HEV Control Strategy for Real-Time Optimization of Fuel Economy and Emissions

Valerie H. Johnson
Co-authors: Keith B. Wipke, David J. Rausen

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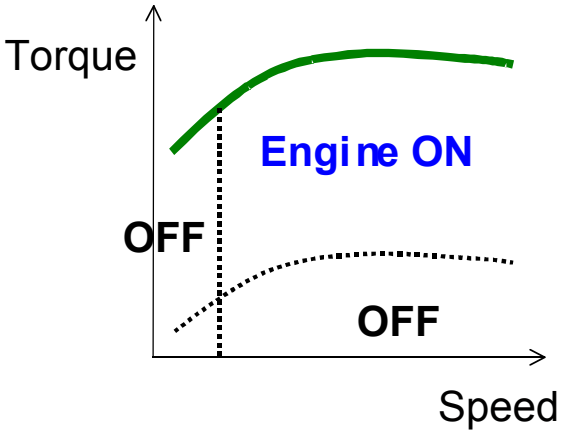
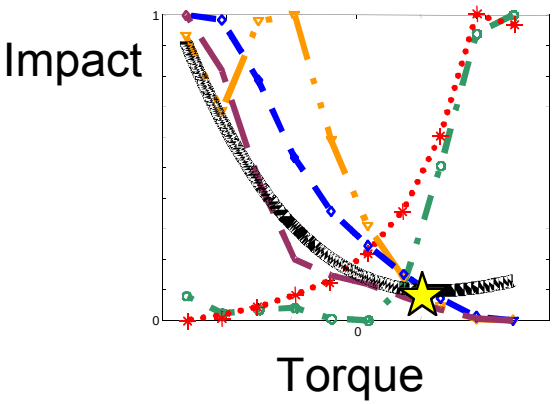
Outline

- Motivation and Introduction
- Guiding Concepts in Real-Time Control Strategy (RTCS)
- RTCS Concepts Explained
- Simulation Results
- Summary of RTCS
- Conclusions and Future Work

Motivation

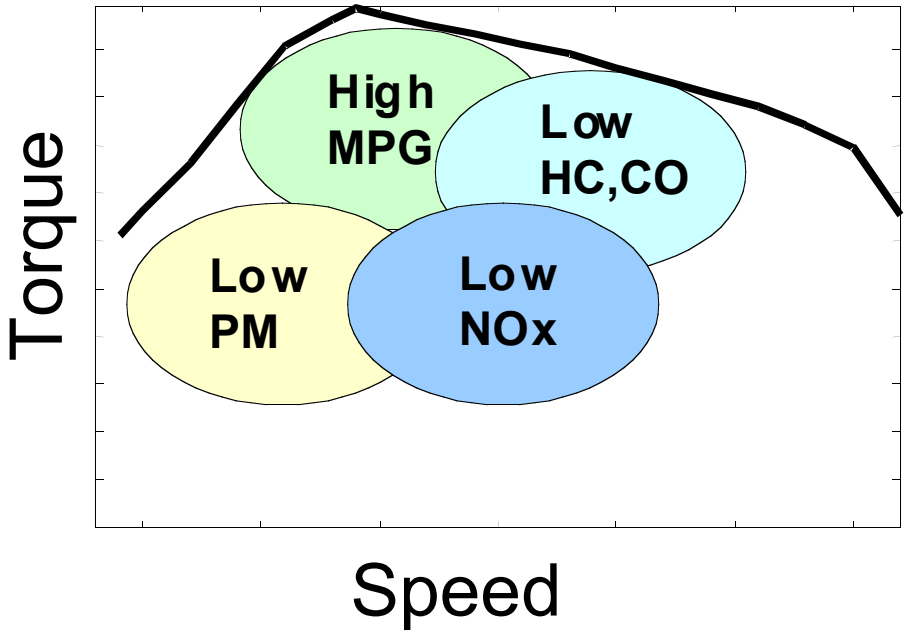
- Background: Parallel control strategies focus on energy use
  - Electric assist, motor used:
    - startup
    - low speeds, low torques
    - additional torque
  - Prius, Insight
- Goal of RTCS: Consider both fuel economy and emissions





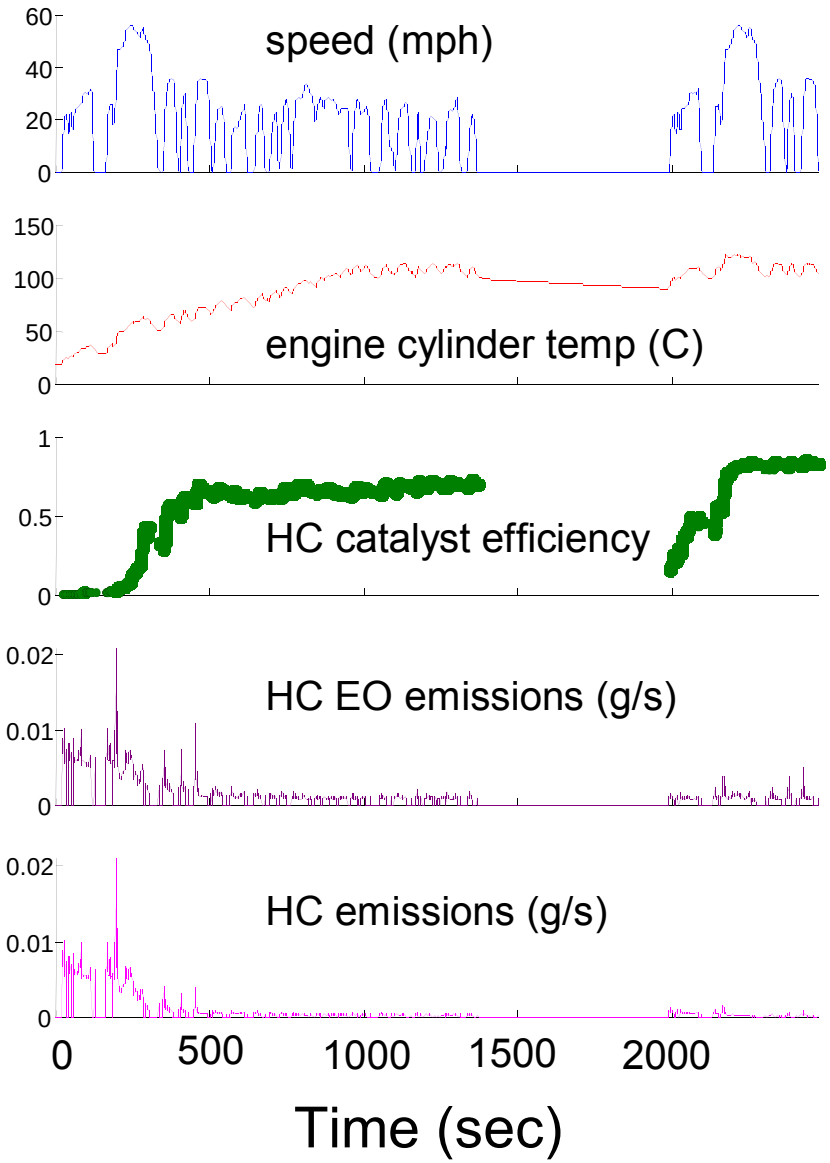
Introduction

- Tradeoffs exist between optimum operating points for ICE fuel efficiency & emissions
- Must account for the energy used by the electric side of the hybrid



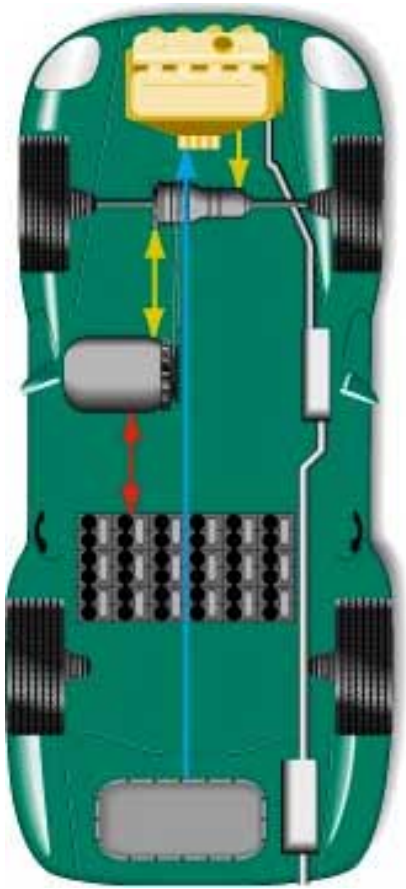
Introduction

- Emissions and fuel use vary with temperature of engine, catalyst
  - 25-55% emissions when T_{engine}<95°C
- RTCS can shift emphasis
  - cold->emissions
  - hot->fuel economy



Guiding Concepts in Real Time Control Strategy (RTCS)

- Entire vehicle optimization
  - Includes instantaneous efficiencies of engine, exhaust removal, motor, and batteries
- Real Time Optimization of operating points
  - Includes temperature effects
- Amount of free regenerative energy calculated as the vehicle drives
  - Smoothing window in time



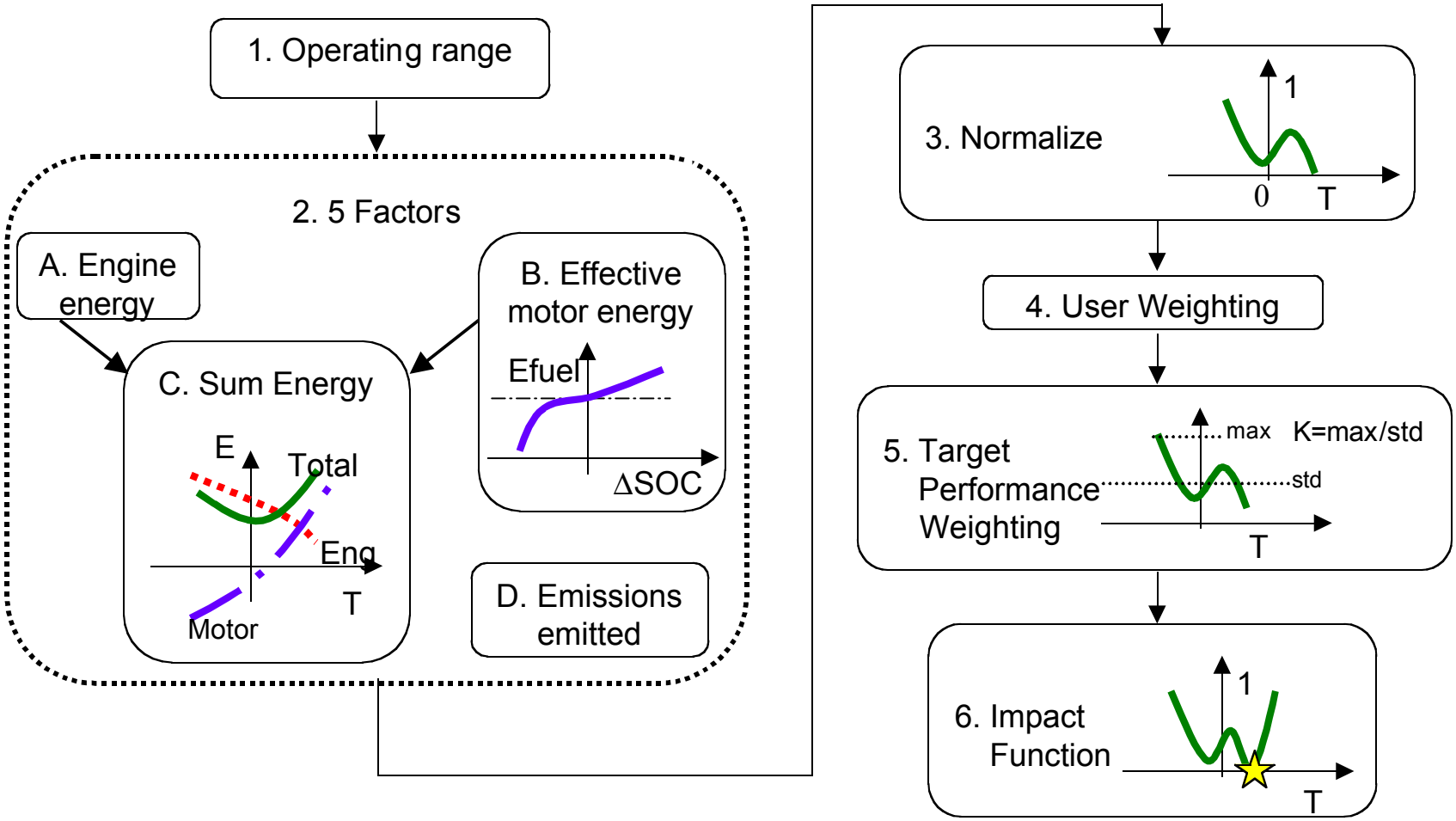
Guiding Concepts in RTCS, cont.

- User-definable targets for fuel economy and emissions
- Entire range of possible motor-engine torque combinations used
  - Optimums determined at each second
- Performance is weighted sum of instantaneous mpg and g/mi by minimizing **Impact Function**

Metric	Value	Unit
Energy	80	mpgge
HC	0.125	grams/mile
CO	1.7	grams/mile
NOx	0.07	grams/mile
PM	0.08	grams/mile

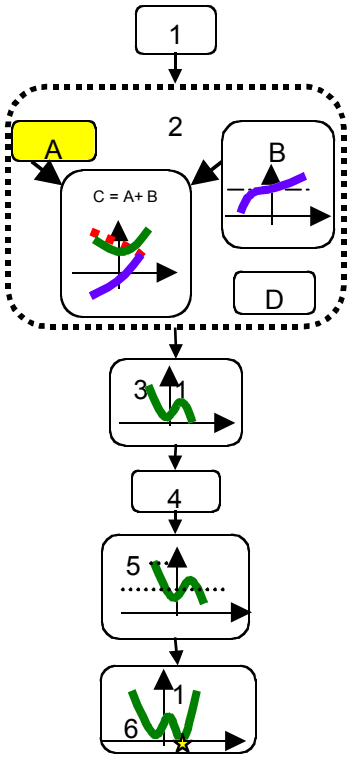
Based on PNGV goals and Tier 2 levels proposed (see www.epa.gov/oms/tr2home)

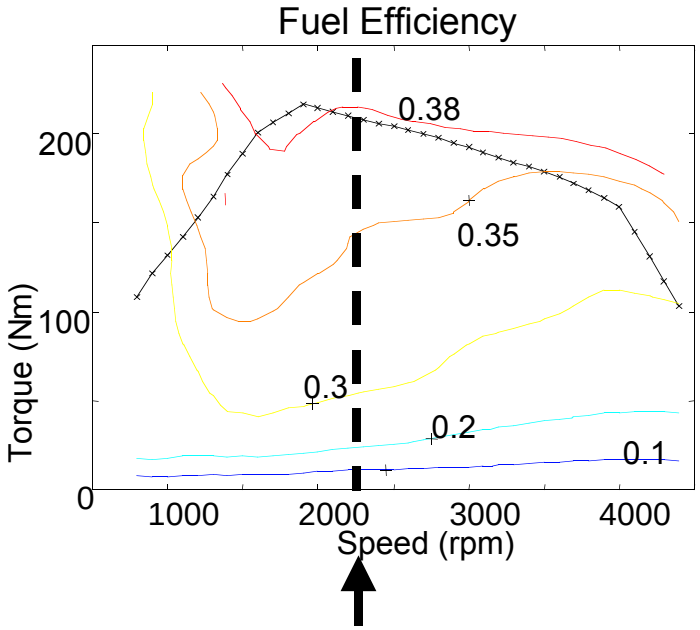
RTCS Flow Chart

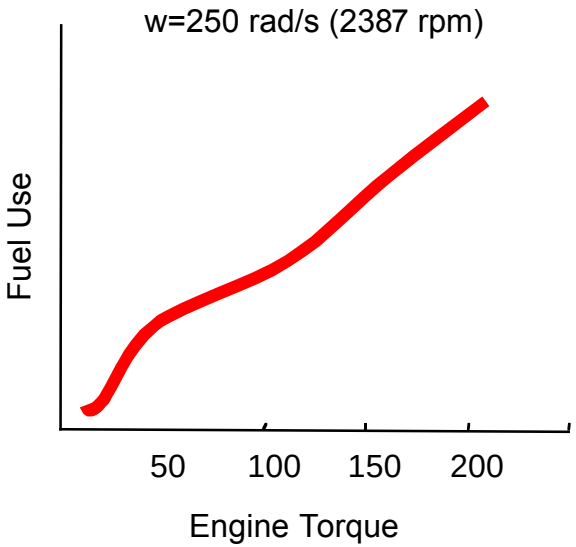


Real Time Control Strategy

Fuel Energy vs. Torque



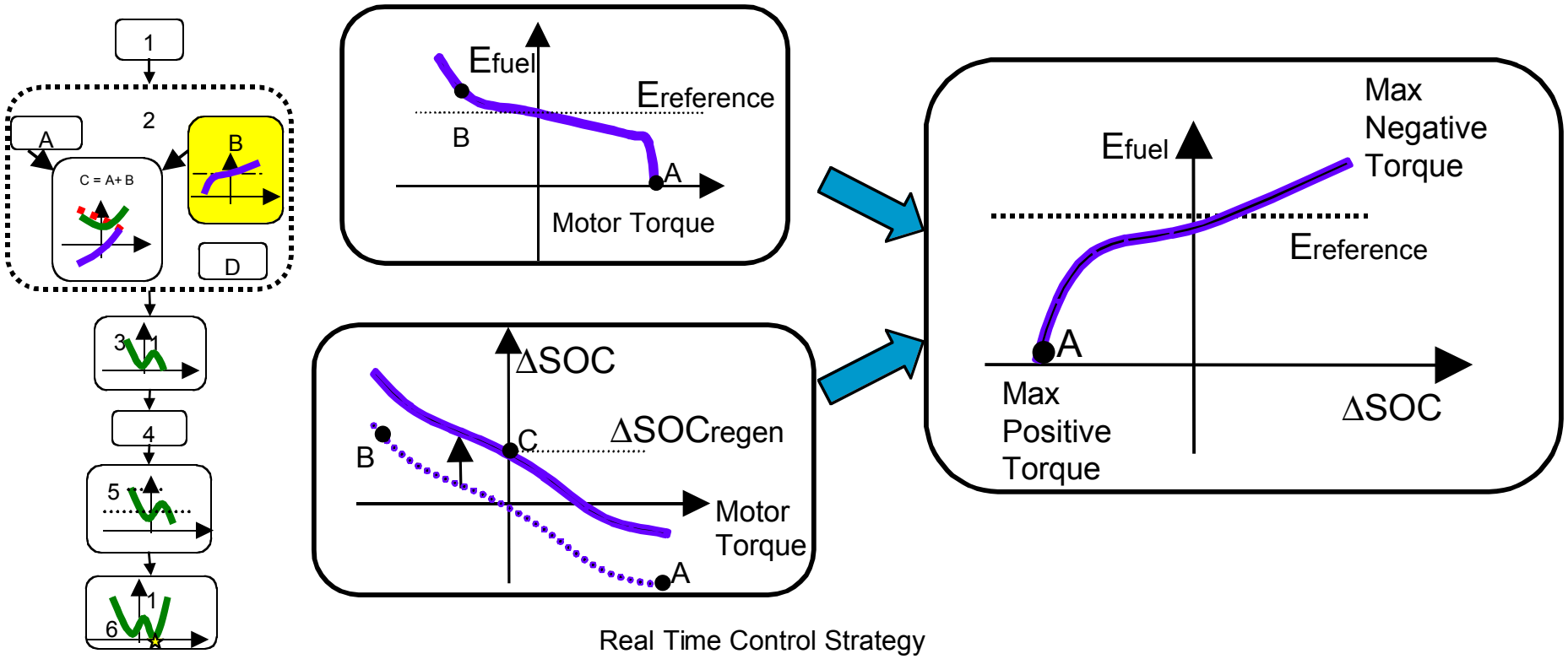




Real Time Control Strategy

Effective Motor/Battery Energy

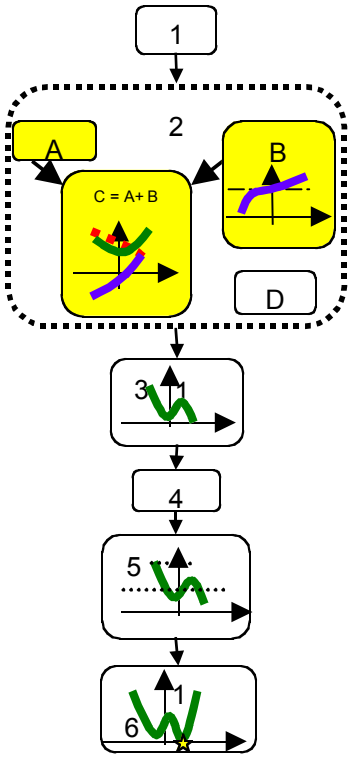
- Battery energy used is converted to an equivalent fuel
  - “Replacement-Energy” assuming similar operating conditions in the future

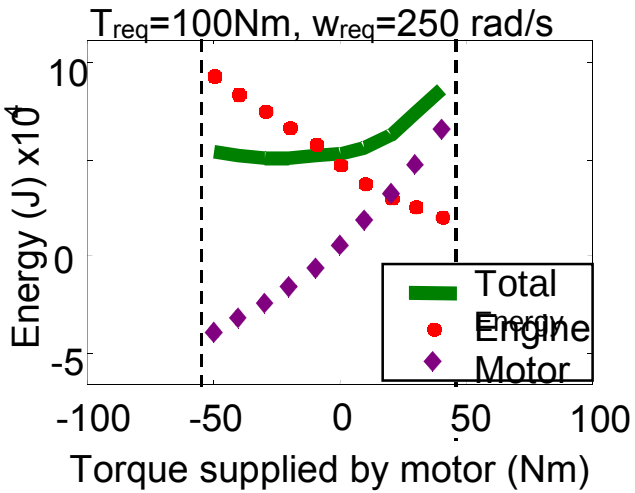


Real Time Control Strategy

Energy & Emissions vs. Torque

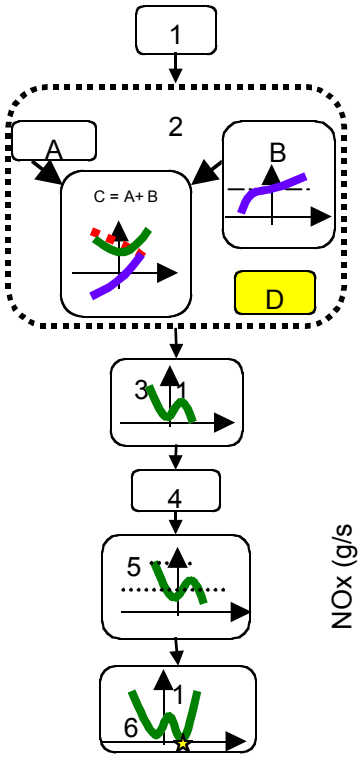
- Electrical Energy, Fuel Energy and Emissions found as they vary with torque distributions

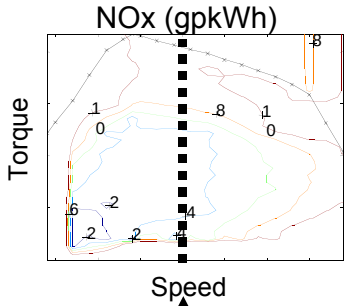


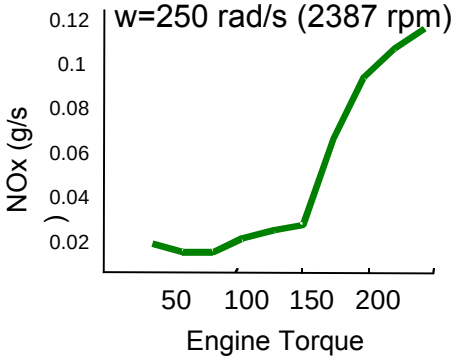


Engine, motor, or battery limited

Motor, battery, or request limited

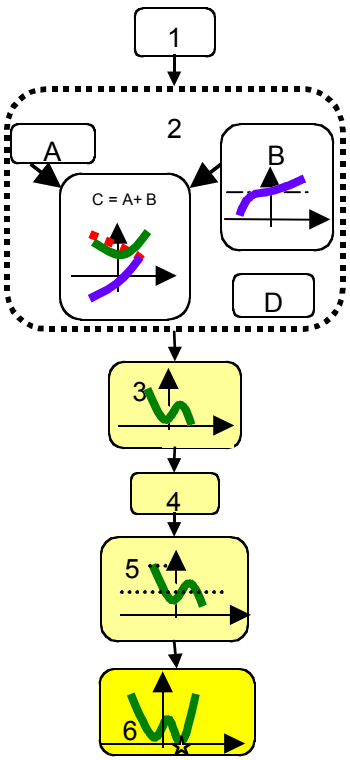




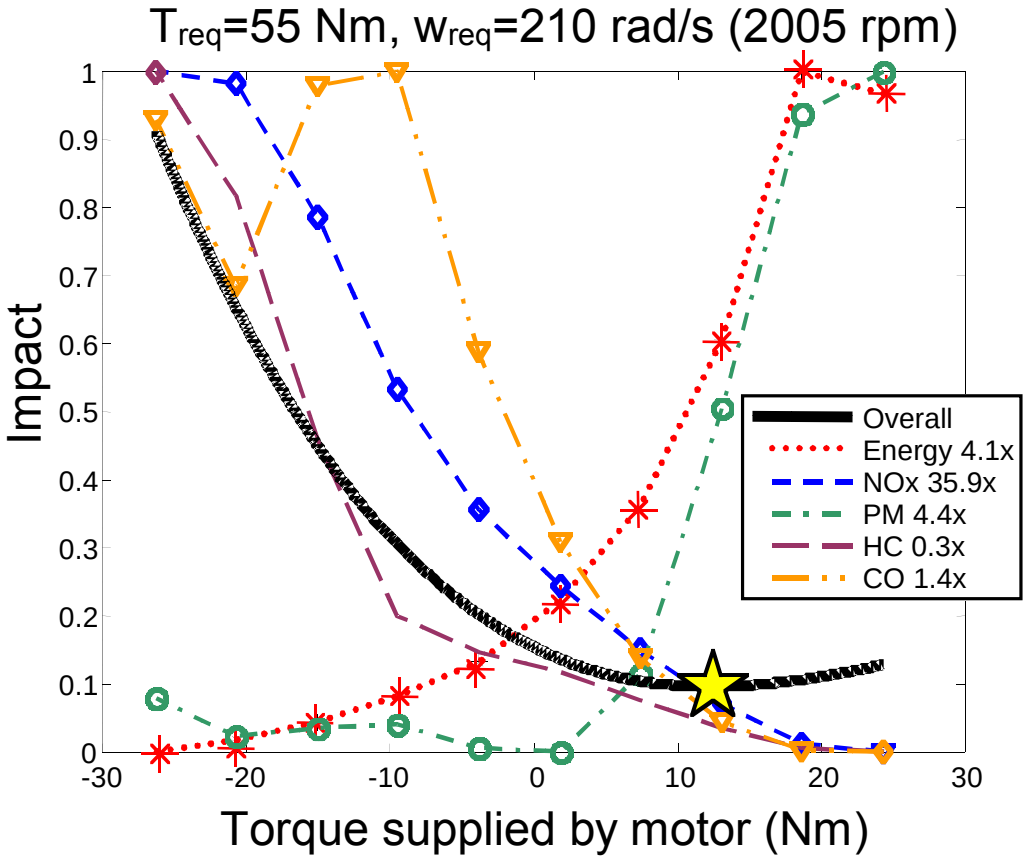


Real Time Control Strategy

Impact Function



- 5 competing metrics are combined into a single **Impact Function**
  - Normalization
  - Target performance weighting
  - Minimize



Simulation Description

- Vehicle Simulated with ADVISOR
- Cycles:
  - FTP
  - HWFET
  - US06
  - J-1015
  - NEDC
- Charge-sustaining

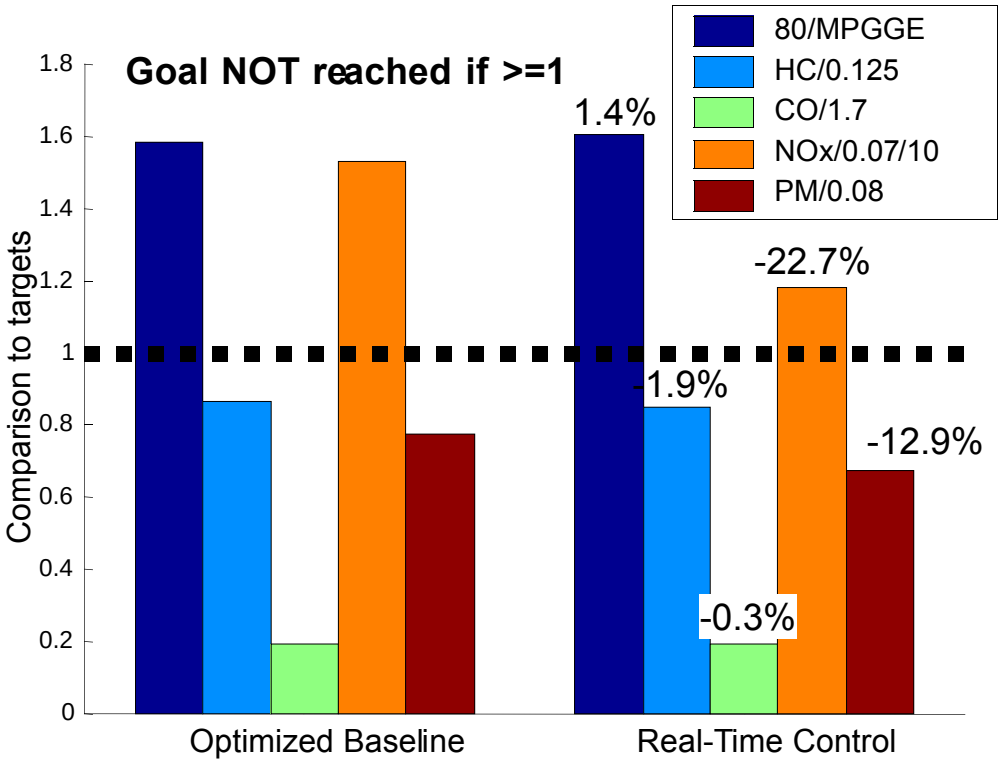
Parameter	*Value*	*Details*
Engine	42 kW	CIDI, scaled from 67kW VW 1.9L
Motor	32 kW	AC, scaled from Westinghouse 75 kW
Batteries	Twelve 18 Ah	spiral-wound lead acid
Mass	1028 kg	(2266 lbs)
Cd	0.2	
Area	2 m^2	

Simulation, cont.

- RTCS was compared to baseline parallel electric assist
  - Baseline optimized over city-highway
- These ADVISOR runs with RTCS showed a heavy reliance of operating point on NOx emissions
  - Baseline steady state map from transient tests
  - Diesel engine used
  - Currently have a temperature correction factor of 8X cold-to-hot for NOx emissions
  - Enhanced emissions modeling in ADVISOR is ongoing

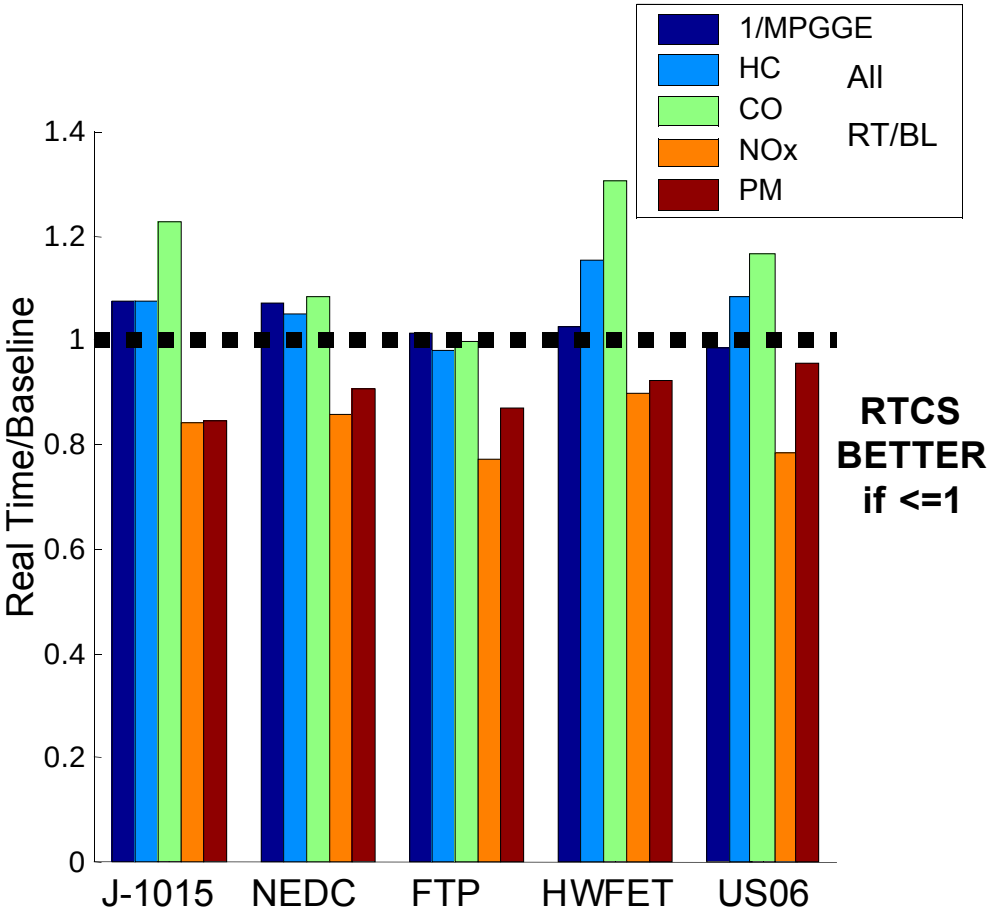
Results: Optimized Baseline and RTCS vs. Targets

- FTP cycle
  - Energy consumption increased 1.4%
  - NOx dropped 22.7%
  - PM dropped 12.9%
  - HC dropped 1.9%
  - CO dropped 0.3%



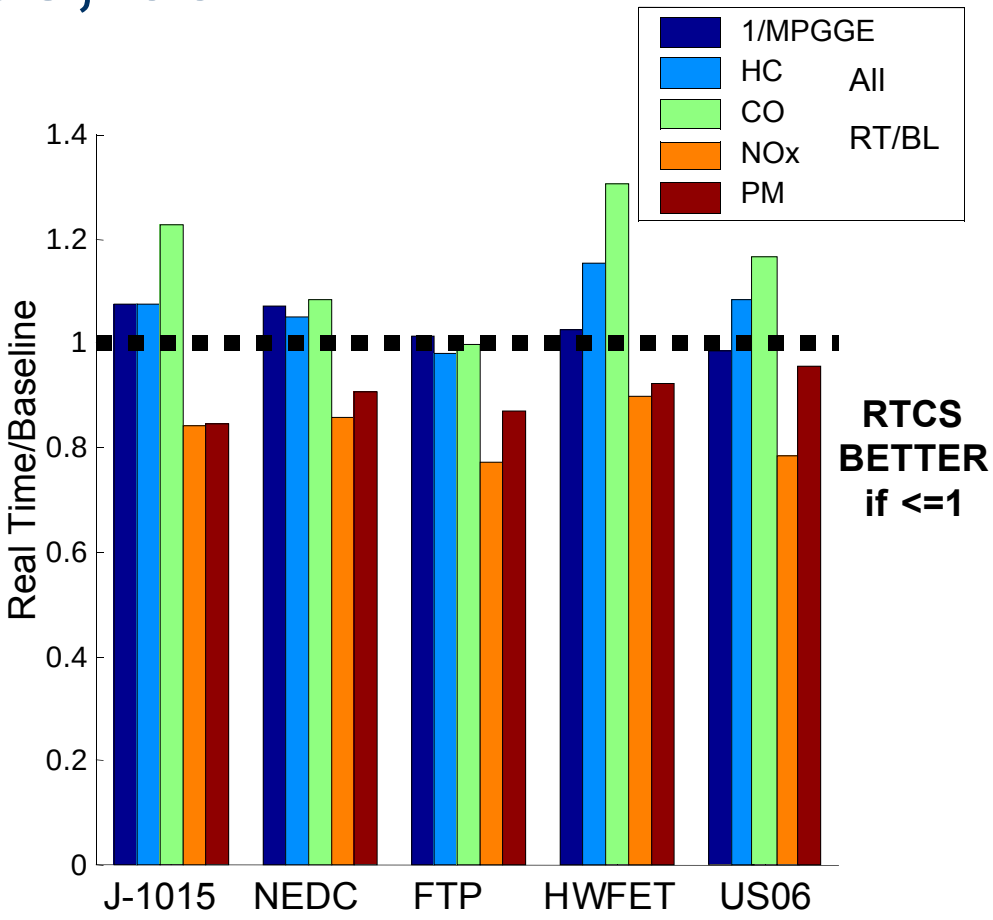
Results: Baseline vs. RTCS over multiple cycles

- NOx and PM significantly lower than baseline
  - 17% NOx and 10% PM on average
- Sacrifice of an increase in energy consumption
  - 3.4% average
- HC and CO emissions allowed to increase
  - remained below targets



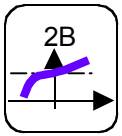
Results: Baseline vs. RTCS over multiple cycles, cont.

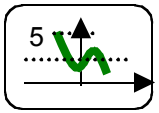
- Flexibility to adjust to drive cycles
- Optimize on the fly



Summary of RTCS

- RTCS Concepts
  - Value of battery charge quantified based on the equivalent amount of fuel to replace that battery energy
  - Relative importance of fuel economy and emissions through weightings.
  - Overall impact function predicts instantaneous cycle performance (mpg, gpm) and combines five goals into one goal





- RTCS Flexibility
  - User-selectable targets
  - Real-time adjustment to driving cycles based on expected free regenerative braking energy
  - Incorporation of temperature effects on fuel use, engine-out emissions, and catalyst behavior

Conclusions and Future Work

- RTCS Advantages
  - Significant NOx and PM emissions benefits over the optimized static control strategy for the FTP cycle (23% and 13% drop) at the price of a slight drop in fuel economy
  - Better emissions performance over a range of drive cycles, coupled with comparable energy consumption
  - Smaller variation in fuel economy over a range of cycles (Baseline: 29% down to RTCS: 16%)
- Future Work
  - Include RTCS in ADVISOR public release
  - Further RTCS development
    - Emissions penalty of battery energy
    - Shifting strategies

The End

- Paper and ADVISOR at www.ctts.nrel.gov/analysis

- Questions