Fatigue Adaptive E-Bike

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ME 6409-A Final Project

Motivation

- The global electric bike market size is projected to grow from $43.32 billion in 2023 to $119.72 billion by 2030 [1].
- Muscle fatigue is a natural byproduct of biking, and is desirable in certain quantities and situations
- Implementing fatigue-assistive technology on E-bike
  - Fatigue Adaptive Controller
  - Seeking a less-fatiguing, more energy efficient ride

Project Overview

- Fatigue Adaptive Control for E-Bikes
  - Modeling E-Bike Riding
  - Modeling Fatigue and Recovery
  - Robot: Power-Multiplier Control (PMC) vs. Fatigue-Adaptive Control (FAC)
- Hypotheses
  1. FAC consumes less electrical power than PMC while maintaining speed
  2. FAC leaves riders less fatigued than PMC while maintaining speed

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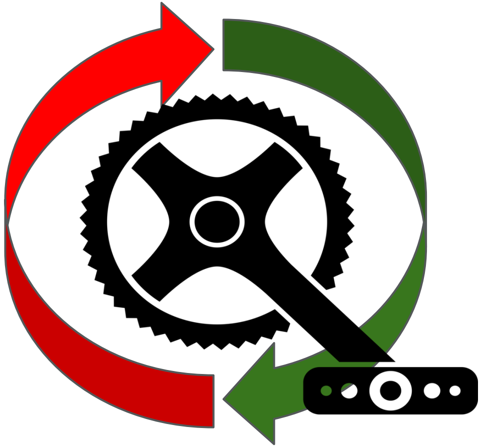
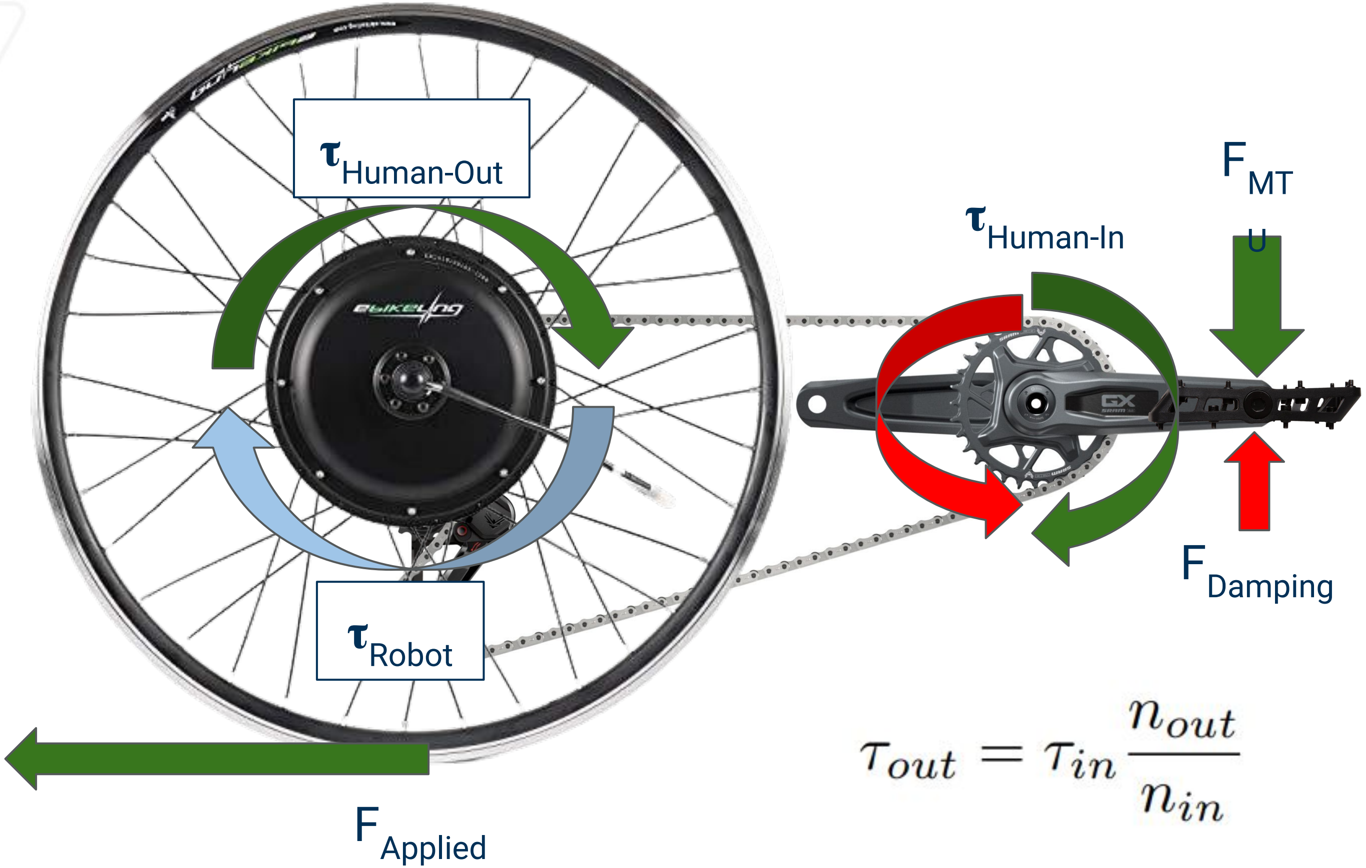
Assumptions

- Human power produced by a single soleus MTU
  - Symmetric *Power Stroke* and *Restoration Stroke*
- Riding is straight and level on smooth surface
- Constant drag profile and rolling resistance
- Human uses mechanical pedaling
- Exo uses direct-drive torque motor



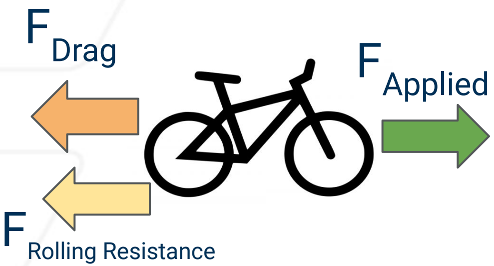
Modeling Drivetrain

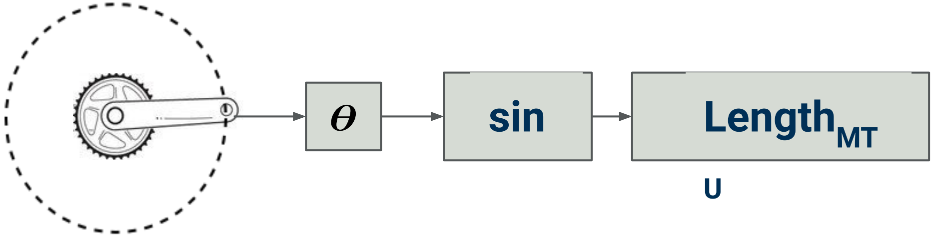


$$\tau_{out} = \tau_{in} \frac{n_{out}}{n_{in}}$$

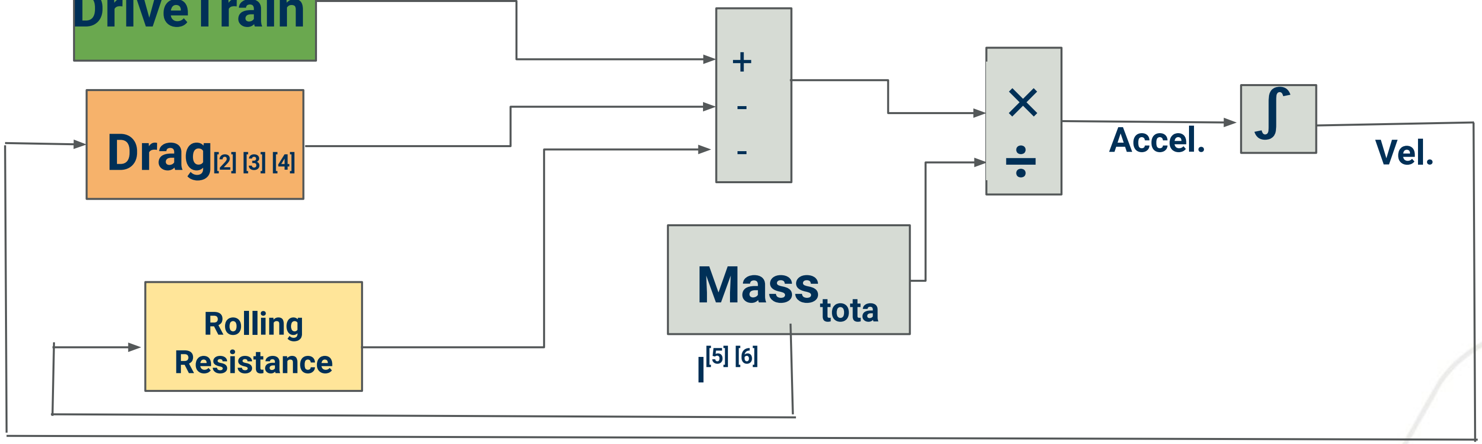
Modeling E-Bike Forces and Motion

Free Body Diagram





Bike Model Overview



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Modeling Fatigue and Recovery

- Acute Muscular Fatigue [2]
  - Central
  - Peripheral
- Fatigue decreases functional F_{max}
  - F_{cem}: Current Exertable Muscle Force

$$\frac{\mathrm{d}F_{cem}}{\mathrm{d}t} = \begin{cases} K_{recovery} \cdot (1 - a(t)) & u(t) = 0 \\ -K_{fatigue} \cdot a(t) & u(t) > 0 \end{cases}$$

[3]

$$\text{Fatigue} = 1 - \frac{F_{cem}}{F_{max}}$$

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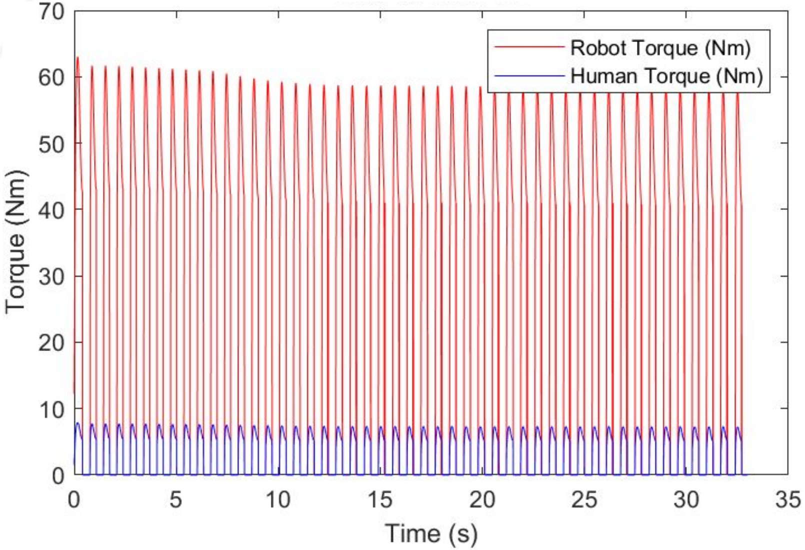
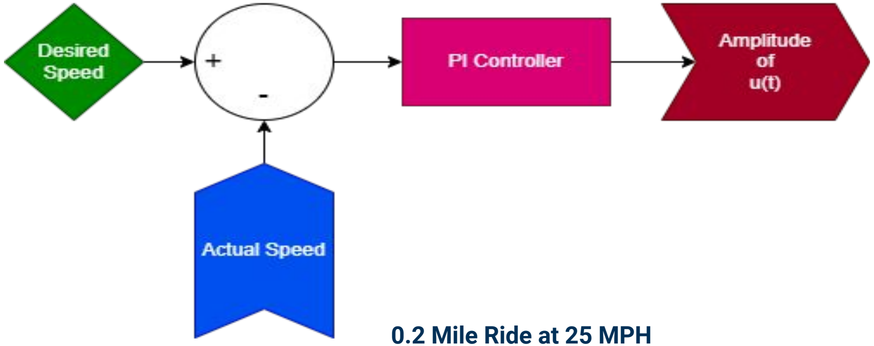
Modeling Power-Multiplier Control (PMC)

Robot

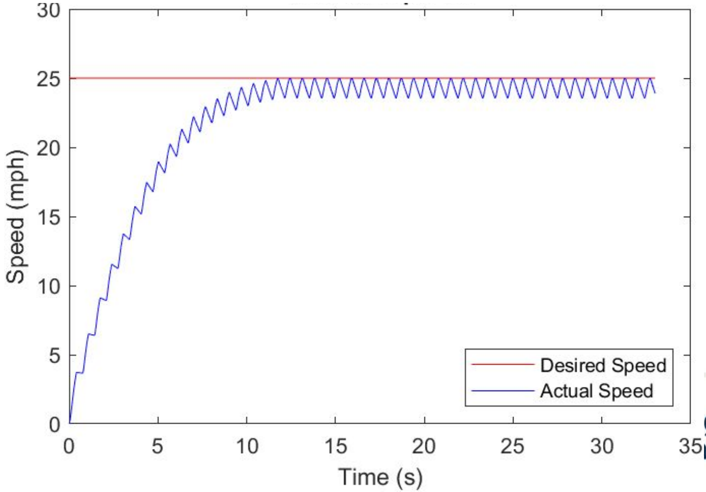
0.2 Mile Ride at 25 MPH



Human

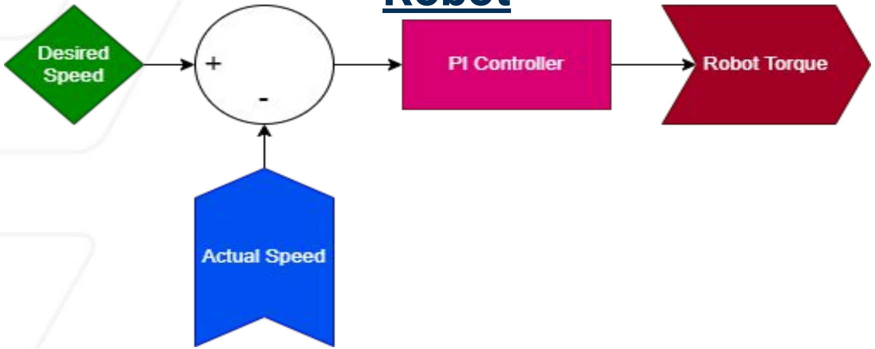


0.2 Mile Ride at 25 MPH

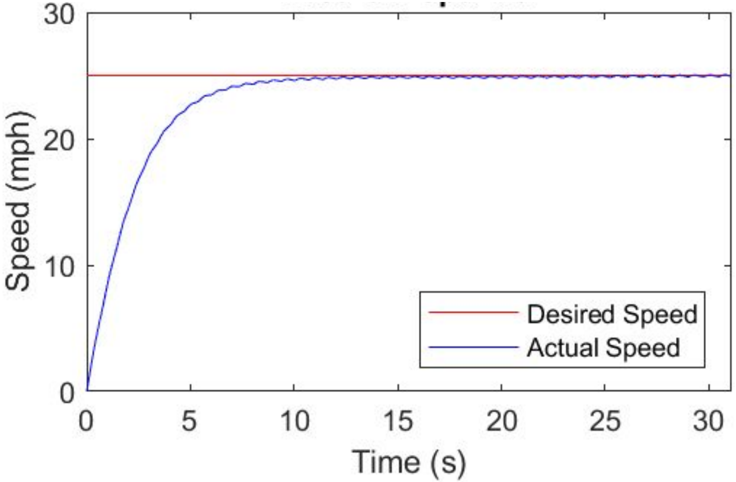


Modeling Fatigue-Adaptive Control (FAC)

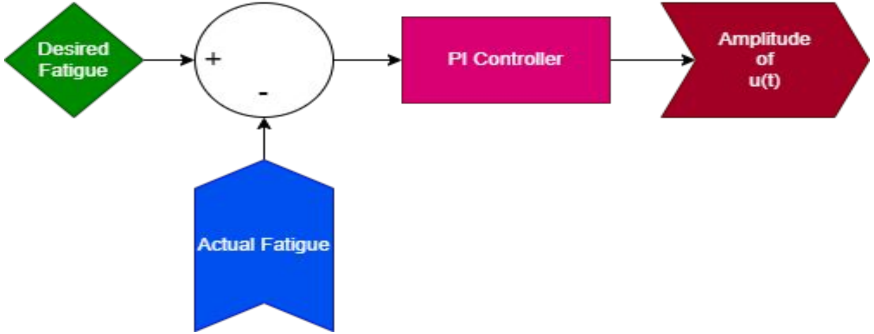
Robot



0.2 Mile Ride at 25 MPH



Human



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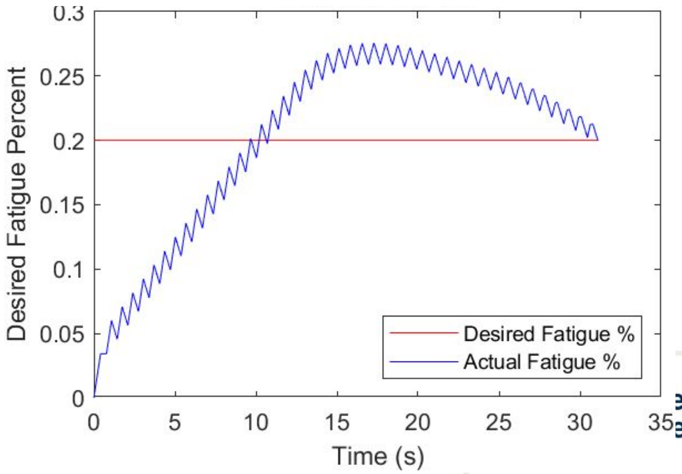


Experiment

Independent Variables:

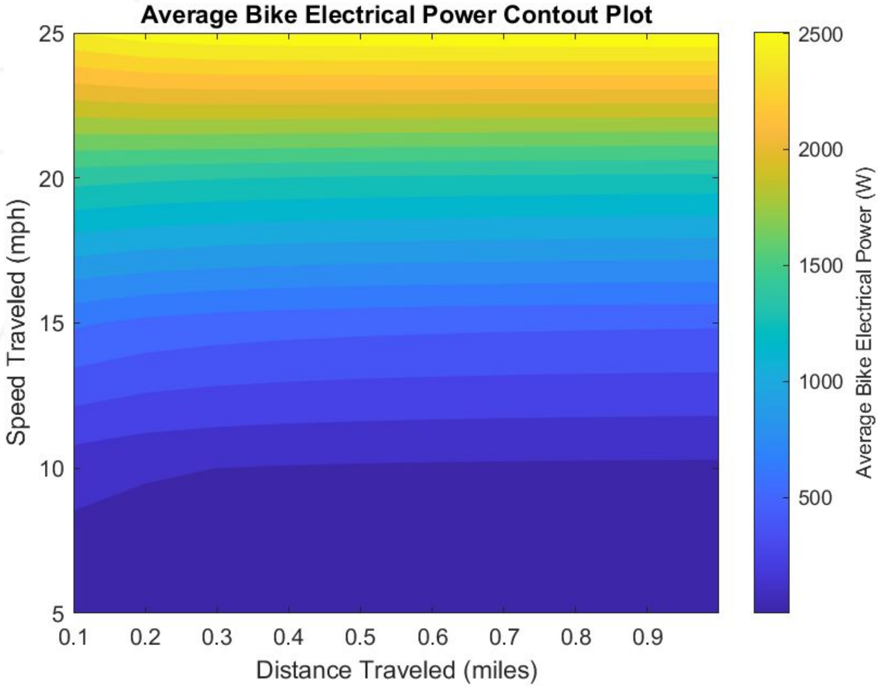
- PMC vs FAC Control Type
- Desired Speed [Tested Between 5 and 25 mph]
- Distance Traveled [Tested Between .1 and 1 miles]

Dependent Variables:

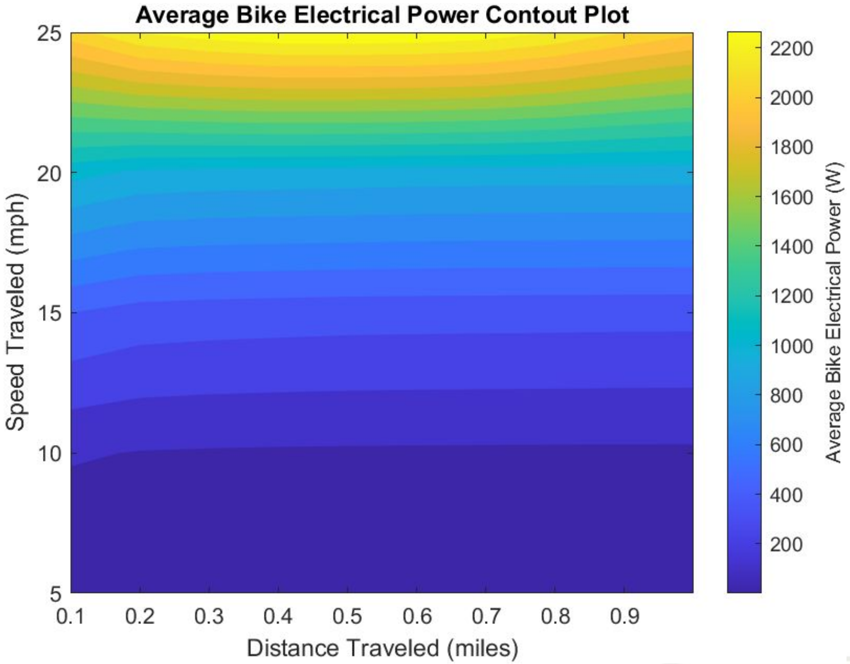
- Fatigue Percent
- Power Consumption of Ebike and Human

Results: Power Consumption Comparison FAC vs. PMC

Fatigue-Adaptive Control (FAC)



Power-Multiplier Control (PMC)



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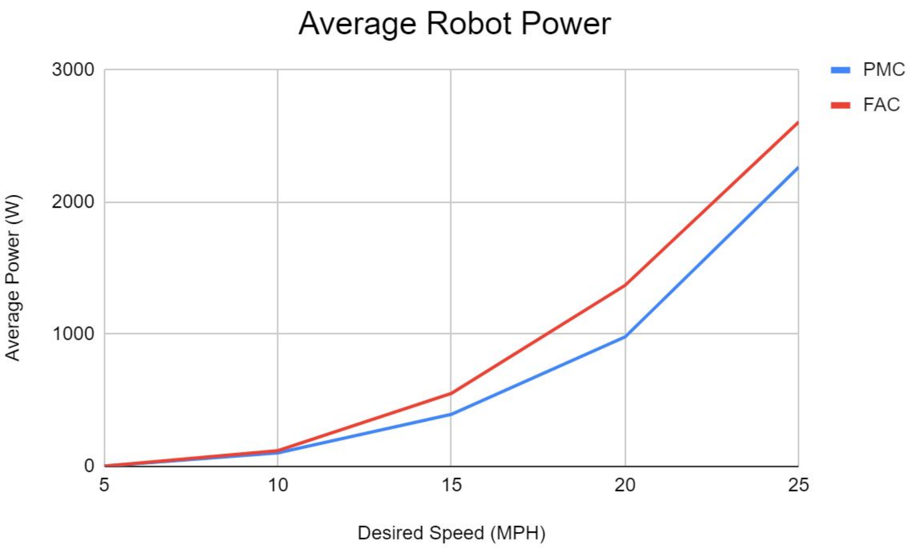
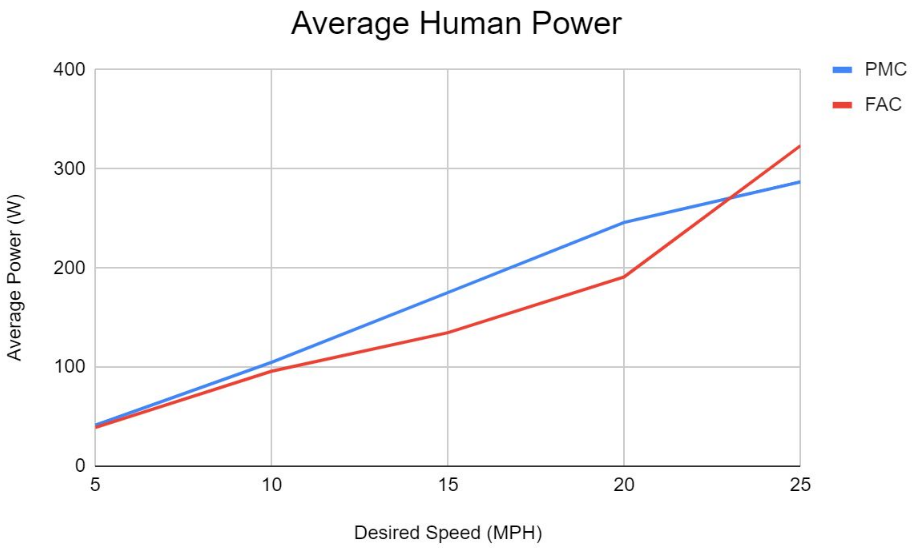
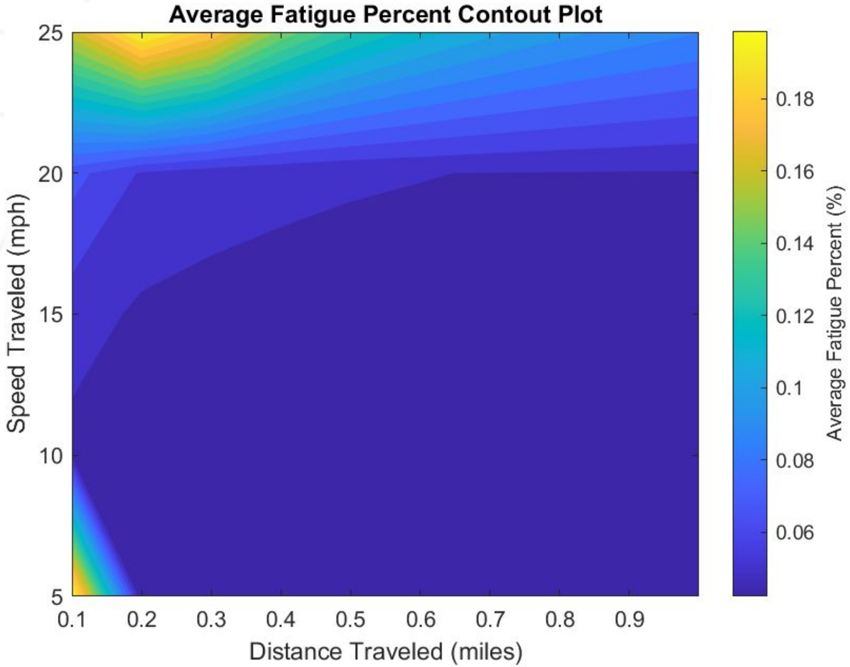
Results: Power Consumption Comparison FAC vs. PMC



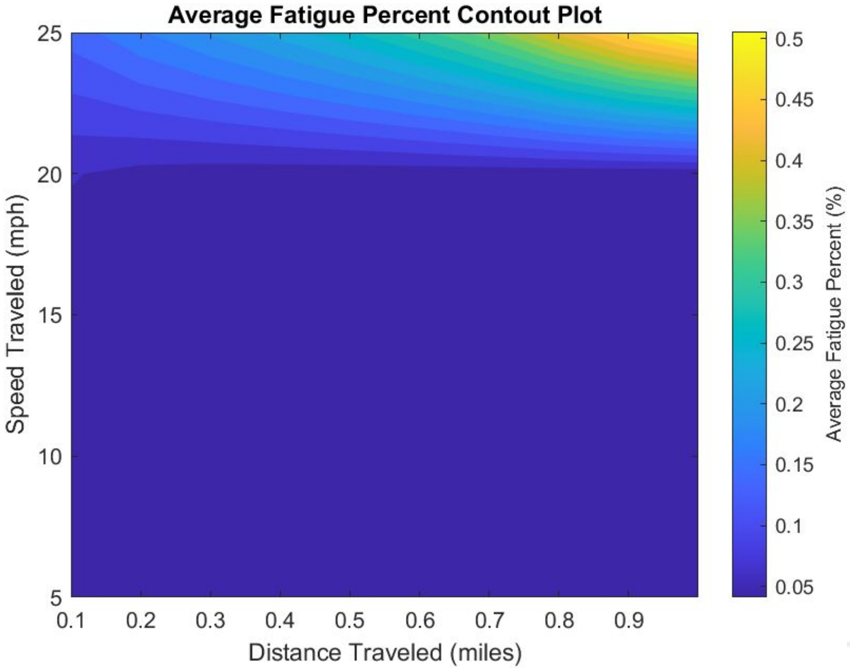


Results: Fatigue Comparison FAC vs. PMC

Fatigue-Adaptive Control (FAC)



Power-Multiplier Control (PMC)



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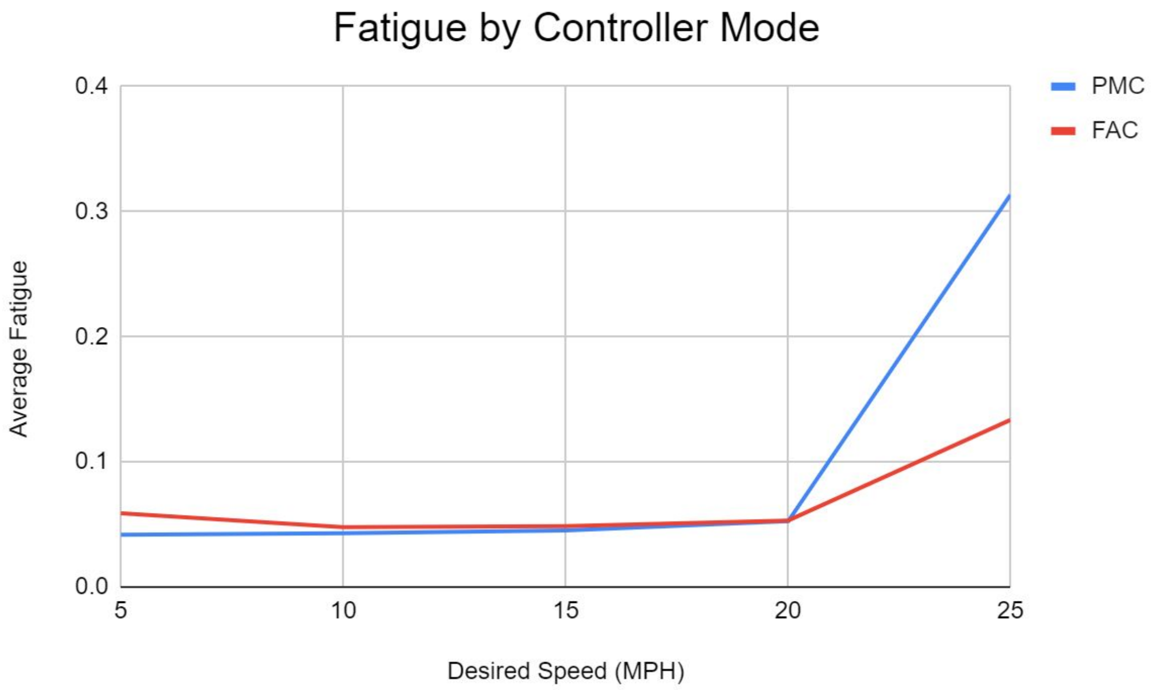
Results: Fatigue Comparison FAC vs. PMC



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Discussion/Conclusions

- FAC underperforms PMC in electrical power consumption
- FAC outperforms PMC in managing fatigue at higher speeds, but produces similar results lower speeds
- FAC demands less human power to achieve and maintain speed than PMC

1. Hypotheses
    1. FAC consumes less electrical power than PMC while maintaining speed
        - FAC consumes more electrical power than PMC in all speed conditions
    2. FAC leaves riders less fatigued than PMC while maintaining speed
        - FAC leaves riders less fatigued than PMC in some conditions

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Future Considerations and Implications

- Implications
  - Fatigue-Adaptive Control does not appear to outperform traditional E-Bikes
  - Fatigue-Adaptive Control is highly effective at maintaining desired speed
  - Fatigue-minimization methods effectively mitigate fatigue, at the cost of electrical power
- Future Considerations
  - Enable higher riding speeds and test at higher desired speeds
    - The edge of some data curves suggested new trends and patterns
  - Test other desired fatigue conditions
  - Model using two symmetric muscles
  - Investigate pedal-recharging E-Bike setup

References

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Constant

$\rho_{air} = \frac{1.2kg}{m^3}$ [4]

$C = 0.68\ (drag\ coeffcient)$ [3]

$A = 0.5m^2\ (effective\ drag\ area)$ [9]

$\mu_{roll} = 0.002\ (Rolling\ Coefficient)$

$C_{damping} = 30$

$m_{human} = 62\ kg$ [11]

$m_{bike} = 8.32\ kg$ [6]

$m_{pedal} = 5\ kg$

$r_{crank} = 0.17\ m$

$T_{gear\ out} = 39\ teeth$

$T_{gear\ in} = 53\ teeth$

$r_{wheel} = 0.311\ m$

$F_{max} = 6000N\ (\max muscle\ force)$

$Fatigue\ constant = 500$

$Recovery\ constant = 250$

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