Optimal Control Strategy Analysis for Parallel Gasoline Hybrid Electric Vehicles

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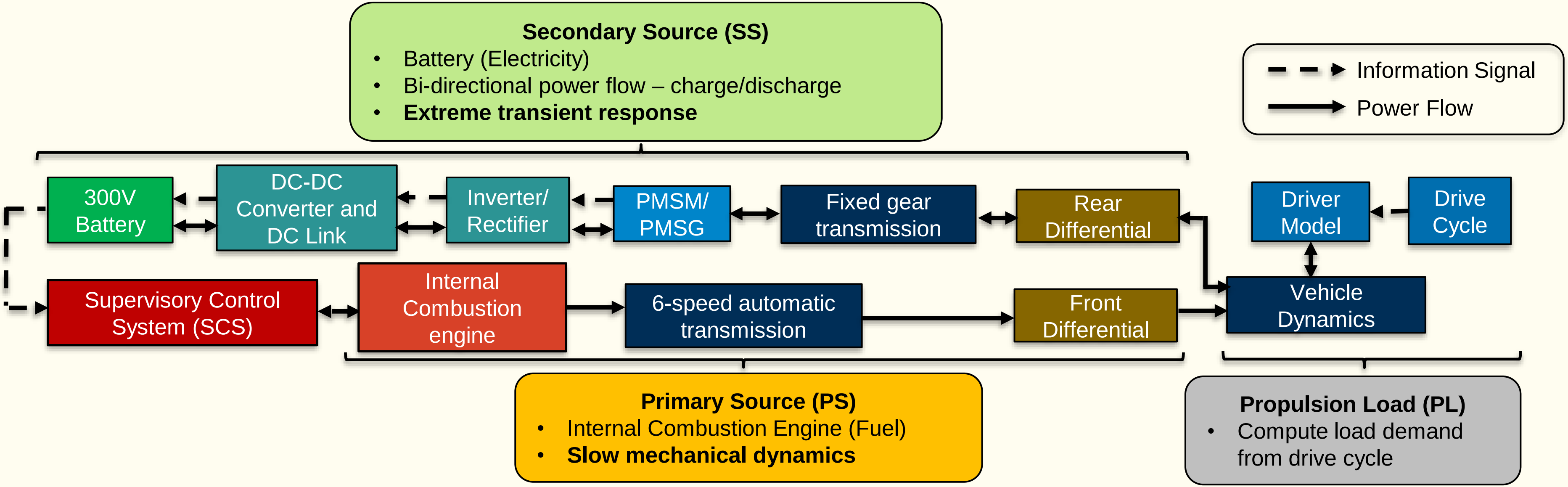
Hybrid Powertrain: Full Parallel, Through-the-road

Vehicle hybridization serves as an **exciting current platform** in **reducing emissions** from the transport sector through **increasing *electrification in vehicle powertrains***



Optimality in Parallel Hybrids

Vehicle hybridization – Increasing Electrification in Powertrains

Gap in timescales between power branches

(Battery Cost Limited)
Zero Fuel Consumption
Minimum Battery Health

- Over-reliant on transient electrical pathway

(Emissions Limited)
Maximum Fuel Consumption
Maximum Battery Health

- Over-preservation of long-term battery ageing

Optimality in Parallel Hybrids

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Optimal engine operation in a parallel gasoline hybrid electric vehicle (HEV)

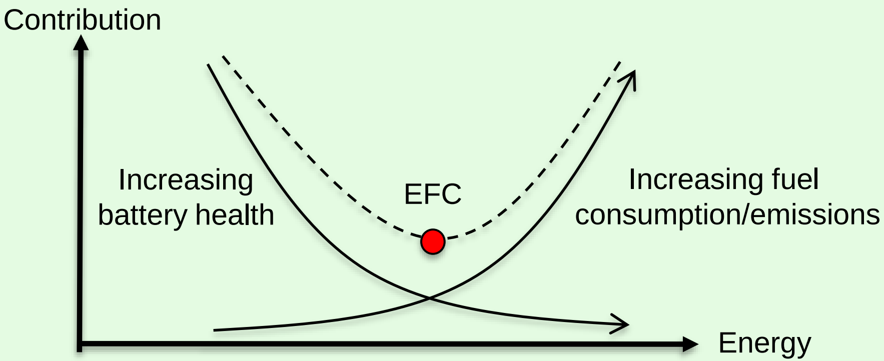
How do we balance between *minimization of fuel consumption/emissions* and *maximization of battery health?*

Optimality in Parallel Hybrids: Criteria

1) Fuel Economy - Equivalent Fuel Consumption (EFC)

- HEV utilizes both fuel and electrical energy.
- For non plug-ins - Battery strictly a buffer source
  - Engine link via direct charging or regenerative braking.

EFC: Fuel + Electricity = Single performance metric



Goal: Minimize m_{efc} across drivecycle

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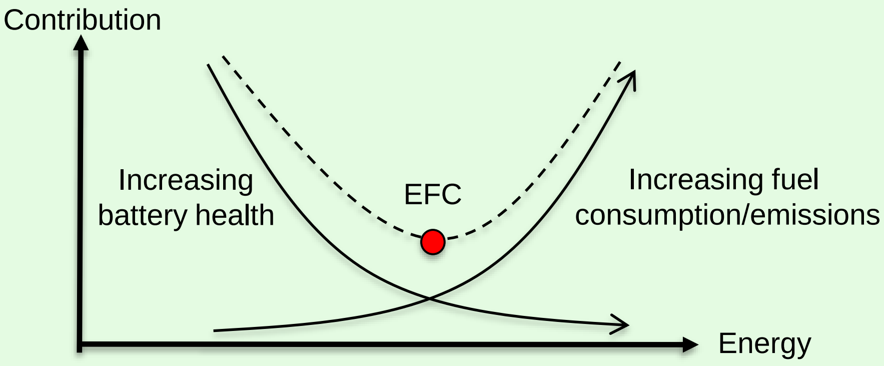
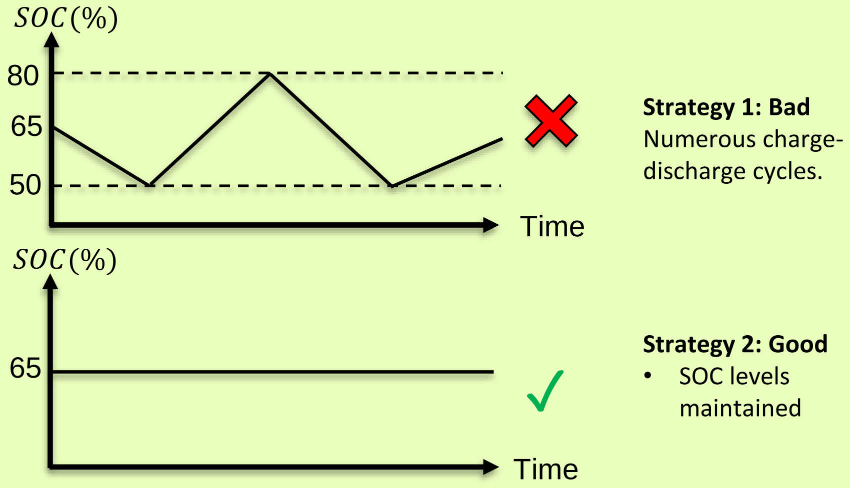


Goal: Minimize m_{efc} across drivecycle

2) Battery Degradation – State of Charge (SOC)

- **Prevent SOC oscillation between upper and lower limits**
  - Limit degradation mechanisms in Li-Ion battery



Goal: Achieve charge-sustaining operation

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Control Strategy Development: Process

Control strategies that facilitate *optimal operation* in a parallel HEV

Global optimization-based Strategies

✓ Optimization – Best-case vehicle performance
Global – Drive-cycle information known beforehand

✗ Complex optimization procedure
Unrealistic global criterion

VS

Conventional **Heuristic Strategies**

✓ Heuristic – Practical implementation for real-world driving (Algebraic functions/rule-based logic)

✗ Sub-optimal vehicle performance

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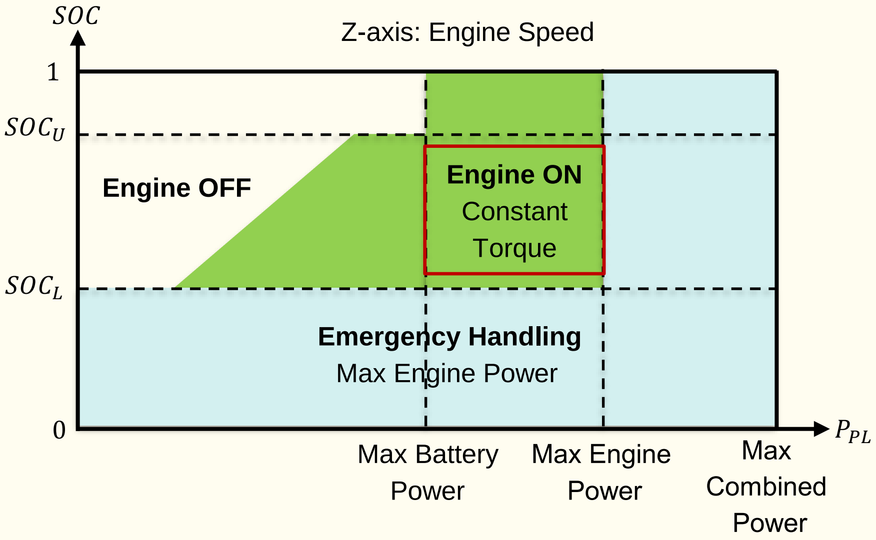
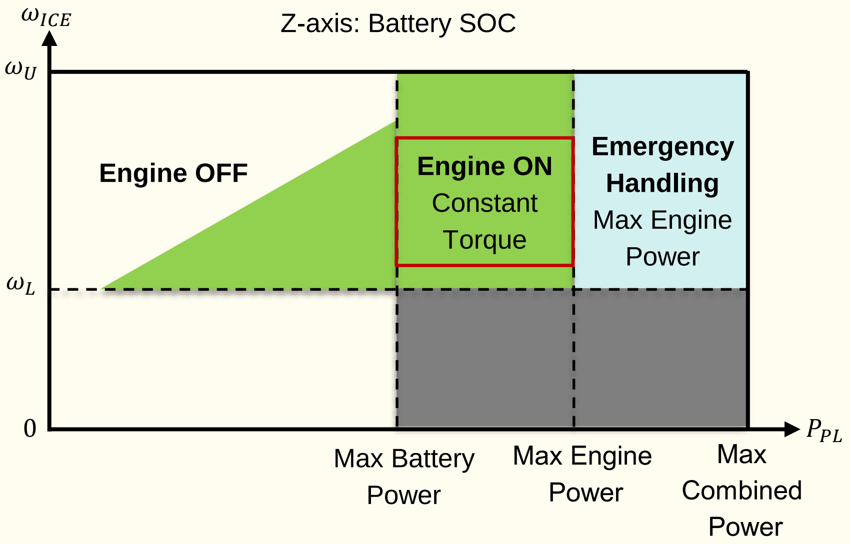
***Modern* Heuristic Strategy**

Develop novel rules to achieve great optimality in parallel hybrids
Maintaining ease of implementation

Control Strategy Development: Novel Heuristic

- **Torque-Leveling Threshold Changing Strategy (TTS)**
  - Propulsion Load P_{PL}, Battery SOC, Engine Speed ω_{ICE}





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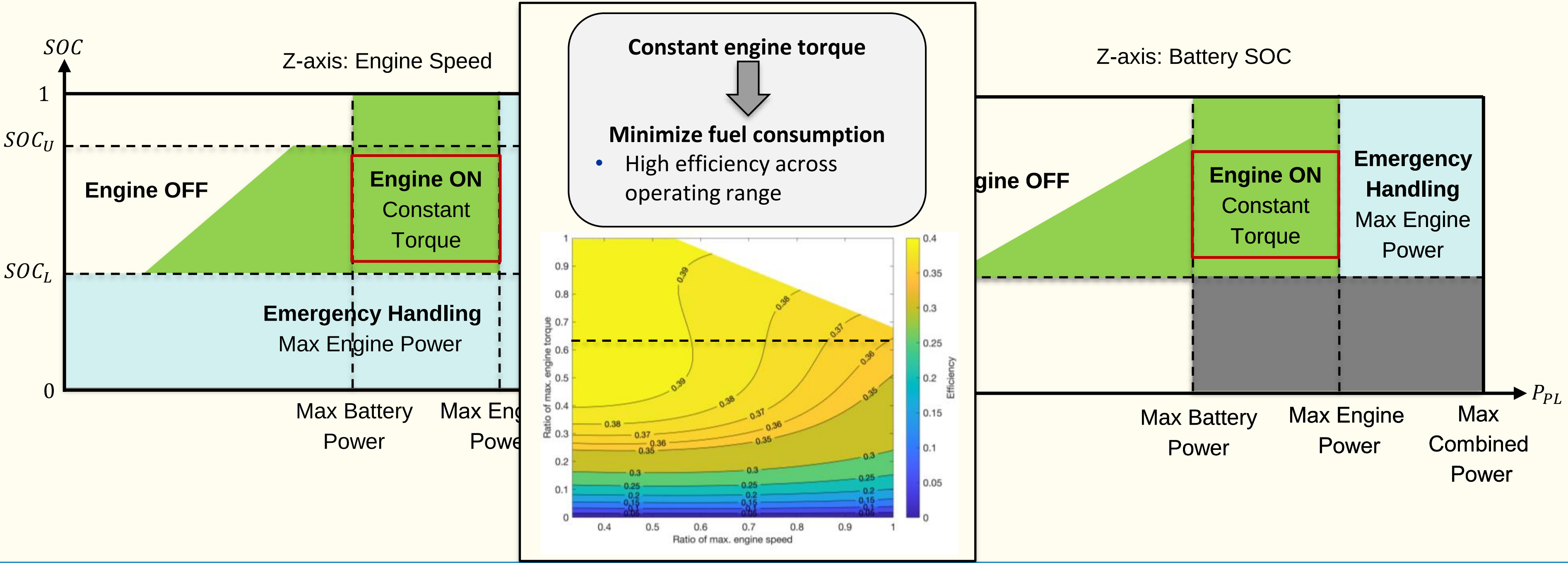

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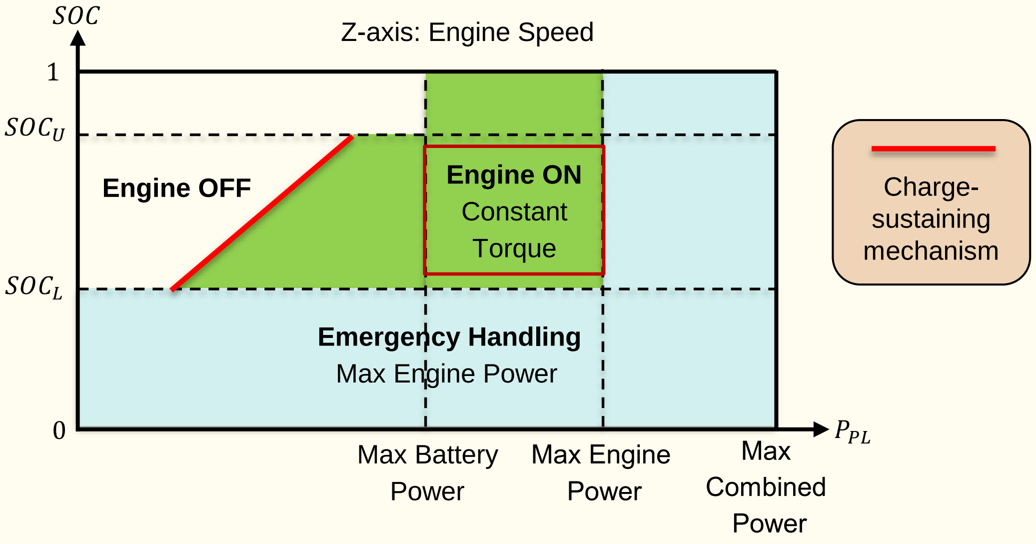

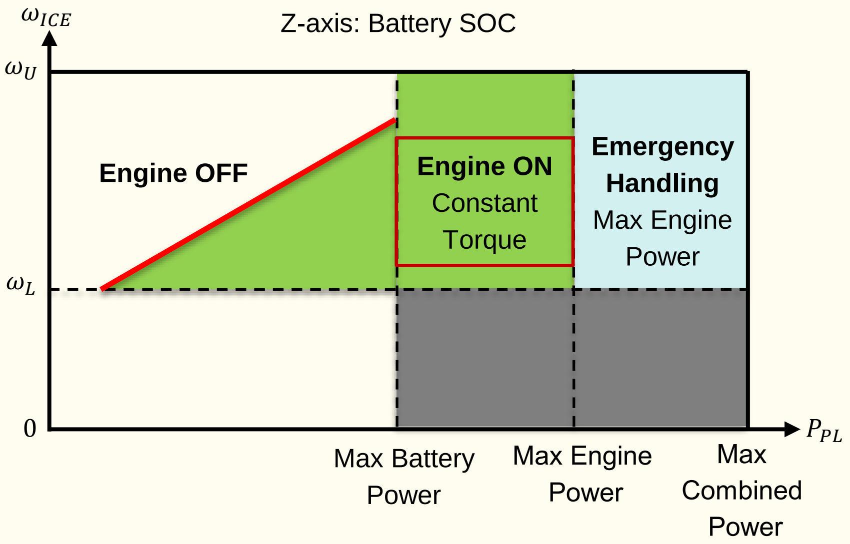

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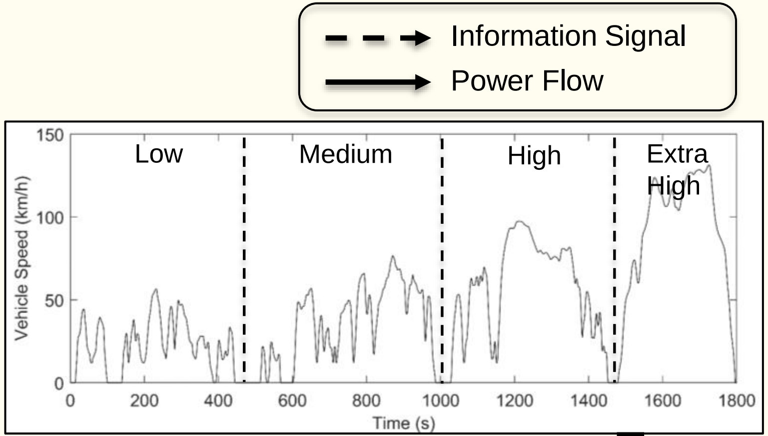
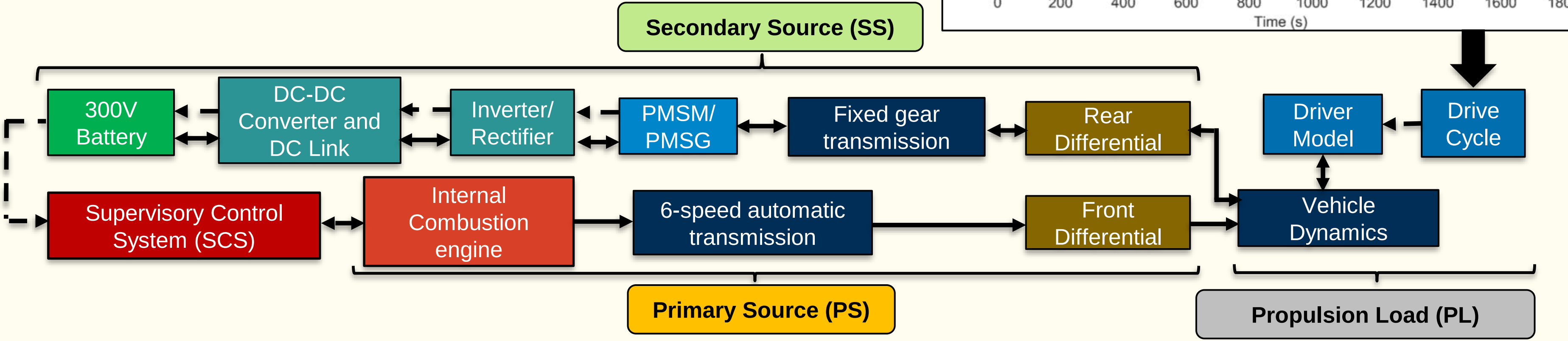
Simulation Methodology

- General c-segment parallel vehicle - High fidelity MATLAB Simulink model

- **Model simulations – 4 main segments of WLTP cycle**
    - Low X8, Medium X8, High X4, Extra High X4
- **Run multiple iterations (xN) – Assess long-term robustness of fuel consumption vs battery degradation**





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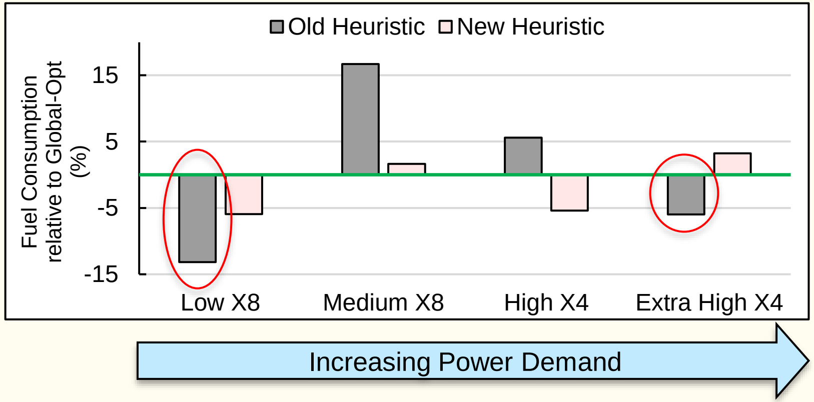
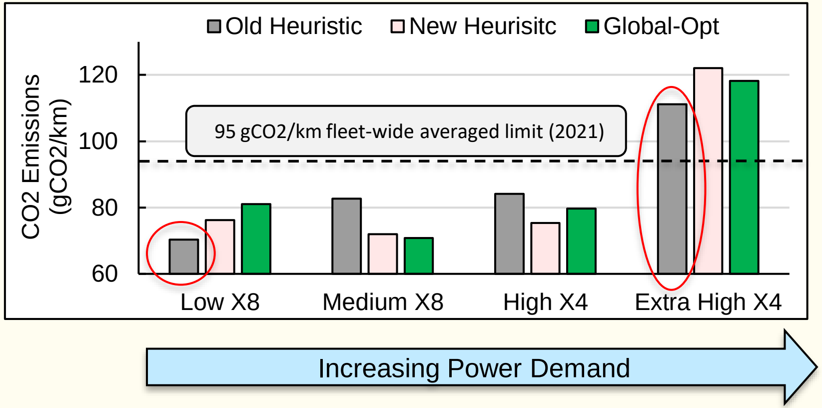
Control Strategy Development: Results (1)

For graphs, Lower = Better





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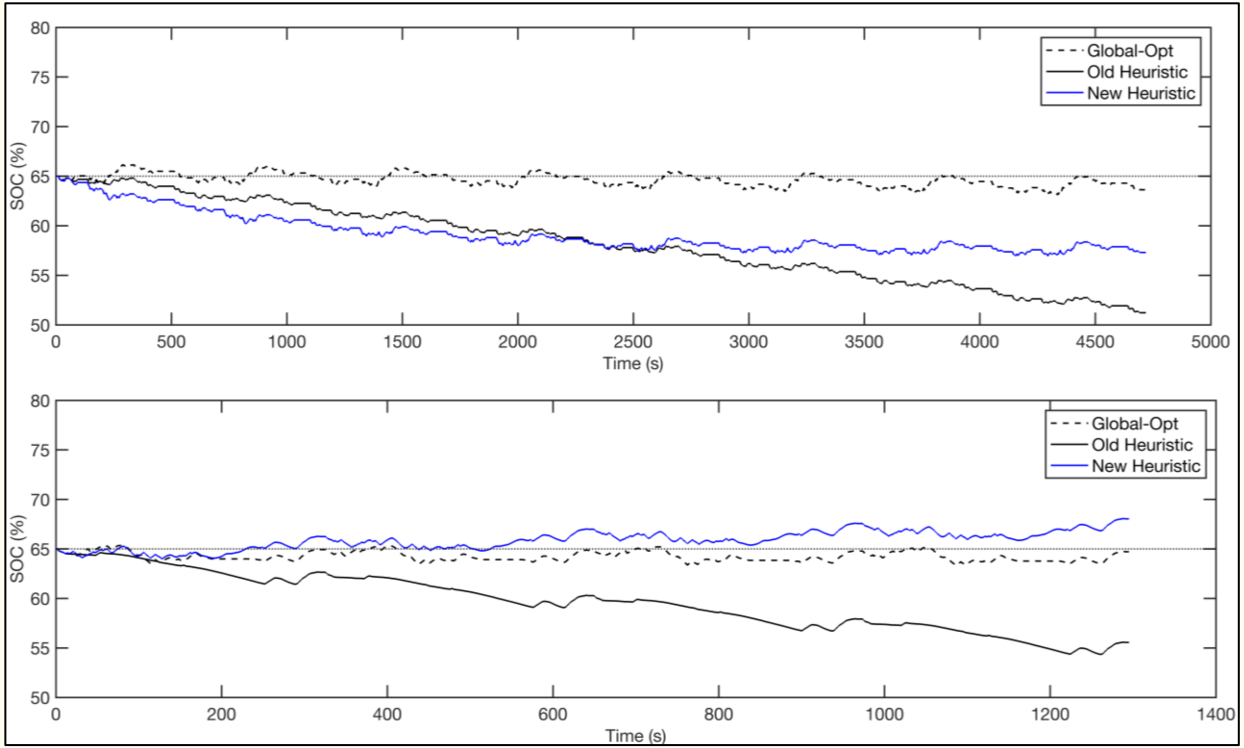
Control Strategy Development: Results (1)

Battery SOC simulation:
$SOC_{initial} = 65\%$
$SOC_{lower} = 50\%$
$SOC_{upper} = 80\%$

Low X8

Extra High X4



Dashed – Global-optimized
- Benchmark-case

VS

Black – Old Heuristic
- Preservation of fuel economy leads to large SOC deficit

VS

Blue – New Heuristic (TTS)
- **Long-term SOC resistance achieved**

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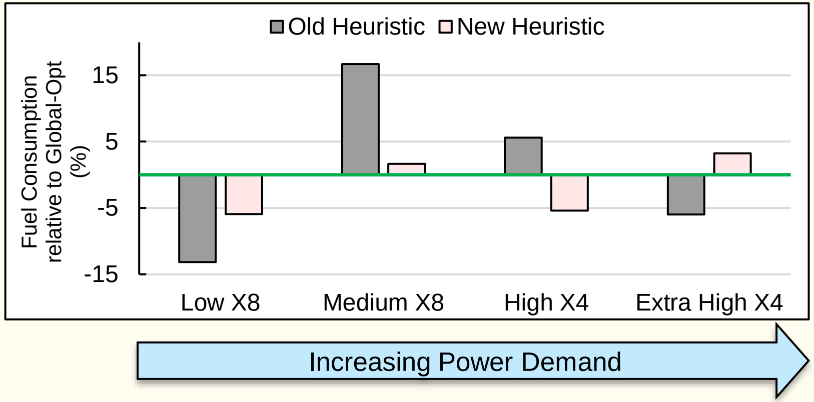
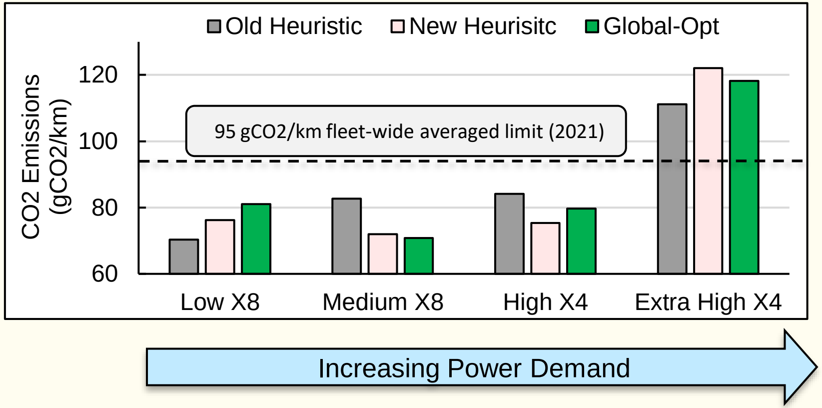
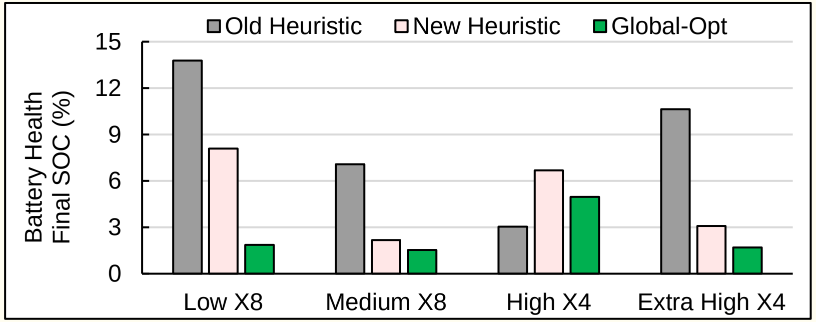
Control Strategy Development: Results (1)

For graphs, Lower = Better





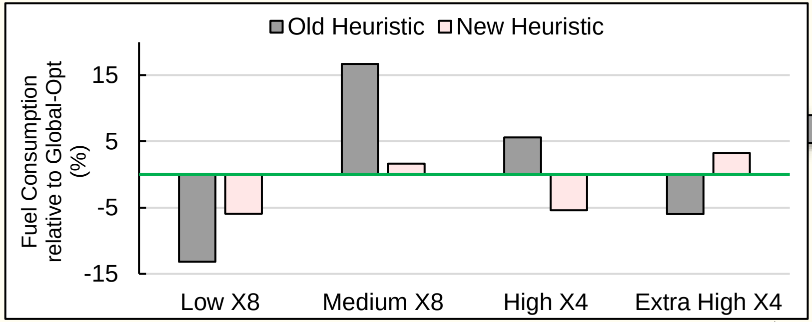


Battery ageing improvement (lower bound)	Low X8	Medium X8	High X4	Extra High X4
Old → New Heuristic TTS	>4%	>5%	>0.1%	>7%

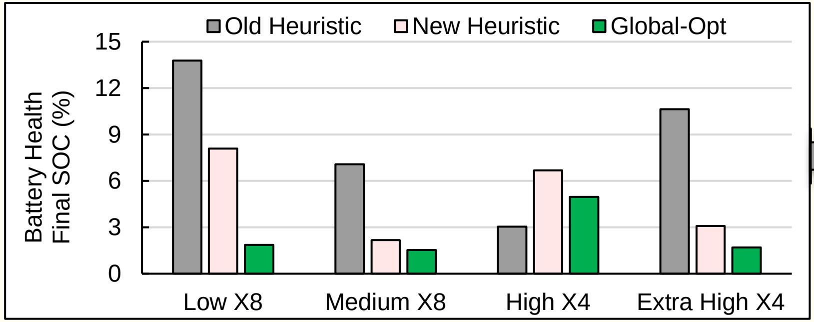
TTS brings *balance in fuel economy and battery degradation* that old heuristic is lacking

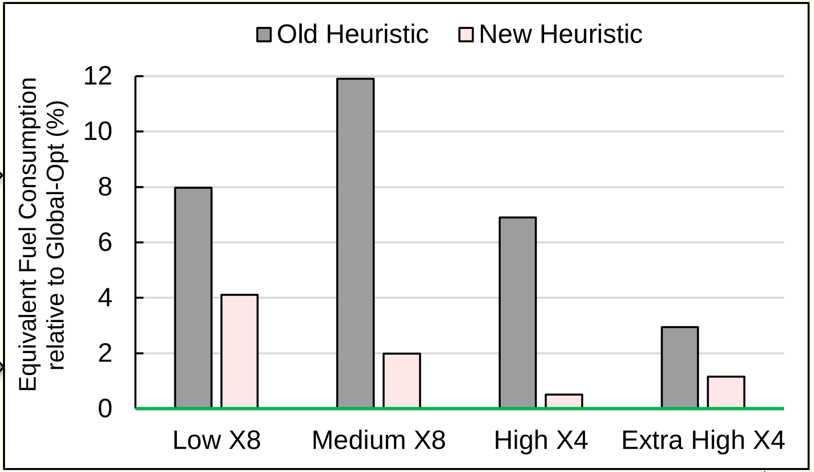
Control Strategy Development: Results (1)

For graphs, Lower = Better



Increasing Power Demand





Increasing Power Demand

TTS brings *balance in fuel economy and battery degradation* that old heuristic is lacking

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Control Strategy Development: Further Improvements

Control strategies that facilitate *optimal operation* in a parallel HEV

1) Global optimization-based (GECMS)

✓ Best-case vehicle performance

✗ Complex optimization procedure
Unrealistic global criterion

AND

2) Novel heuristic (TTS)

✓ Practical and easy to implement
Improved performance over old heuristic

✗ Slight sub-optimal battery performance
(Pure heuristic definition limit)

Control Strategy Development: Global Heuristic

Control strategies that facilitate *optimal operation* in a parallel HEV

1) Global optimization-based (GECMS)

✓ Best-case vehicle performance

✗ Complex optimization procedure
Unrealistic global criterion

AND

2) Novel heuristic (TTS)

✓ Practical and easy to implement
Improved performance over old heuristic

✗ Slight sub-optimal battery performance
(Pure heuristic definition limit)

End: Global Heuristic Strategy (Global TTS)

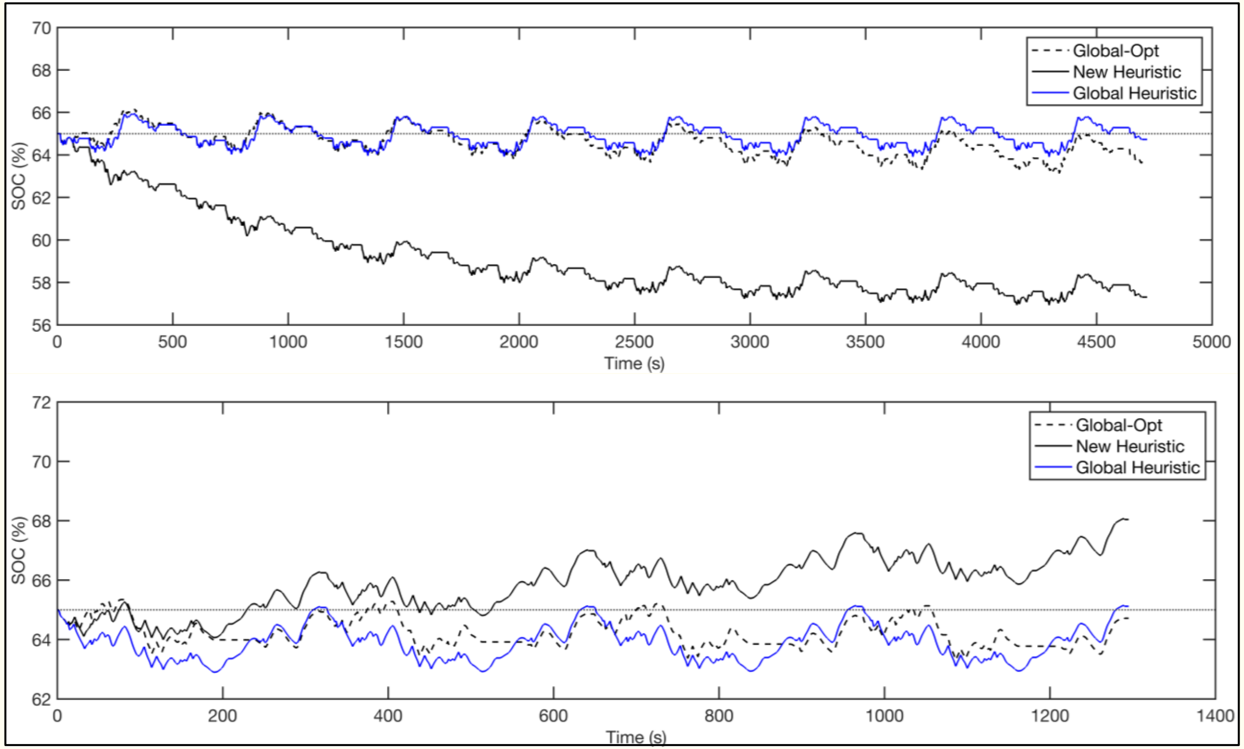
✓ **Dedicated drive cycle optimization**
AND
✓ **Retaining rule-based simplicity and practicality**

Control Strategy Development: Results (2)

Battery SOC simulation:
$SOC_{initial} = 65\%$
$SOC_{lower} = 50\%$
$SOC_{upper} = 80\%$

Low X8

Extra High X4



Dashed – Global-optimized
- Benchmark-case

VS

Black – New Heuristic
- Strict heuristic definition limit

VS

Blue – Global Heuristic
- **Significant charge-sustaining gains with dedicated parameter tuning**

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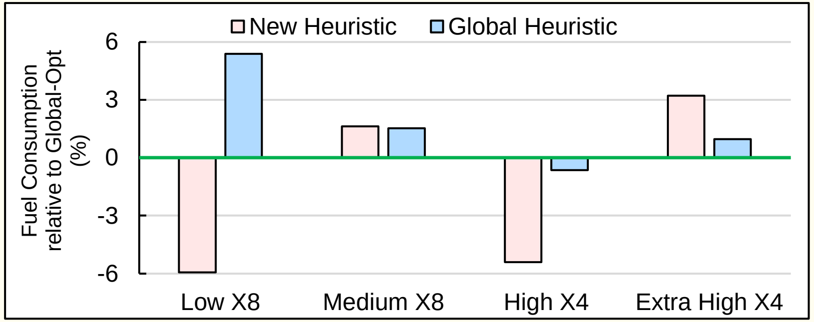
Control Strategy Development: Results (2)

For graphs, Lower = Better



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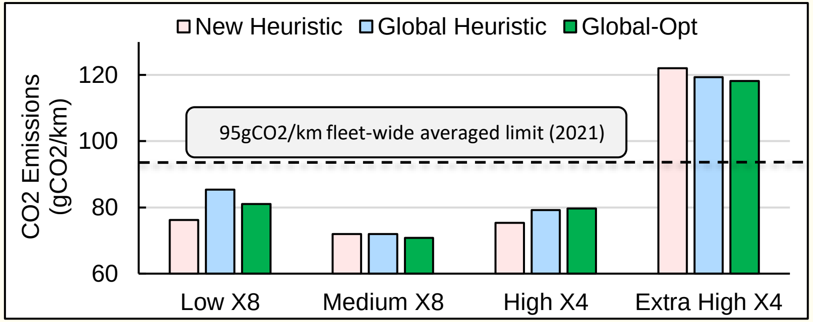

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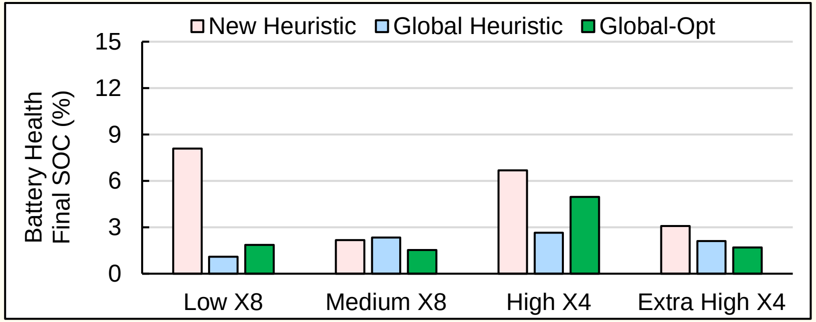

Battery ageing improvement (lower bound)	Low X8	Medium X8	High X4	Extra High X4
New → Global Heuristic TTS	>6.8%	≈0%	>3.9%	>1.0%

Value of global heuristic = *maximization of battery health*
Potential outperformance of global-optimized methods

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Control Strategy Development: Results (2)

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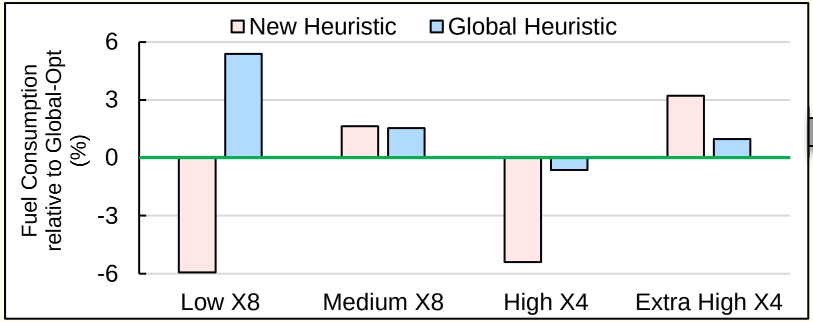

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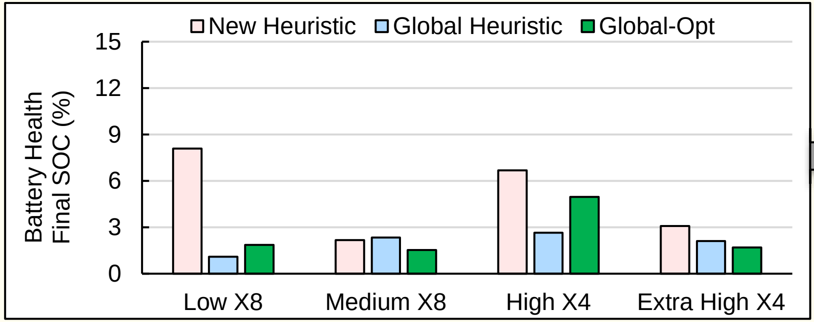

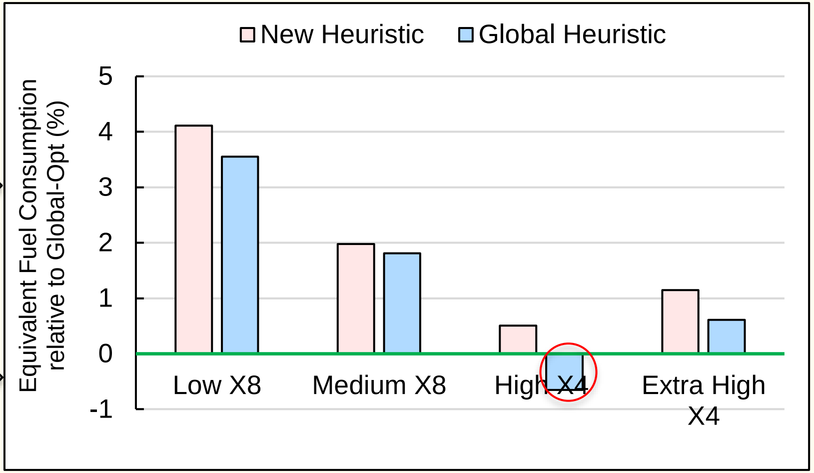

Increasing Power Demand

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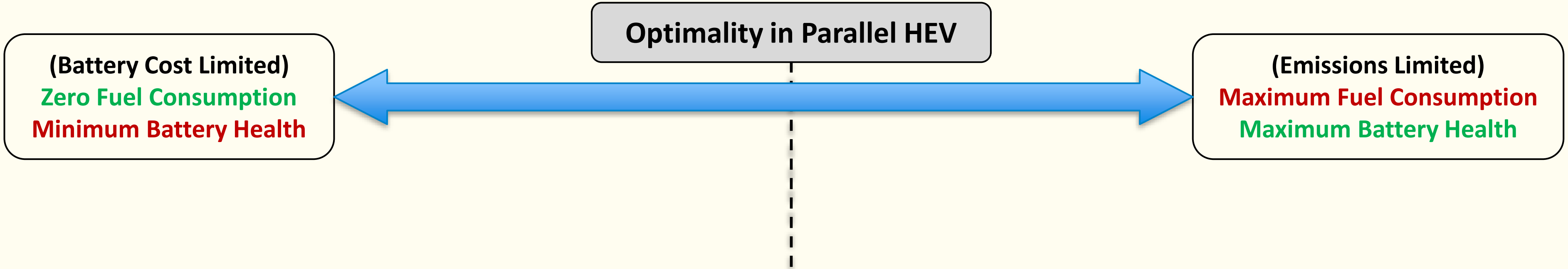
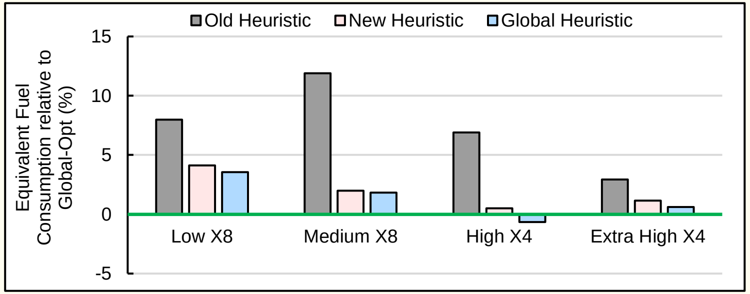
Optimality in Parallel Hybrids: Final Comparisons



Hybrid Fuel Economy



Maximizing battery health

Battery ageing improvement (min. bound)	Low X8	Medium X8	High X4	Extra High X4
Old → New Heuristic	>4%	>5%	>0.1%	>7%
New → Global Heuristic TTS	>6.8%	≈0%	>3.9%	>1.0%
Old → Global Heuristic TTS	>11.4%	>5%	>0.4%	>7.8%

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Optimality in Parallel Hybrids: Final Comparisons

Optimality in Parallel HEV

(Battery Cost Limited)
Zero Fuel Consumption
Minimum Battery Health

(Emissions Limited)
Maximum Fuel Consumption
Maximum Battery Health

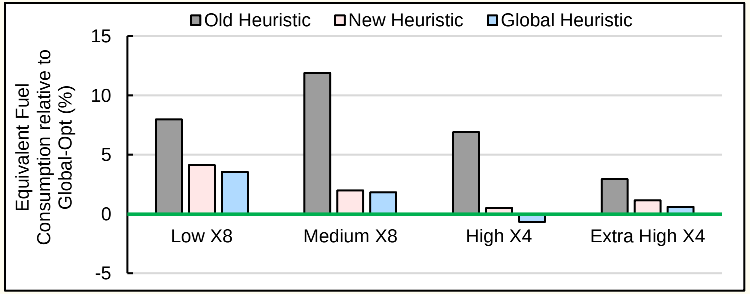
Increasing strategy complexity

Global-optimized
$\sim 10^5$ state-space 3D maps

Global TTS – Real-time Heuristic
4 sets for each drive cycle profile
GPS data + predictive switching

TTS – Simple Heuristic
1 set of 3 parameters
Universal application

Hybrid Fuel Economy



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Optimality in Parallel Hybrids: Future Development

Optimality in Parallel HEV

(Battery Cost Limited)
Zero Fuel Consumption
Minimum Battery Health

(Emissions Limited)
Maximum Fuel Consumption
Maximum Battery Health

Other forms of battery degradation:

- **Reducing current draw** to further *reduce long-term battery ageing*
- Correlates to lower operating temperatures

Increasing strategy complexity

- GECMS – Global-optimized
- Global TTS – Real-time Heuristic
- TTS – Simple Heuristic

How far can we **deviate from optimality** in the **service of further maximizing battery health?**

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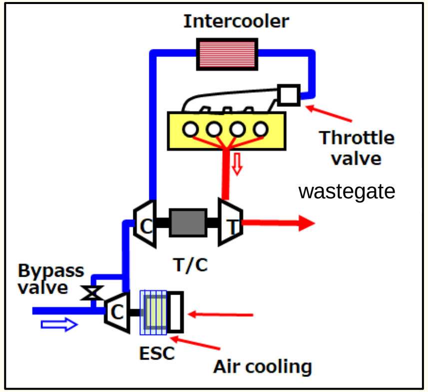
Optimality in Parallel Hybrids: Future Development

Deviating away from Optimality:
Reducing current to **further maximize battery health**

(Emissions Limited)
Maximum Fuel Consumption
Maximum Battery Health

E-booster Integration in Turbocharged Gasoline ICE

New Control Strategy: TTS with current protection



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Optimality in Parallel Hybrids: Future Development

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Maximum Fuel Consumption
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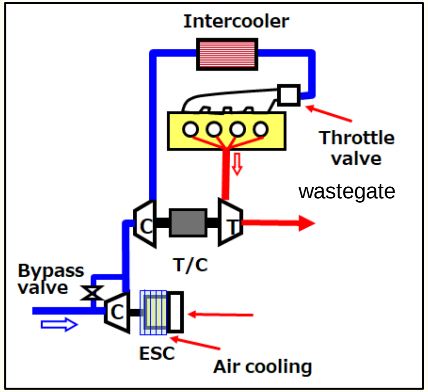
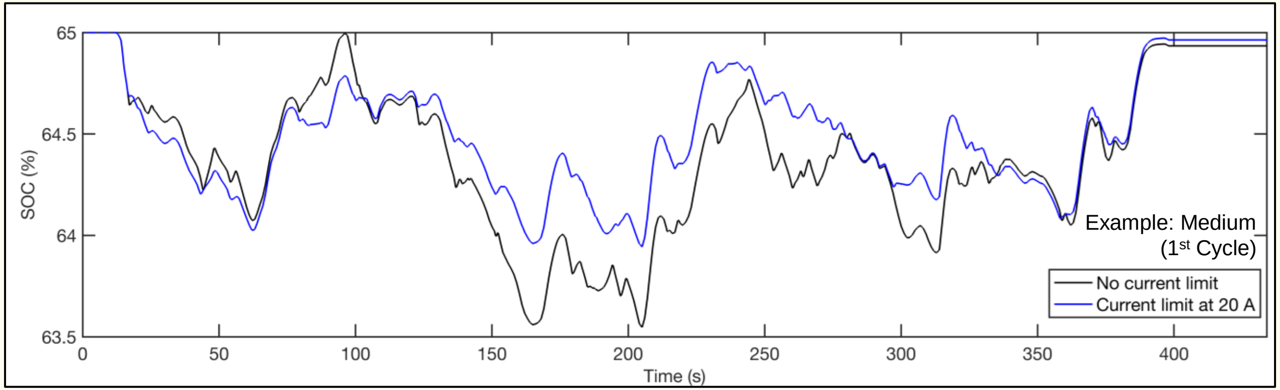
E-booster Integration in Turbocharged Gasoline ICE + New Control Strategy: TTS with current protection = Utilizing ***high-response engine*** to ***alleviate battery demand***





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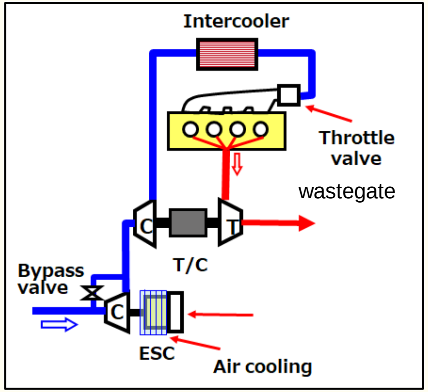

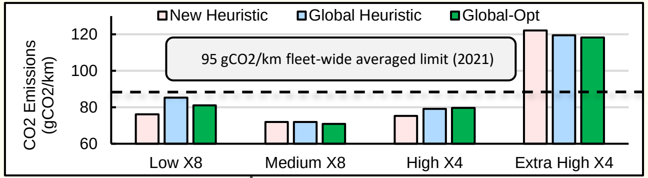

Battery ageing improvement (min. bound)	Low	Medium	High	Extra High
EACS → Global TTS	>11.4%	>5%	>0.4%	>7.8%
Global TTS → Current Protected TTS	Current research			

Penalty in fuel economy – within CO2 emission limits → Maximize current reduction potential → **Minimize long-term degradation in *power and capacity fade***

Cost

Benefit

Optimality in Parallel Hybrids: Future Development

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Reducing current to **further maximize battery health**

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Maximum Battery Health

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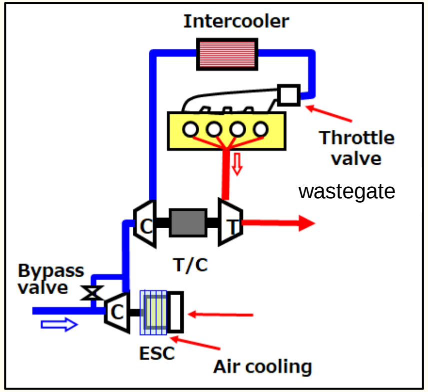

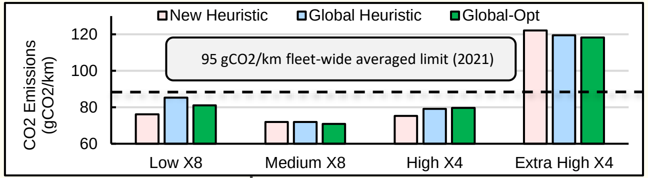

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Cost

Penalty in fuel economy – within CO_2 emission limits

Benefit

Maximize current reduction potential → **Minimize long-term degradation in *power and capacity fade***

Reward

Reduce initial battery kWh capacity specification → **Reduce cost, vehicle weight power demand material waste**

End of Presentation