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Length	36 mo.

Integrated Power and Thermal Management for Connected and Automated Vehicles (iPTM-CAV) Through Real-Time Adaptation and Optimization

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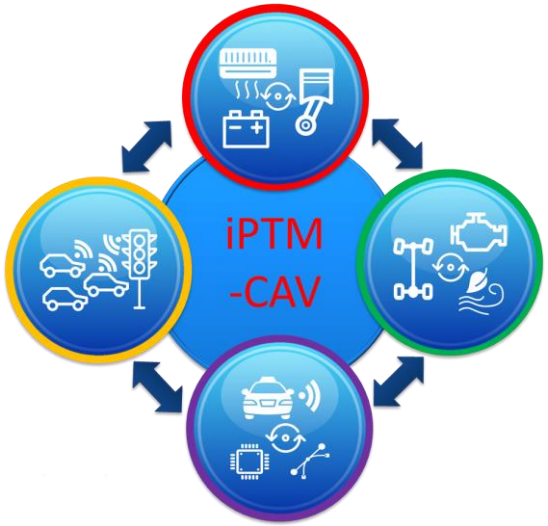
Project Goal

Achieve 20% fuel saving target for CAV by exploring power and thermal system integration in CAV through prediction and real-time optimization

Current Technical Status

Initial eco-driving testing confirms the viability of the technical approach. Further energy saving achieved through eco-cooling/heating of the cabin and battery. Implementation of iPTM on the test vehicle is underway.



Technical Accomplishments

Eco-Driving

- Design Eco-trajectories with consideration of traffic signals and queuing dynamics via V2I communication, and of cut-in intention via V2V
- Build and calibrate microscopic simulation models based on real-world traffic patterns
- Eco-driving experiments on the test vehicle

Eco-Cooling

- Real-time implementation of Hierarchical MPC (H-MPC) for cabin Eco-cooling
- Comfort-based predictive cabin Eco-cooling for improved energy efficiency

Eco-Heating

- Multi-dimensional DP for integrated engine and cabin thermal management
- PMP-based optimization for integrated power and thermal management

Integration

- Sequential optimization with Eco-driving, Eco-cooling, and power split optimization

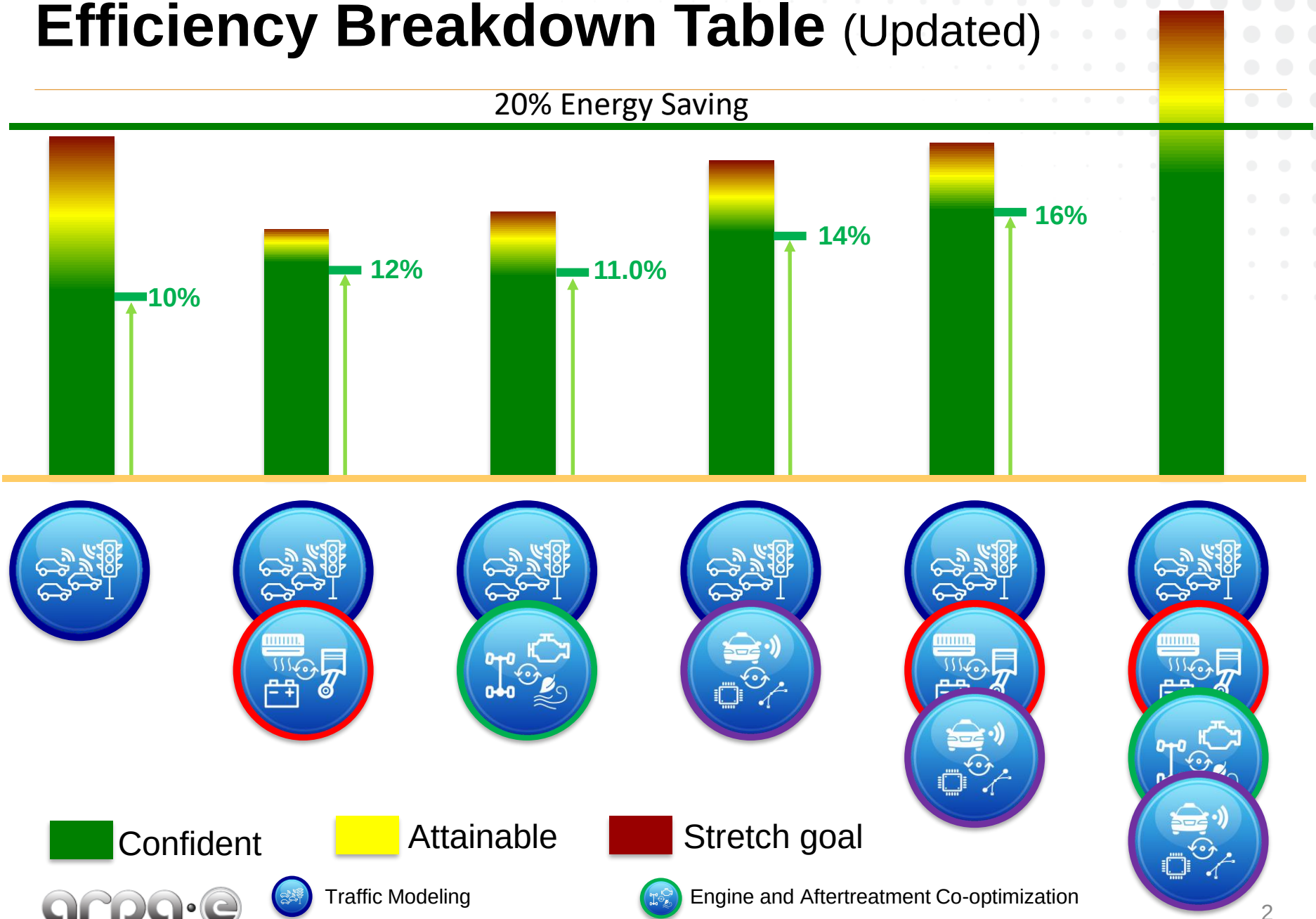
Battery Thermal Management

- High-efficiency internal battery preheating in winter
- Battery temperature optimization for reducing the energy loss exploiting traffic preview
- Hierarchical MPC (H-MPC) for EV battery Eco-cooling

Aftertreatment Co-Optimization

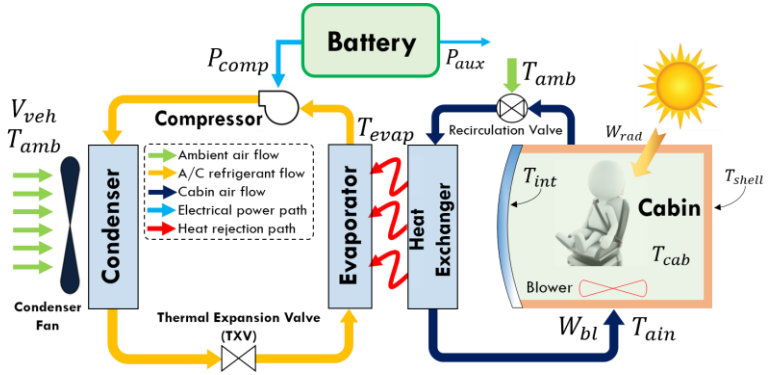
- Sensitivity analysis of the thermal responses of connected HEVs engine and aftertreatment systems to Eco-Driving
- Neural network-based co-optimization of aftertreatment and powertrain with incorporated traffic preview

Efficiency Breakdown Table (Updated)

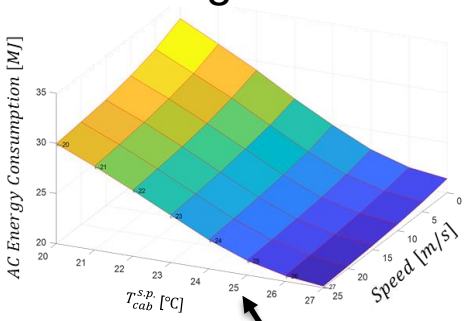


Hierarchical MPC (H-MPC) for Cabin Eco-Cooling

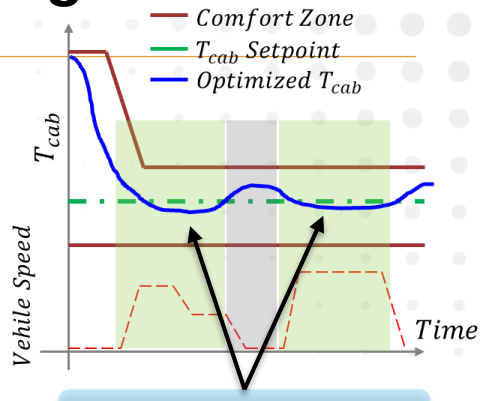
System: A/C and Cabin



Eco-Cooling via H-MPC

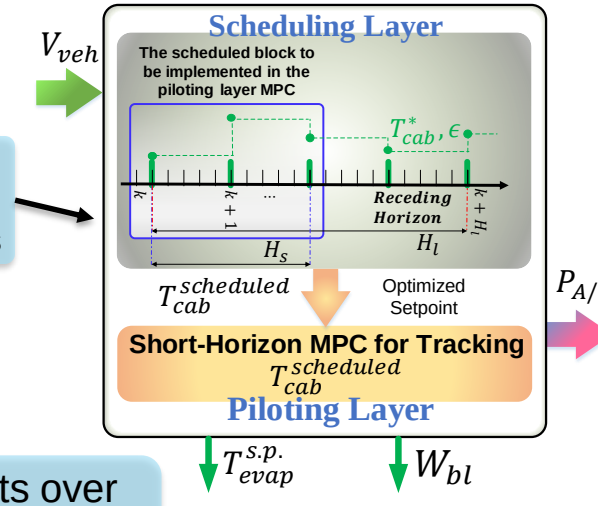


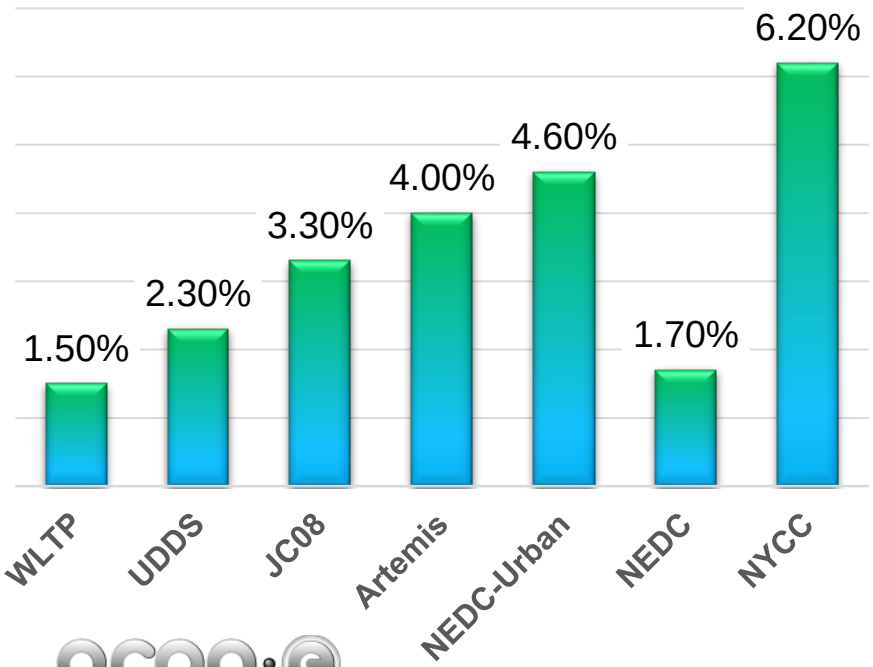
A/C system efficiency is sensitive to vehicle speed



Cabin air temp manipulated by exploiting the speed preview

H-MPC for handling time scale difference and uncertainties in predictions

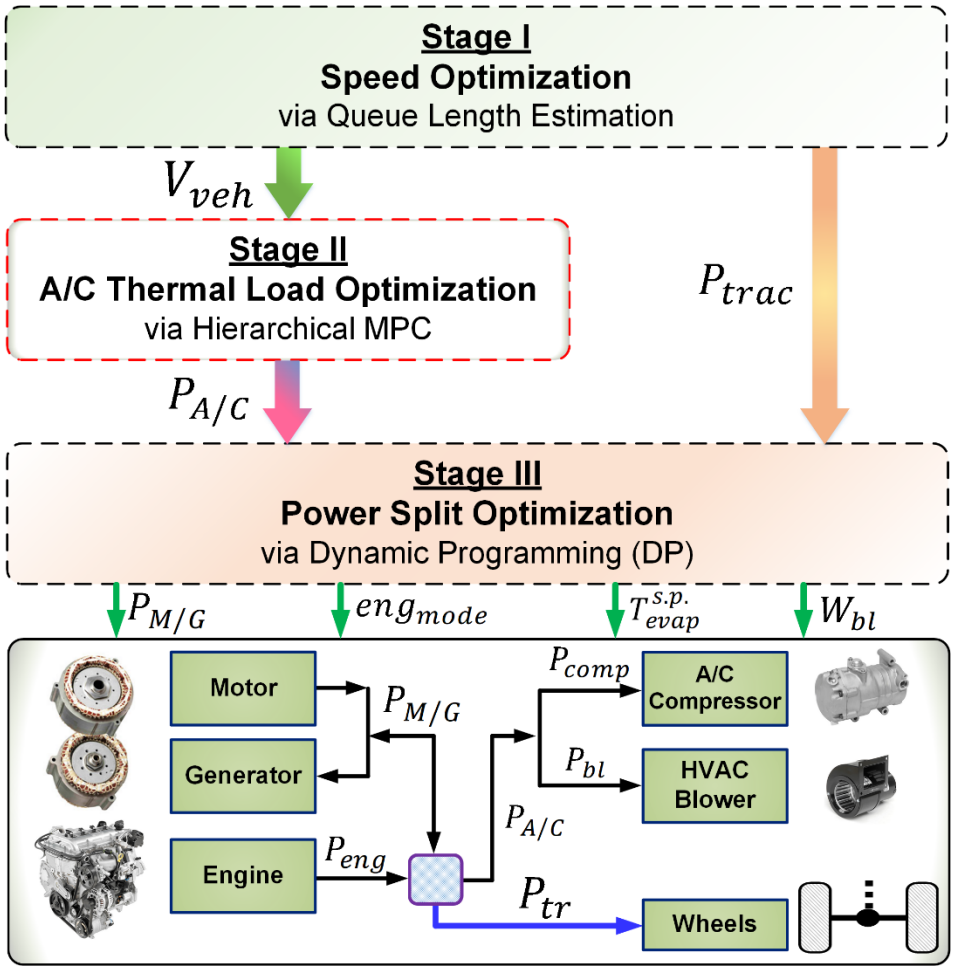




Energy saving results over different driving cycles compared with the baseline A/C for tracking constant T_{cab} setpoint

iPTM-CAVs: Sequential optimization with Eco-driving, Eco-cooling, and power split optimization

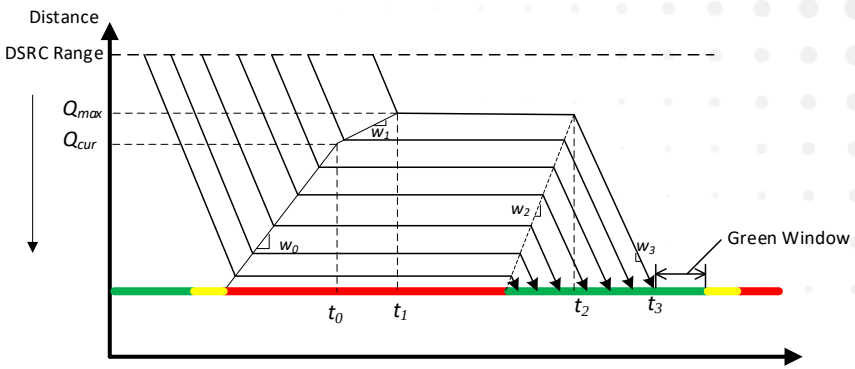
- Vehicle speed profile optimization (Eco-driving)
  - Queuing dynamics at intersection
- A/C thermal load profile optimization (Eco-cooling)
  - A/C system efficiency to speed sensitivity
- Power split optimization
  - Power balance dynamics

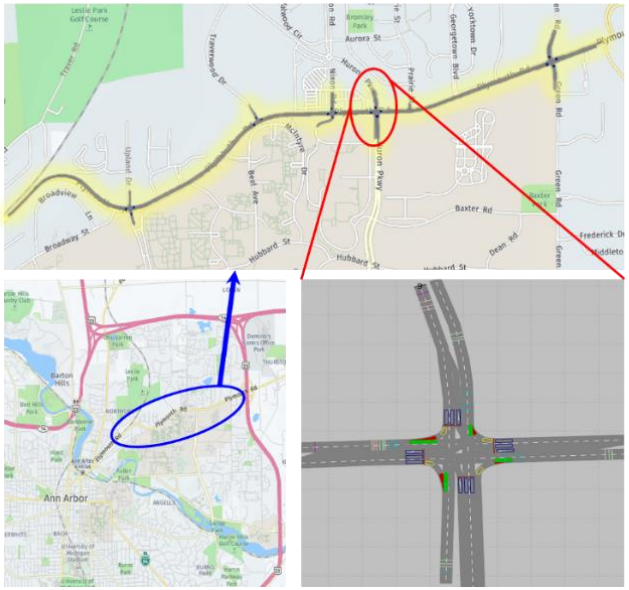


[1] Z. Yang, Y. Feng, X. Gong, D. Zhao, and J. Sun, “Eco-trajectory Planning with Consideration of Queue Along Congested Corridor for Hybrid Electric Vehicles”, Transportation Research Record, 2019.
[2] M.R. Amini, H. Wang, X. Gong, I. Kolmanovsky, and J. Sun, “Cabin and battery thermal management of connected and automated HEVs for improved energy efficiency using hierarchical model predictive control,” submitted to IEEE Transactions on Control Systems Technology, July, 2018.
[3] M.R. Amini, X. Gong, Y. Feng, H. Wang, I. Kolmanovsky, and J. Sun, “Sequential Eco-Optimization of Speed, Thermal Load, and Power Split in Connected HEVs”, 2019 American Control Conference (ACC), Philadelphia, PA, USA.

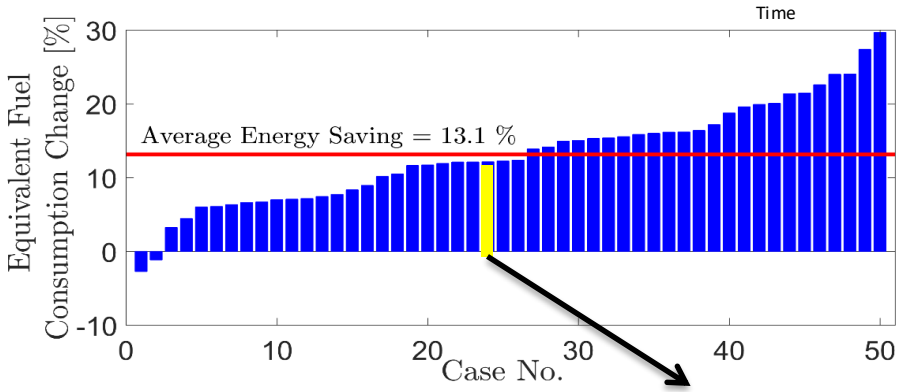
iPTM-CAVs: Sequential optimization
Stage I: Eco-driving (**CAV-Based Vehicle Speed Optimization**)

- Plymouth Road corridor (2.2 miles, 6 intersections)
- 50 cases simulated
  - Shockwave profile model to estimate the queuing dynamics at an intersection
  - Provide a green window for Eco vehicle to plan trajectory





Plymouth Corridor, Ann Arbor, MI

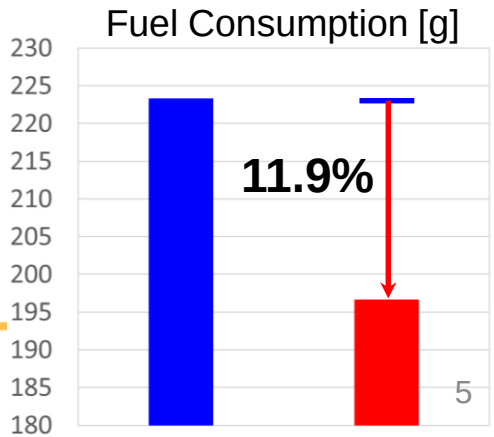


Baseline:

- The A/C controller with constant cabin temperature setpoint of 26 C
- Rule-based powertrain controller

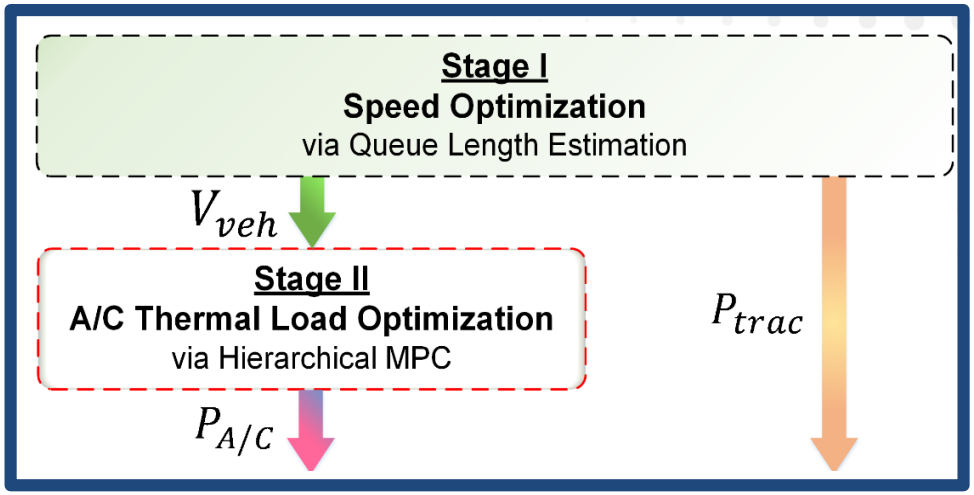
Baseline

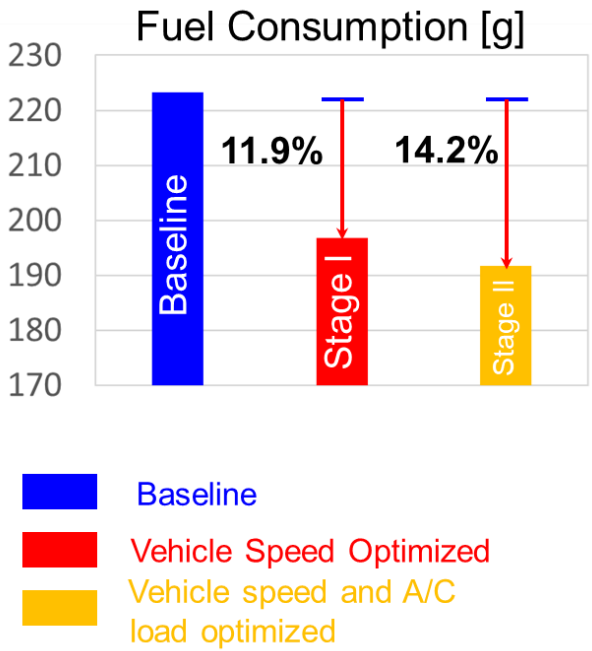
Vehicle Speed: **Optimized (eco-driving)**

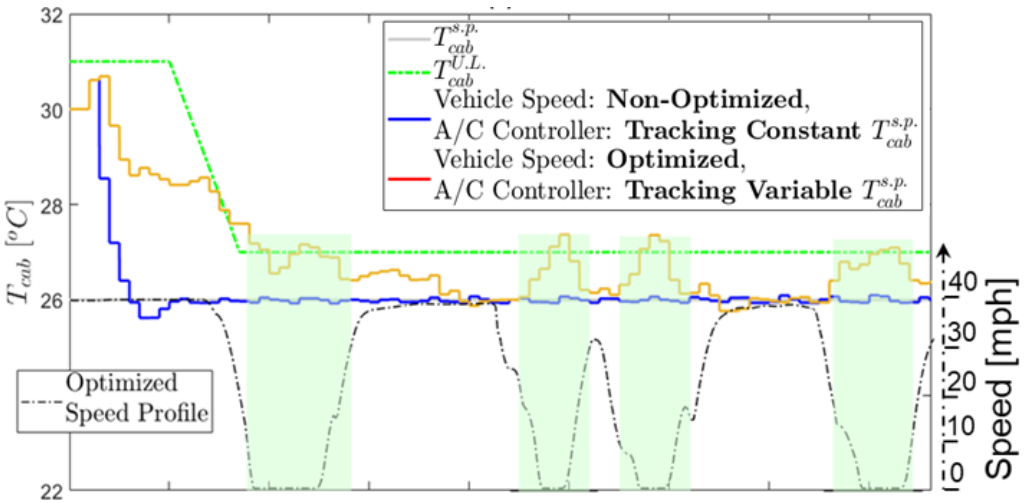


iPTM-CAVs: Sequential optimization
Stage I+II: Eco-driving + Eco-cooling (**A/C Thermal Load Optimization**)

- Optimize A/C power load by exploiting
  - Predictive vehicle speed information
  - Compressor efficiency sensitivity to vehicle speed
  - Cabin as thermal energy storage

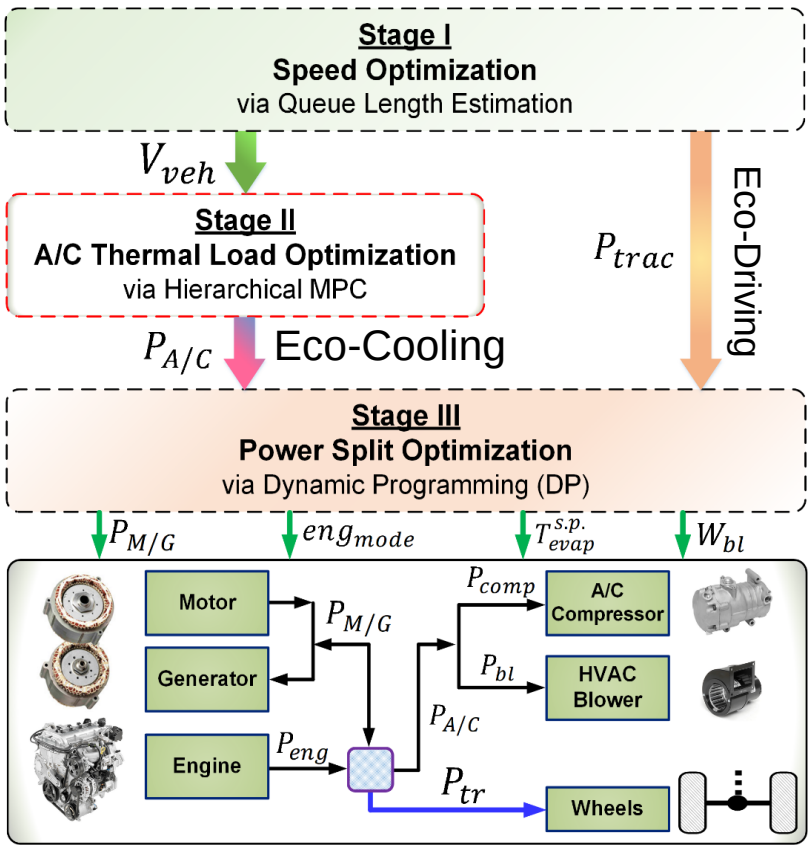


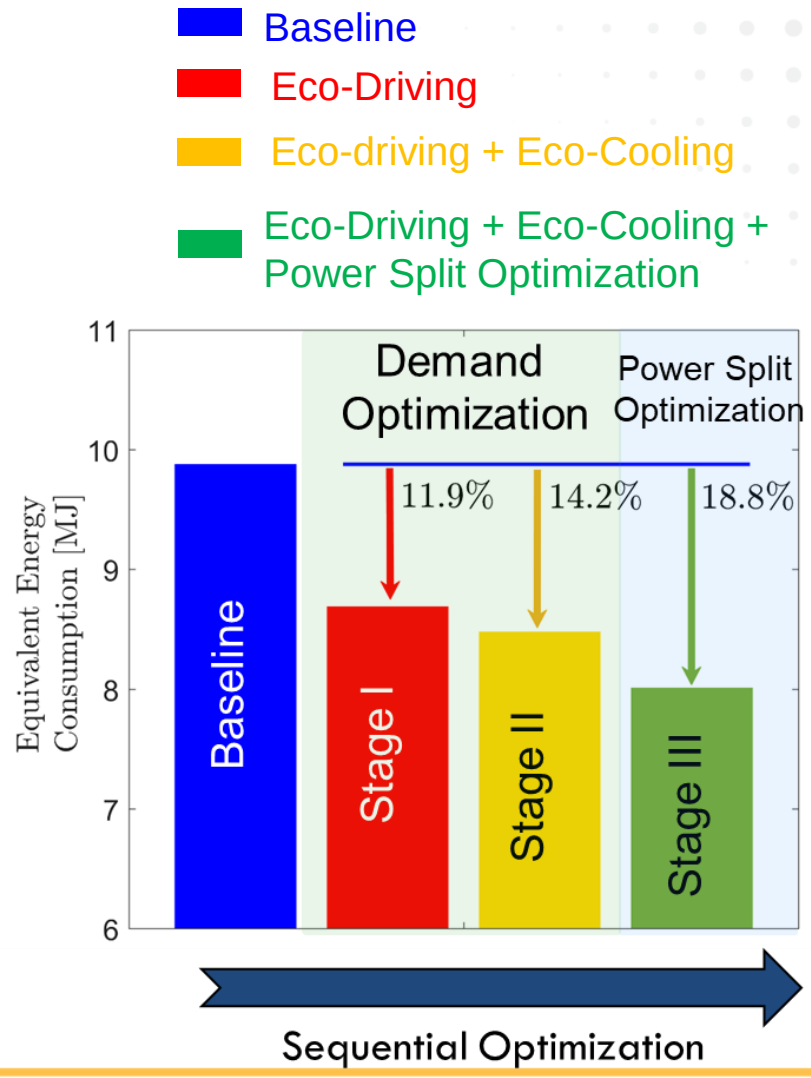




iPTM-CAVs: Sequential optimization
Stage I+II+III: Eco-driving + Eco-cooling + Power Split Optimization

- HEV optimal power management with optimized power and thermal load demands





[1] M.R. Amini, X. Gong, Y. Feng, H. Wang, I. Kolmanovsky, and J. Sun, "Sequential Optimization of Speed, Thermal Load, and Power Split in Connected HEVs", 2019 American Control Conference (ACC), Philadelphia, PA, USA.

Tech-to-Market Strategy

- Market Approach – new vehicles
  - Primary: OEM partnership
    - Collaboration with Ford Motor Company
      - MPC-based Precision Cooling Strategy (PCS) for Efficient Thermal Management of Automotive Air Conditioning System
      - Robust Power and Thermal Management (PTM) Incorporating Traffic Preview
        - A collaborative project has been established with Ford Motor Company since October 2018
  - Secondary: Supplier partnership
- Initial Market(s)/Value Proposition
  - **Traffic modeling**
    - Estimating real-time and predicting short-term traffic conditions to support thermal and power demand prediction
  - **Predictive thermal management**
    - Modeling battery thermal status to support a battery thermal management to enable operation at optimum temperature
  - **Co-optimization of engine and after-treatment**
  - **Real-time optimization**
    - Integration of climate control system with the powertrain system for HEV
- Verification and Validation
  - Mcity
  - American Center for Mobility

Key Lessons Learned & Main Findings

- Major fuel/energy consumption benefits come from eco-trajectory planning
- Due to the time-scale difference between the power and thermal systems, multi time-scale and multi-layer optimization approach is required for iPTM
- Incorporating the traffic preview allows for effective thermal load shift
- Integrated engine thermal and cabin heating optimization allows for eco-heating and further energy saving in winter
- Eco-driving could impact the thermal responses of the engine and aftertreatment system unfavorably
- Reducing the battery internal loss is the key to save energy in battery thermal management system

Current Challenges

- Reliability of long-term predictions of the traffic states required for eco-driving and eco-cooling
- Robustness of Eco-Cooling/Heating to uncertainties associated with long-term traffic prediction
- Implementation of Eco-Cooling/Heating strategies on the test vehicle given the limited control authority over the test vehicle
- Robustness of the trajectory planning algorithm to the change of penetration rate of CAV and its impact on the fuel economy