National Renewable Energy Laboratory
Innovation for Our Energy Future

Route-Based Controls Potential for Efficiency Gains

2009 DOE Office of Vehicle Technologies Annual Merit Review

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Project Overview

Timeline

- Started in 2006
- End and percent complete TBD pending research outcomes

Budget

- DOE funding prior to FY08 ($250K)
- FY08 DOE funding ($75K)
- Anticipated FY09 funding
  - DOE ($75K)
  - Industry partner via CRADA ($75K)

Barrier/Mission Areas

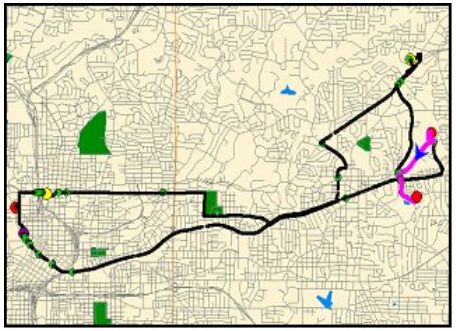
- Improve vehicle fuel efficiency
- Optimize controls
- Demonstrate/deploy technology

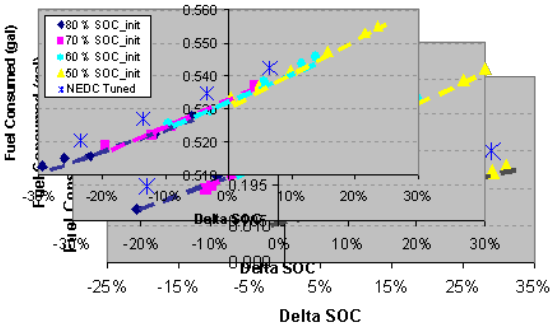
Partners

- Interactions/collaborations:
  - HEV transit bus developers
  - ORNL
  - Light-duty OEMs
- NREL is the project lead

Objective: Use route knowledge to cost-effectively improve fuel efficiency (only requires software changes)

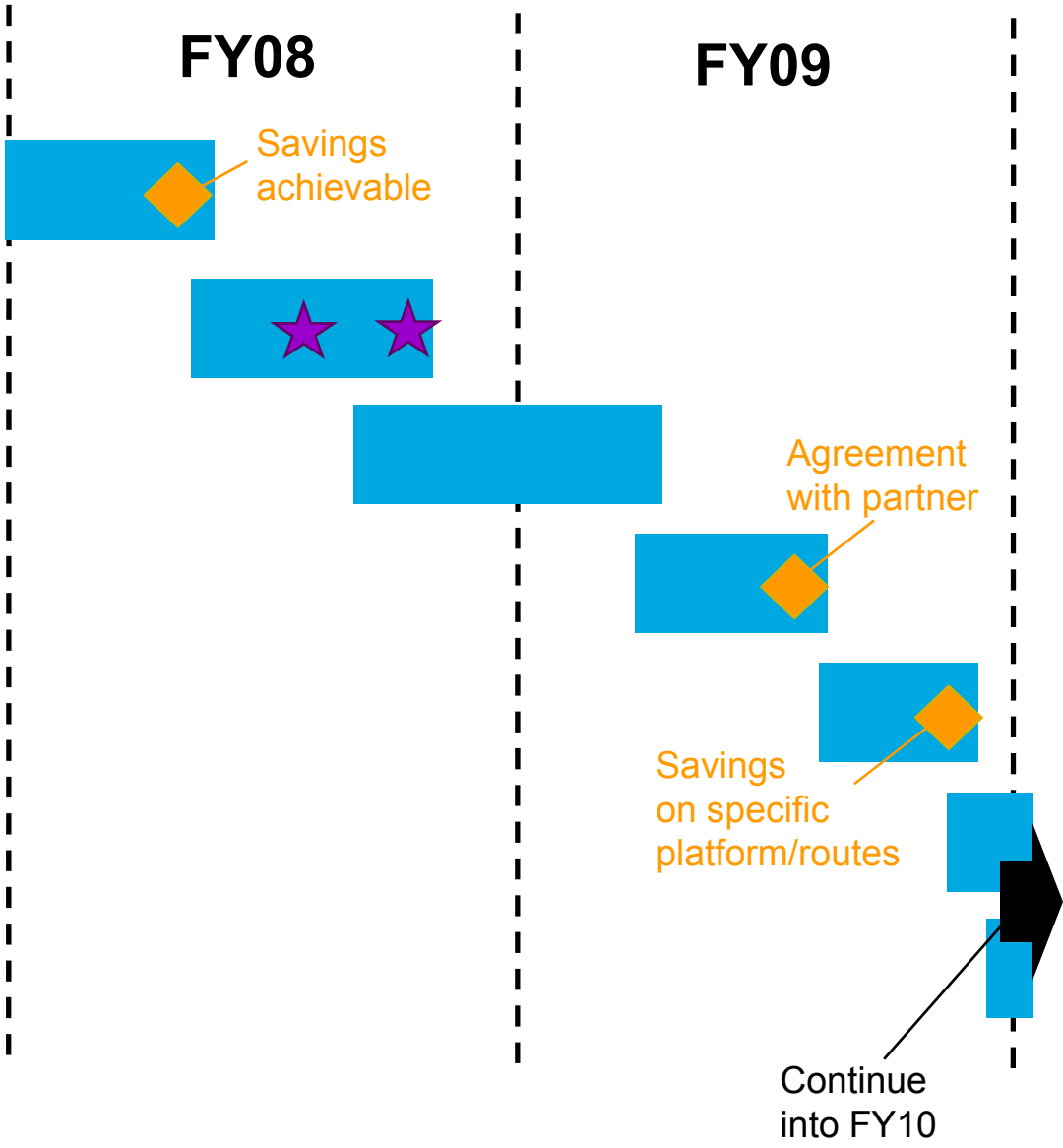
- General HEV/PHEV controls are not optimal over all cycles
  - Route-based tuning could save fuel with no recurring hardware costs
  - Increasing GPS prevalence also enables widespread application
- Current FY objective: Begin hardware validation of 2-4% fuel savings potential (predicted from prior FY simulations)
- Project supports program goals for fuel savings, other benefits
  - Evaluate advanced vehicle technology in a systems context
  - Potential battery life benefit → Reduce HEV/PHEV cost increment
  - Potential emissions benefit (pre-emptive HEV/PHEV engine start to avoid cranking while cold/under load; minimize in tunnels/city centers)





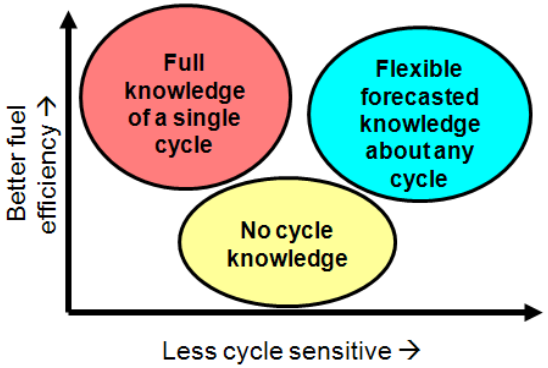
Milestones/Decisions in FY08 and FY09

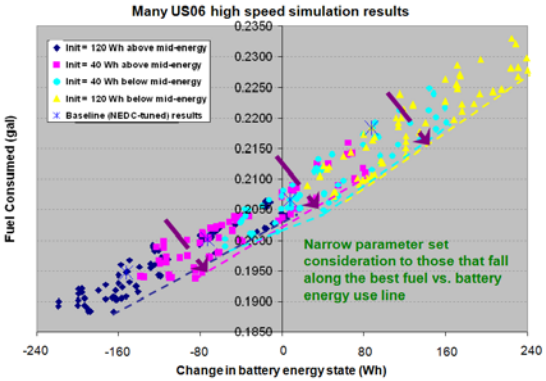
- Refine implementation approach
  - Generic HEV platform simulations
- Publish results
  - SAE paper and DOE Milestone
- Collaboration discussions
  - With potential partners
- Execute CRADA
  - With industry partner
- Predict platform-specific fuel savings
  - For partner's HEV on real routes
- Integrate control adjustments
  - Into vehicle control hardware
- Demonstrate fuel savings achieved
  - Validate simulation predictions



Approach: Long-term summary and details of industry collaboration/hardware demonstration phase

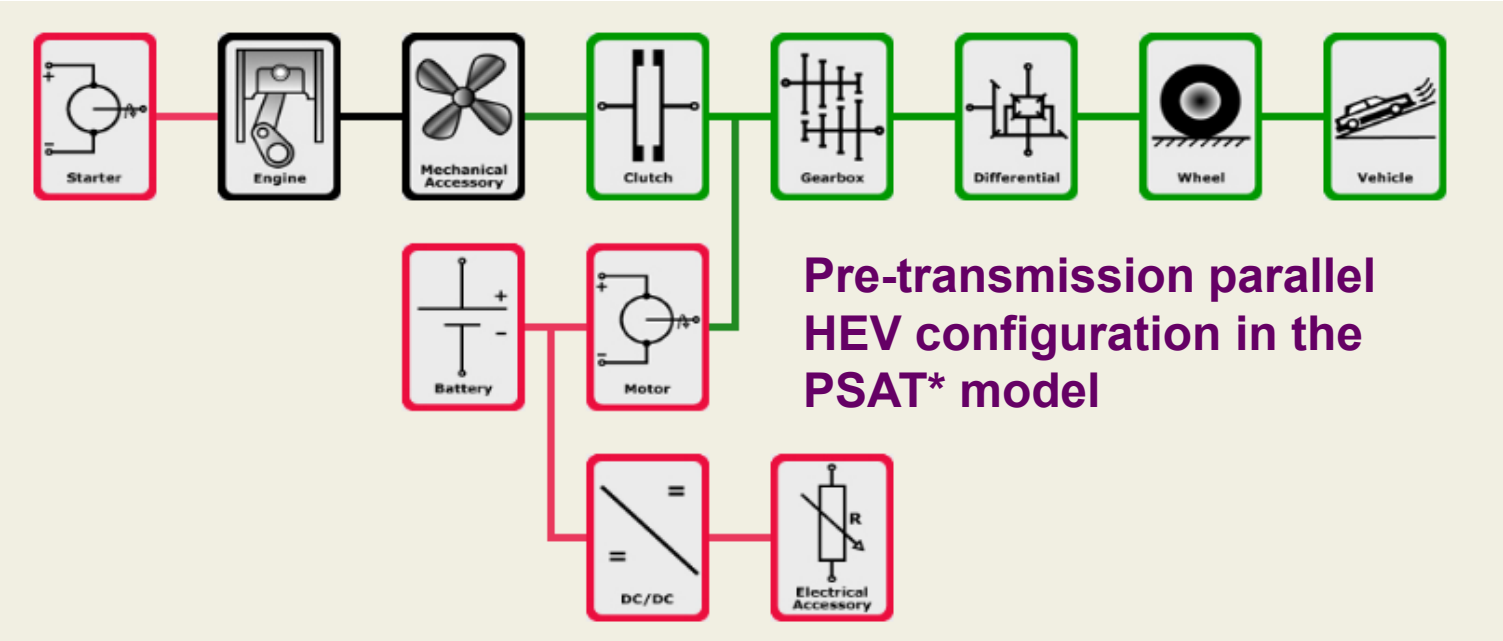
- Survey existing techniques/evaluate the opportunity
- Develop and implement route-based control (RBC) technique via simulation
- Publish results/engage potential industry partners
- Collaborate to demonstrate/verify savings in hardware
  - Start with repeatable route vehicle; collect cycles
  - Apply route-based control tuning to model of actual vehicle and controls over identified cycles
  - Implement route-based control variations into vehicle hardware (using simulation results as a guide)
  - Compare vehicle operation with route-specific controls against the baseline performance





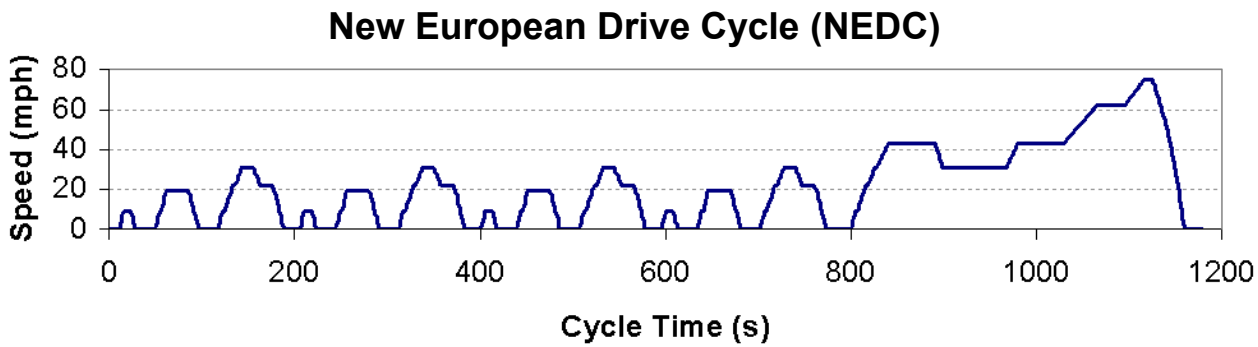
Accomplishments: Refined approach and published results using simulations with a general HEV platform

- 1540 kg midsize HEV
- 90 kW gasoline engine
- 30 kW electric motor
- ≈320 Wh usable battery energy window

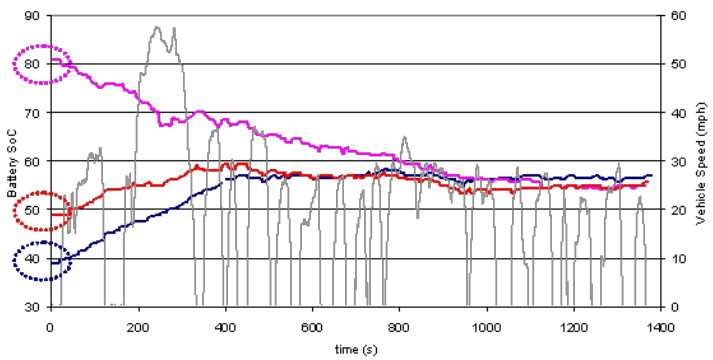


* Powertrain Systems Analysis Toolkit (PSAT) – Managed at Argonne National Lab (ANL)

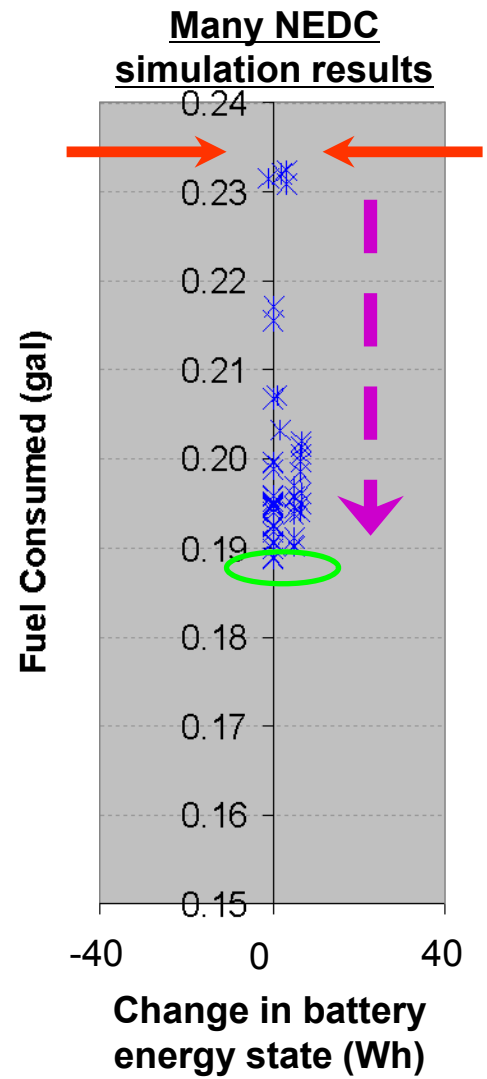
Analysis included important initial step of tuning the base comparison strategy (parametric optimization on NEDC*)



- Charge-sustaining simulations (iterate on initial battery energy state)

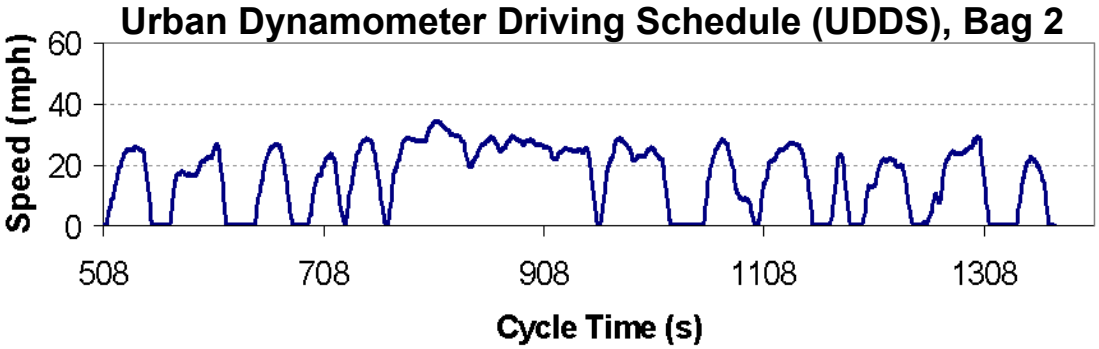


- Select control tuning(s) for minimum fuel consumption (→ two cases identified)



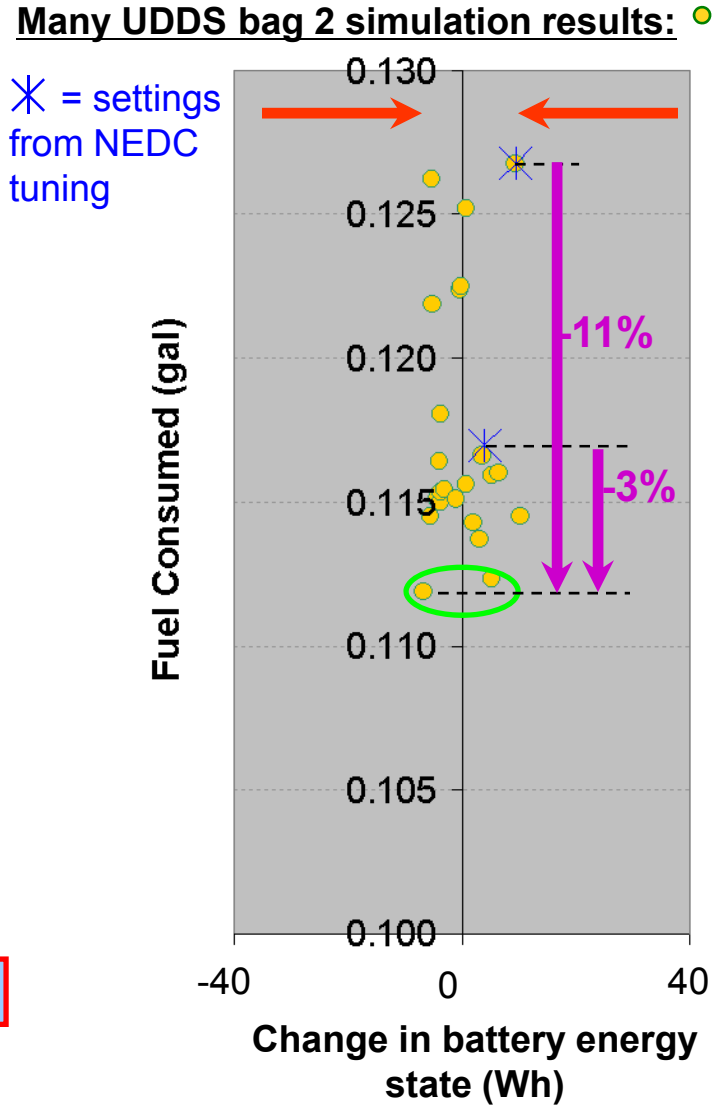
* Cycle for best general tuning suggested by: Wipke, K., Markel, T. and Nelson, D., "Optimization of Energy Management Strategy and Degree of Hybridization for a Hydrogen Fuel Cell SUV," EVS 18, 2001.

Optimizing for segments of a particular driving type can provide a noticeable improvement (≥3% for this example)



- Appreciable savings, especially if did not identify second NEDC-optimized parameter set
- Note: for multi-segment cycles, do not necessarily achieve (or desire) charge sustaining (CS) operation over each segment

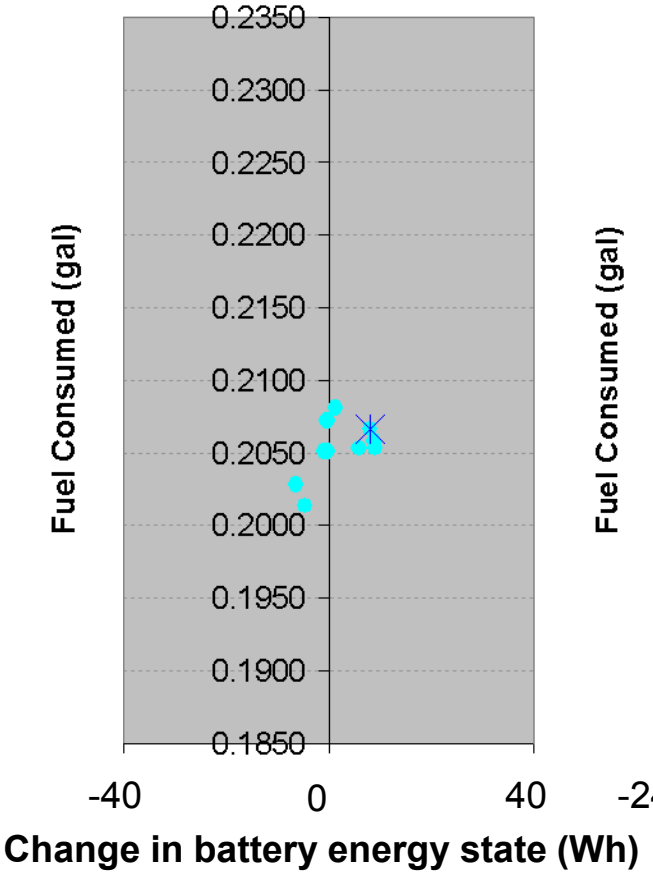
Segment 1 + Segment 2 + Segment 3



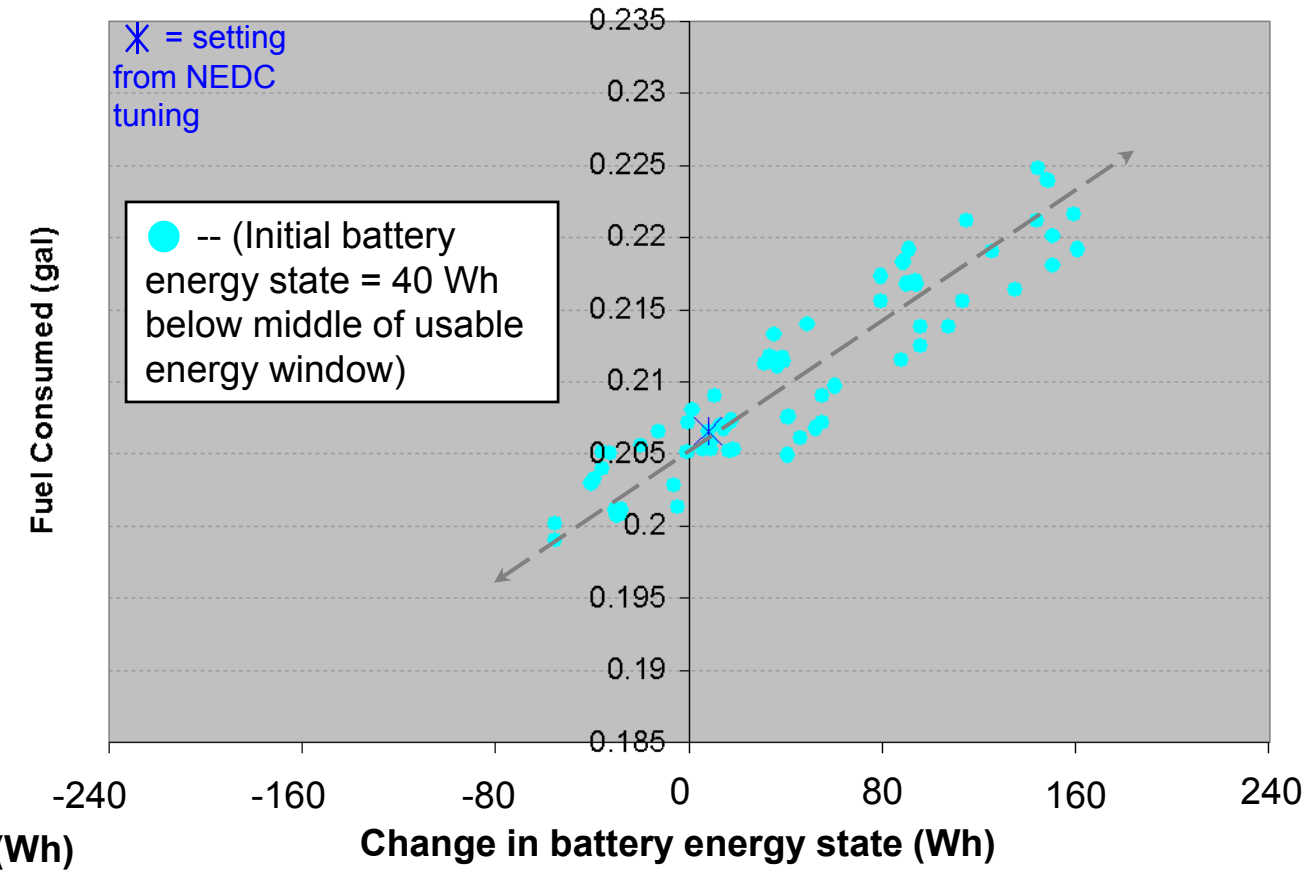
Consider parametric controls study from a given initial battery energy state

Many US06 high speed simulation results

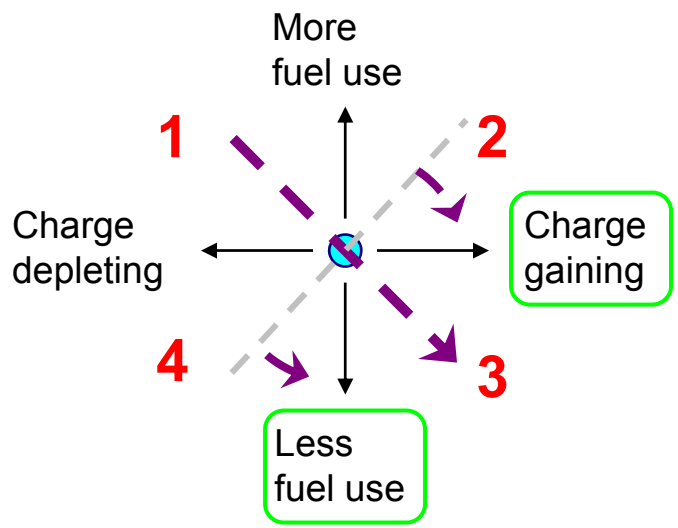
Some (≈CS) results can be compared as before

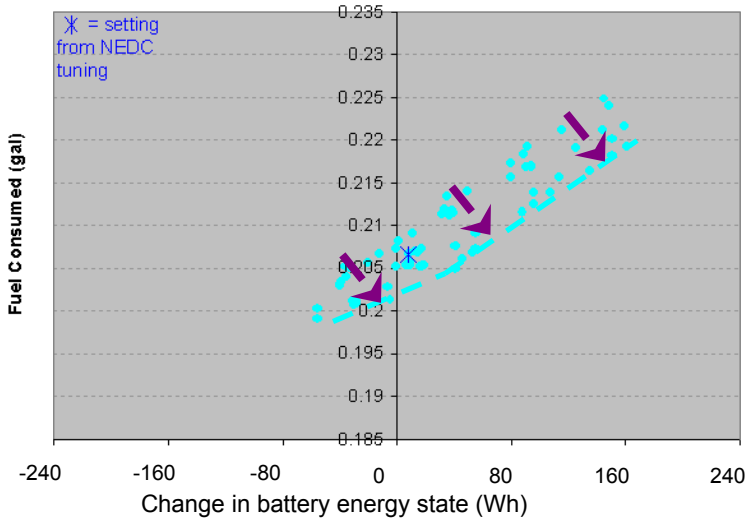


Full results show battery energy vs. fuel use tradeoffs from different control settings



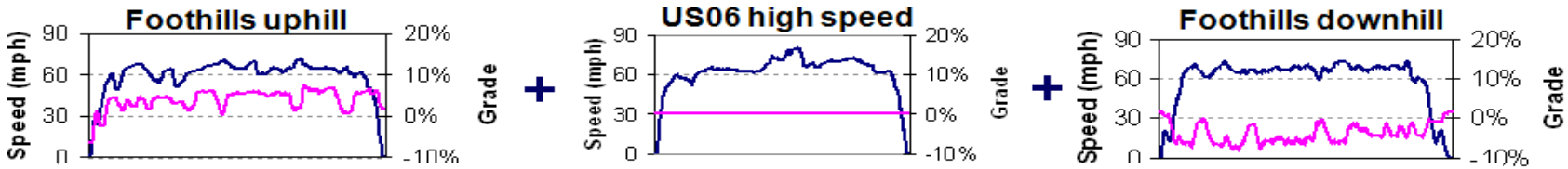
How to evaluate control options within the fuel vs. battery energy use space?

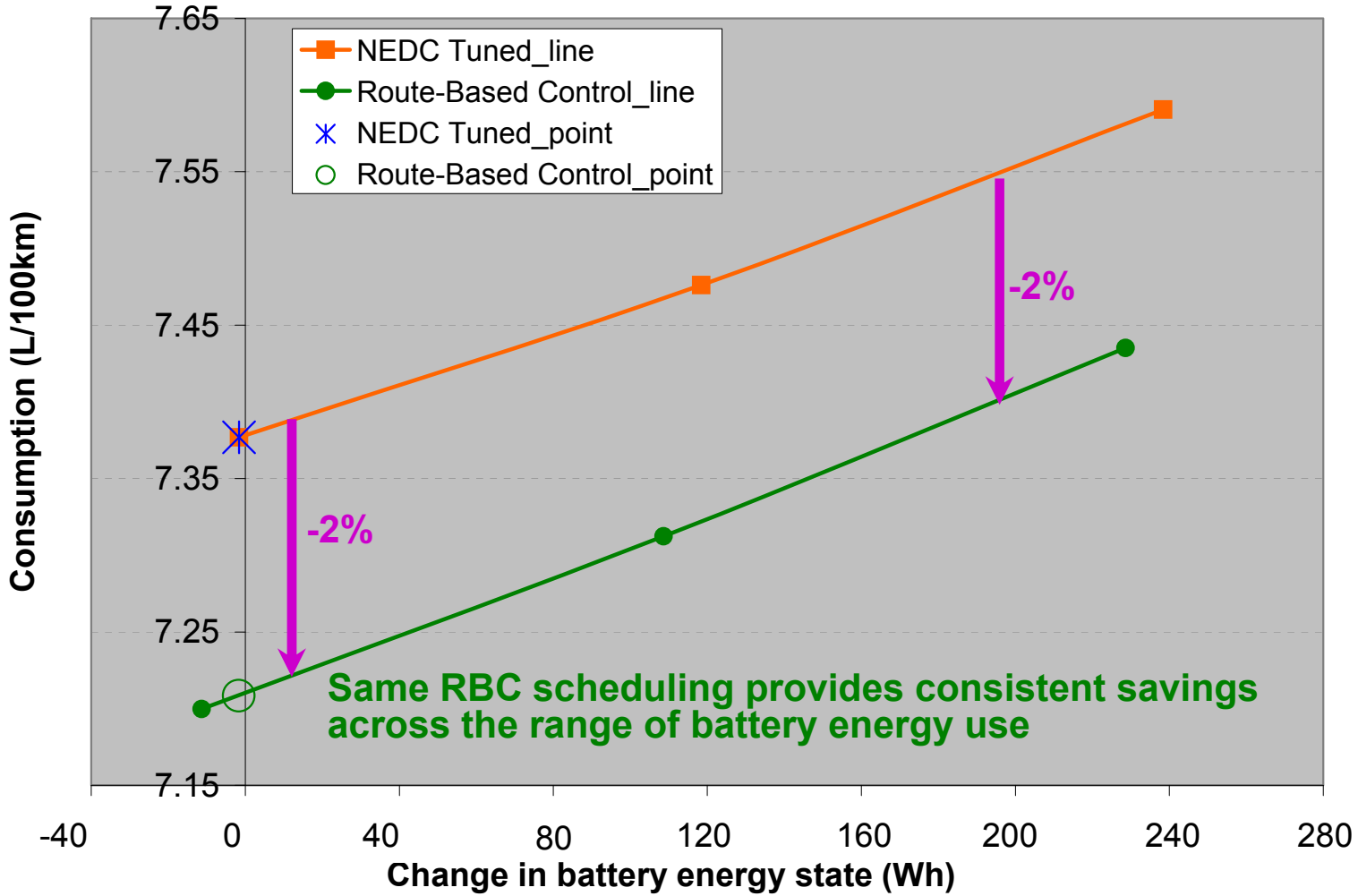




- Considerations for weighing a given option against others
  - Never move to quadrant 1
  - Always move to quadrant 3
  - Consider moving to quadrants 2 & 4
- Narrow consideration of control options to those with results along the lowest fuel vs. battery energy use line
- Schedule control sequence from narrowed options to optimally trade off fuel use vs. SOC control

Example savings achieved over a cycle with segments of different driving types (combined foothills/US06 high speed cycle):





Simulation Observations: Route-based control can provide a sizable benefit for specific expected driving types

Cycle	Control Comparison	Consumption Improvement	Change in Wh Window
UDDS bag2 segment (low-speed stop and go)	RBC vs. Baseline Tuning (initial)	**10.6%**	66 → 151 Wh
	RBC vs. Baseline Tuning (revised)	**2.8%**	86 → 151 Wh

Considerations:

- Savings depend on robustness of 'baseline/default' parameter tuning
- Battery operation may be altered in order to realize savings

Further Observations: Route-based controls can also save fuel over cycles with different driving segment types

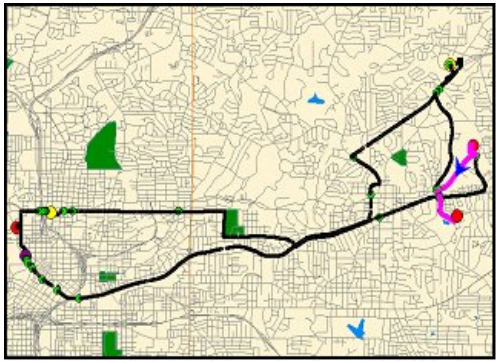
Cycle	Control Comparison	Consumption Improvement	Change in Wh Window
Foothills grades with US06 high speed	RBC vs. Baseline Tuning (revised)	**2.3%**	321 → 270 Wh
Foothills grades with HWFET (mis-prediction)*	Same RBC vs. Baseline Tuning	0.4%	306 → 275 Wh

Additional comments:

- Unanticipated result of lower fuel and battery energy window use for the RBC simulations
- Simulation of RBC sequence over a different than expected cycle* still performed at least as well as the baseline control

* Middle segment = HWFET (not US06 high speed)

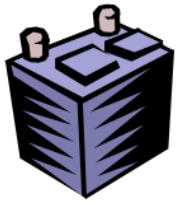
Generated hardware demonstration work plan with HEV transit bus developer

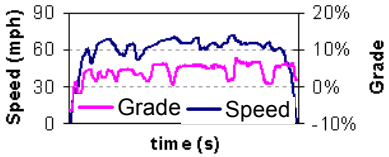


- Ideal initial test platform
  - Repeatable/predictable routes
  - Customers highly motivated by fuel savings
- Work plan
  - Collect cycles for an actual application
  - Apply route-based control tuning to model of actual vehicle and controls over identified cycles
  - Implement route-based control variations into vehicle hardware (using simulation results as a guide)
  - Compare vehicle operation with route-specific controls against the baseline performance

Future Work: Complete hardware demonstration in FY09-10; Other areas could also merit investigation

- Near-term critical steps/gates
  - Finalize CRADA with partner
  - Determine fuel-saving control adjustments to implement in hardware
- Potential expanded/follow-on work
  - Successful bus demonstration could pave way for integration into light-duty HEVs (higher vehicle volumes, but greater predictability challenge)
  - Demonstrate approach benefits for PHEVs (driving type and distance important)
  - Evaluate battery life and emissions benefits (both for HEVs and PHEVs)
  - Validate route prediction/cycle translation techniques





Summary: Simulations suggest cost-effective aggregate fuel savings; Currently in hardware demonstration phase

- Note that a 3% across-the-board reduction in U.S. HEV fuel use would save ≈6.5 million gallons of fuel annually
  - Savings will increase with greater HEV market penetration
  - Comparable approaches have recurring vehicle cost premiums (e.g., use of exotic lightweight materials or component upgrades)
- Industry collaboration/demonstration provides pathway for market penetration
  - Validation of benefits
  - Confidence with implementation

* Images source: iStockphoto