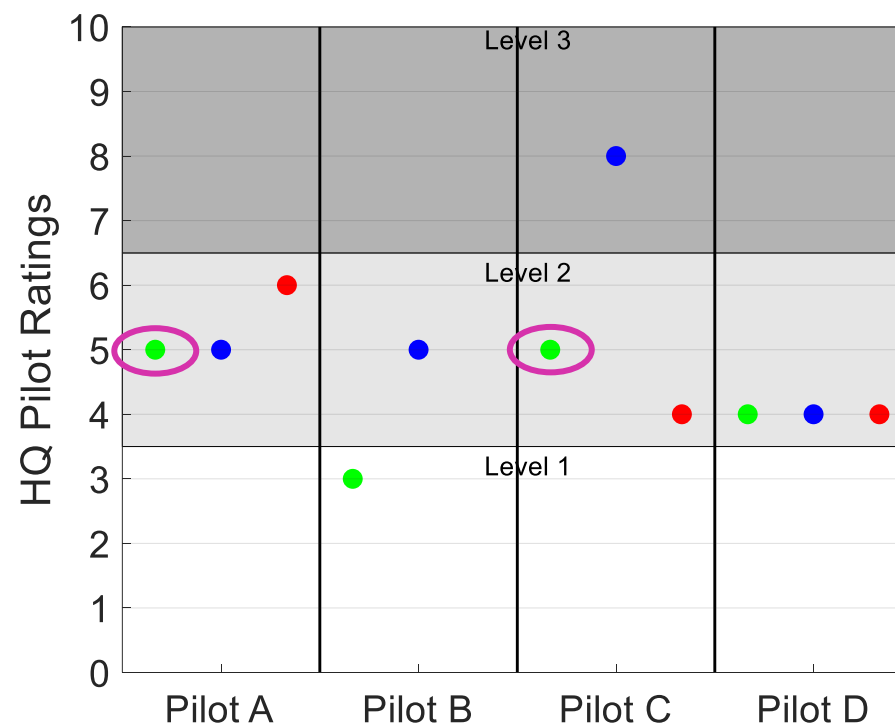
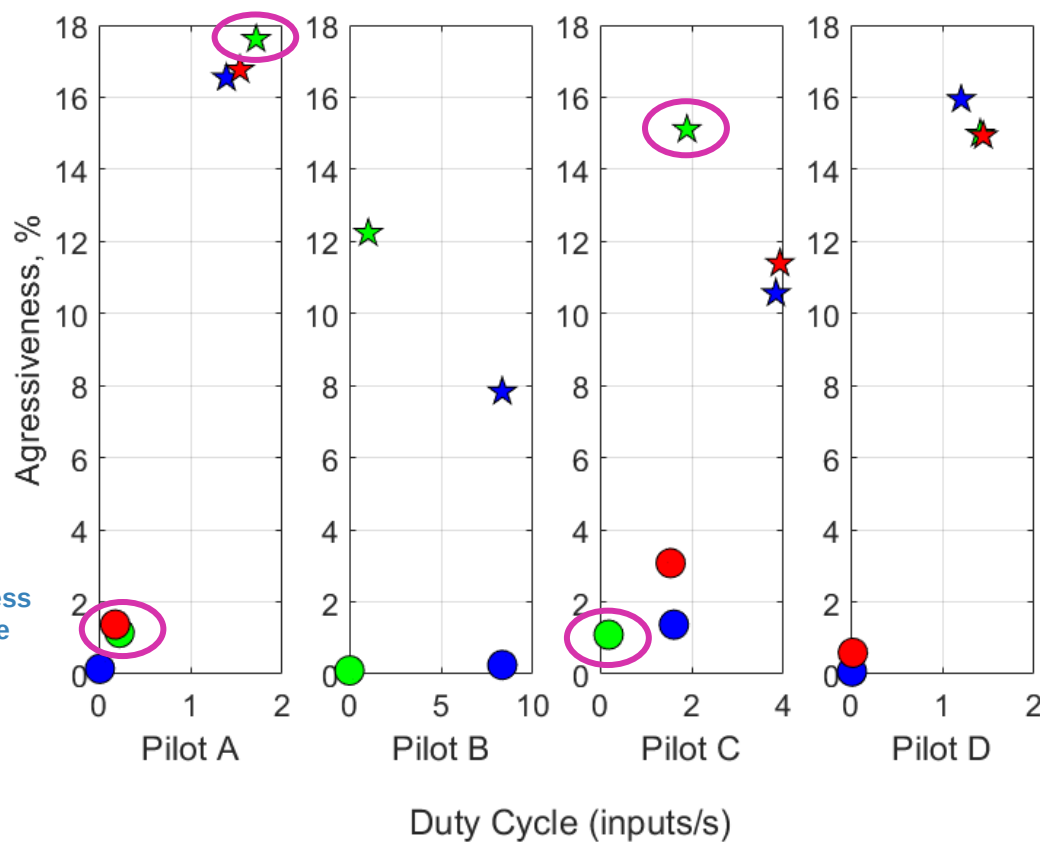
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Healthy/Nominal	(1/4)	(1/2)	(3/3)	(x/x)
Low SOC	(3/4)	(x/4)	(3/5)	(x/x)
High Temp.	(4/4)	(3/x)	(3/4)	(x/x)

Note: x indicates that no rating was collected

- Did Not Tolerate Elevated Aggressiveness
 - Lat/Lon Inceptor
 - Vertical Inceptor (not necessary for hover MTE)



Hover Maneuver w/ Turb MTE: Inceptor Workload and Ratings



Cooper-Harper
Ratings for all
Pilots

- Increased Healthy HQRs
 - Smaller difference between healthy and degraded



Summary

- Torque Saturation Due to Voltage Saturation
 - Flux weakening control mitigation
 - Decrease motor torque output
- Unpredictable Vehicle Behavior Due to Voltage Saturation
 - Vehicle attitudes did not follow pilot inputs
 - Cross-axis coupling
 - Controller torque commands did not account for torque saturation
- Degraded vehicle did not tolerate preferred aggressiveness Due to Voltage Saturation
 - Pilots forced to reduce aggressiveness
 - High aggressiveness often resulted in **cross-axis coupling, PIO, and/or LOC**



Questions