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2009 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review:

PHEV development test platform Utilization

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Overview of the MATT (Modular Automotive Technology Testbed) Project

Timeline

- FY06 Development of tool
- FY07 Integration and calibration
- FY08 Major completed studies:
  - Conventional vehicle baseline
  - Electric vehicle cold losses
  - PHEV Highway cold start correction factor study
- FY09 Major studies
  - PHEV EV capable drive cycle sensitivity (100% complete)
  - Soak time sensitivity (100% complete)
  - Hydrogen engine evaluation (80% complete)
  - PHEV fuel economy and emissions trade off (60% complete)

Budget for HIL MATT

- FY08: $ 1000k
- FY09: $ 800k

Technical Barriers / Target

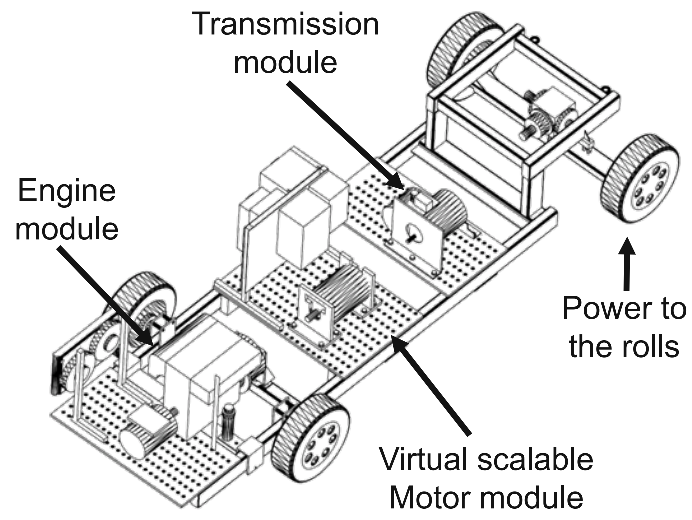
- Complexity of hardware
- Complexity of control
- HIL Component technology integration and validation

Partners

- Hydrogen testing
  - Ford Motor Company
- PHEV fuel economy and emissions trade-off
  - J1711 test standards
  - University of Tennessee

What is the Modular Automotive Technology Testbed?

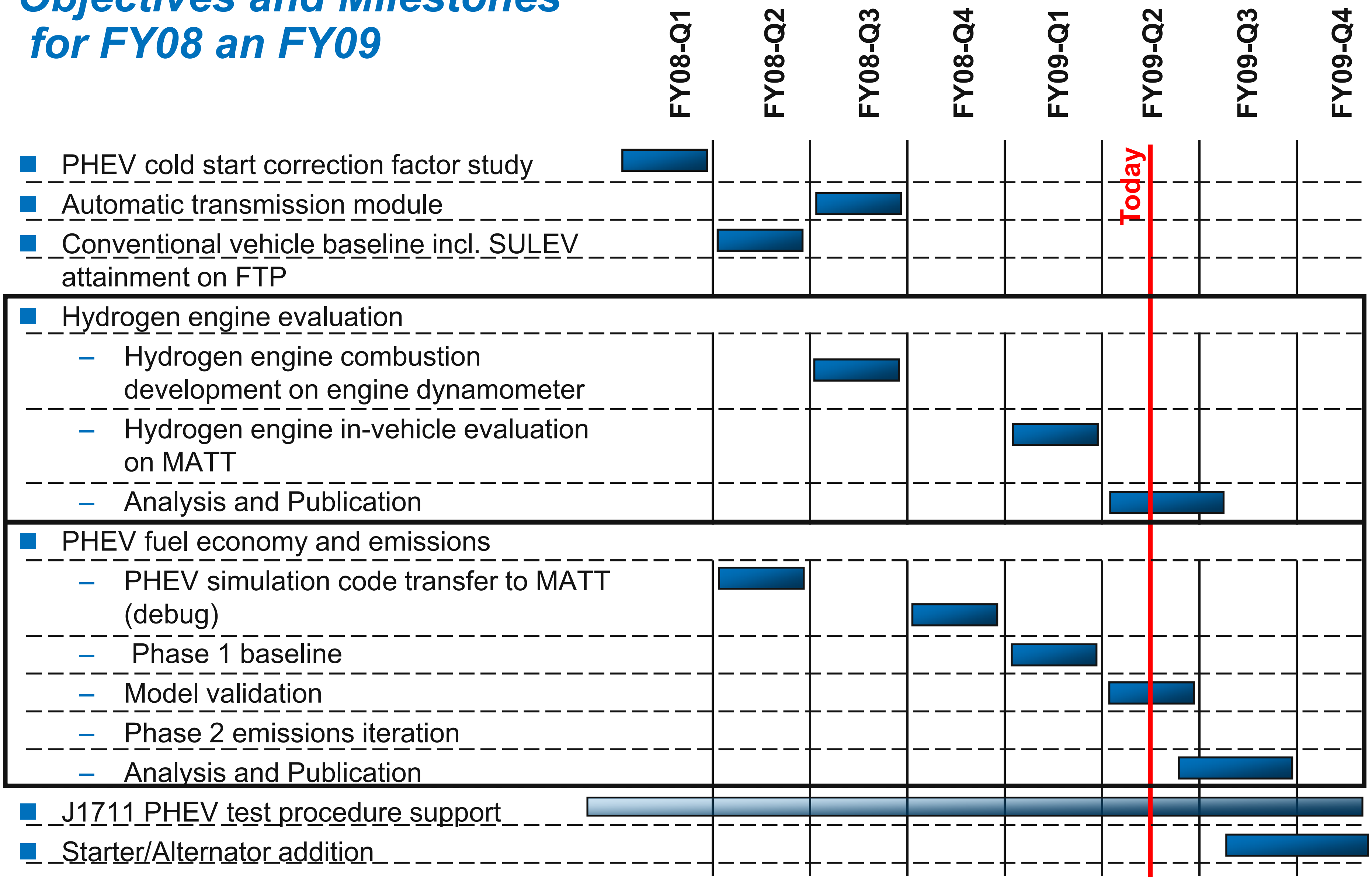
- MATT is a unique tool:
  - to study physical components in a hybrid vehicle system environment on transient drive cycles
  - to validate simulation models
  - to evaluate torque split and energy management strategies including emissions and thermal related losses of components
- MATT's Objective:
  - generate hardware based data for a wide range of very specific studies



MATT's features:

- **Flexibility:** component modules (emulated and physical)
- **Open controller:** changeable control strategy
- **In-depth:** full instrumentation
- **Realism / measured:**
  - Physical fuel economy
  - Physical emissions
  - Temperature effects
  - Hardware limitations
- **Validation:** simulation parallel

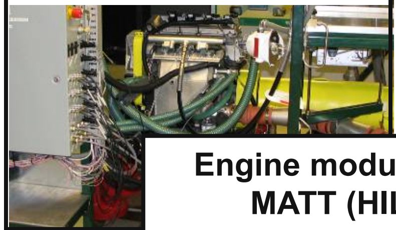
Objectives and Milestones for FY08 an FY09



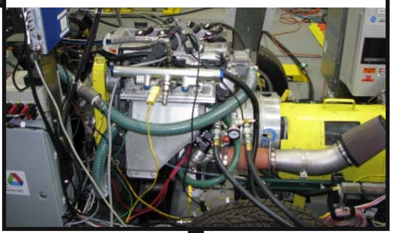
Approach to Studies using MATT

- For **Component evaluation**:
  - Modular design approach
  - Tested in same vehicle environment
  - Direct comparison
- For **PHEV studies:**
  - Open controller approach
  - Virtual scalable motor and energy storage module
  - Different PHEV philosophies can be emulated, from mild hybrid blended strategies to EV capable full hybrids
- Ultimately the hardware and software configurations are tested in DOE's APRF (Advanced Powertrain Research Facility)

Engine dynamometer development



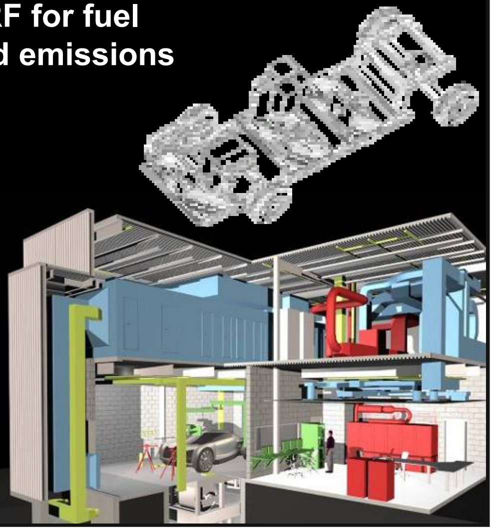
Engine module for MATT (HIL)



PHEV studies from simulation to hardware (RCP)

Testing in APRF for fuel consumption and emissions

Instrumentation:
- Power
- Energy
- Temperature
- Specialty
  - -Indicated pressure
  - -Hydrogen specifics



Technical Accomplishments and Results Overview

1. PHEV baseline investigation
   - Conventional Vehicle
   - EV capable PHEV
   - Blended PHEV
   - Emissions Summary

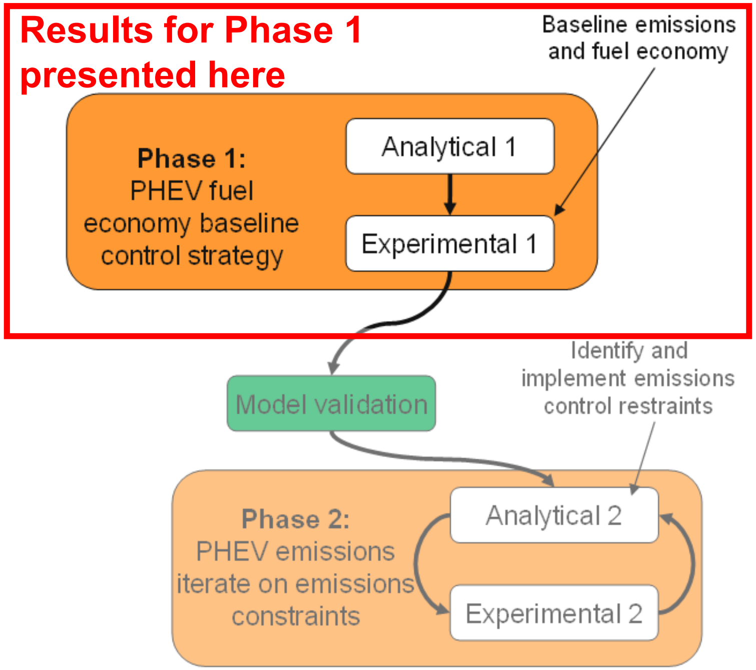
2. Other featured studies
   - EV capable PHEV drive cycle sensitivity
   - Soak time sensitivity

3. Evaluation of a hydrogen engine
   - Combustion strategies
   - Evaluation on MATT
   - UDDS results

PHEV

PHEV Control Strategy Impact on Fuel Economy and Emissions in a Collaboration with the University of Tennessee

- What:
  - Quantify the impact of aggressive engine usage in PHEV mode on emissions as well as on fuel economy
  - Investigate emissions reduction through hybrid control
- Importance:
  - The engine starts and aggressive usage for PHEV poses emission problems
  - Provide hardware data for different PHEV configurations to evaluate the proposed PHEV test standards from J1711
- Results: Established the baseline case for
  - *Conventional*
  - *UDDS EV capable PHEV with an 'engine optimum' control strategy*
  - *Blended PEV with an ' engine load following' control strategy*

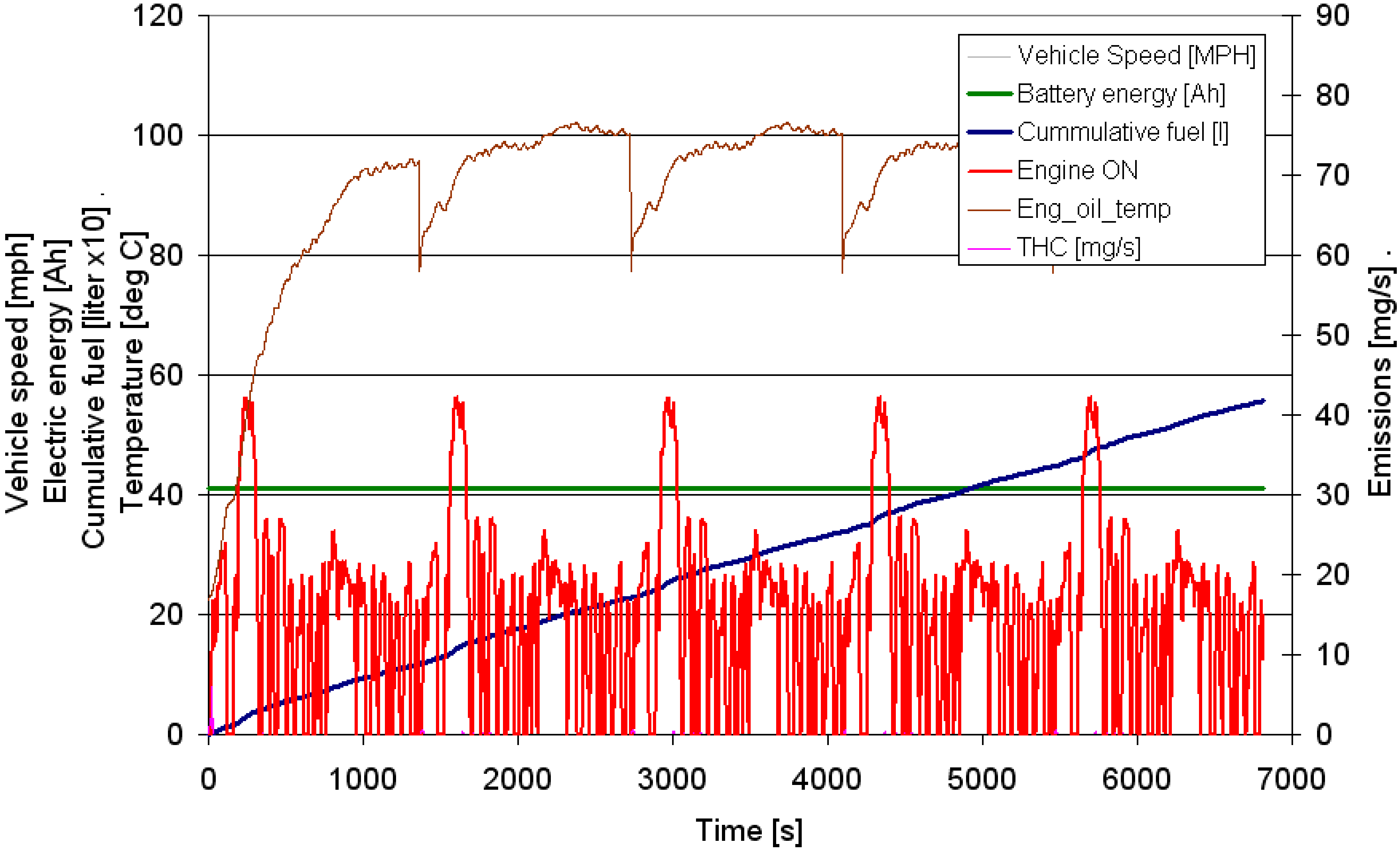


	MATT
Engine	2.3L gasoline
Motor	Emulated UQM 75
Battery	Emulated JCS VL41M
Control software	PSAT-Pro
Transmission	Automatic 5R55

Physical component (yellow) Emulated component (blue)

Conventional Vehicle – Baseline Case

PHEV
Phase 1 data

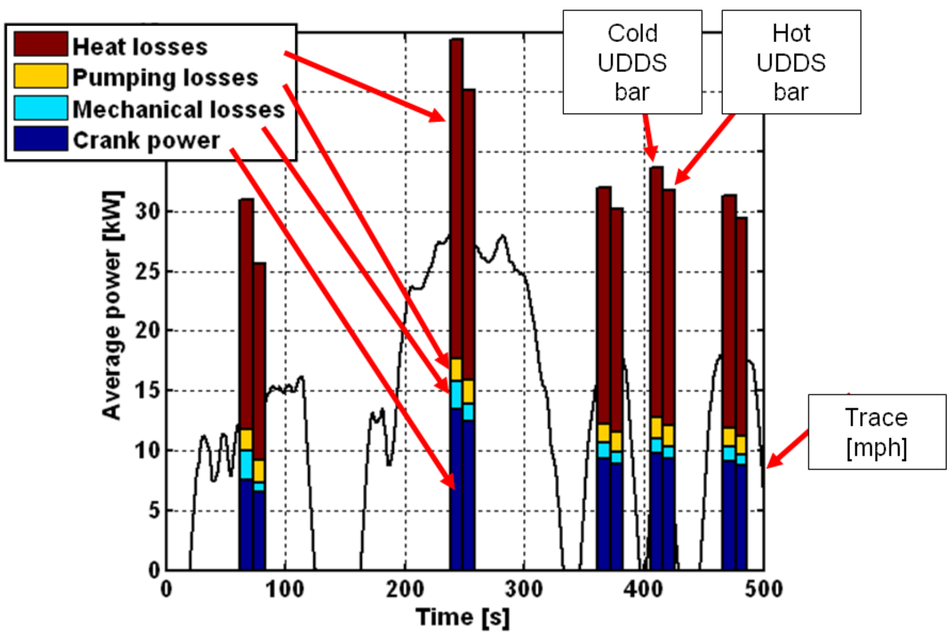


With the Comprehensive Instrumentation, Each Powertrain Component is Analyzed In Depth

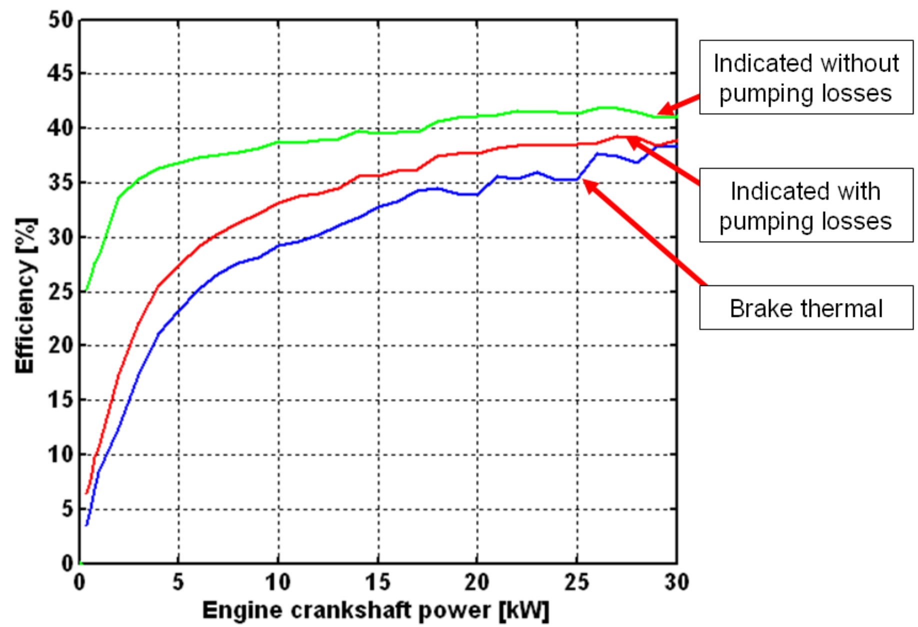
PHEV
Phase 1 data

- An example of comparing detailed engine losses from a cold start and a hot start UDDS cycle

Cold start versus hot start engine related losses on per hill basis

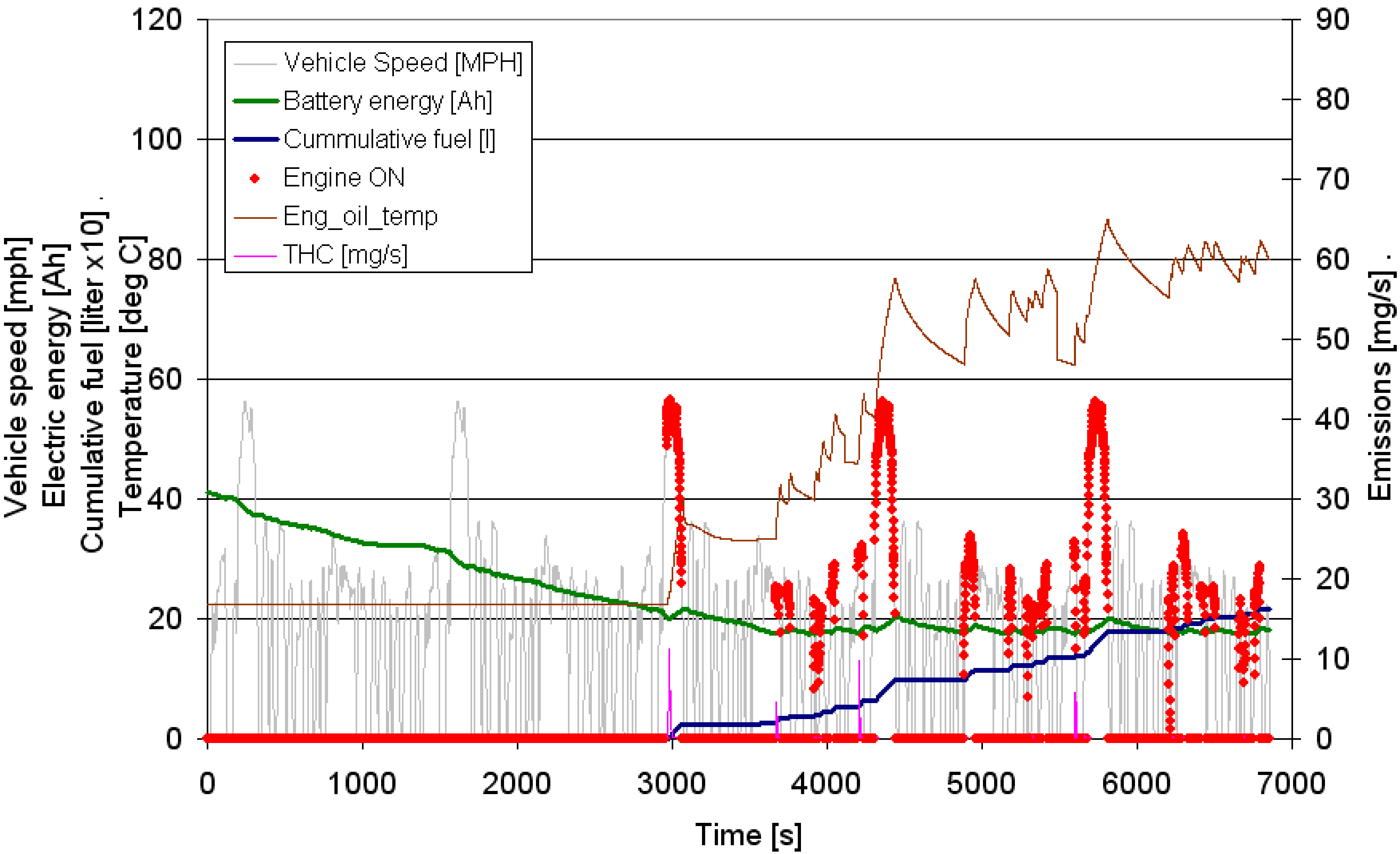


Engine efficiencies derived using IMEP from in cylinder pressure data from a UDDS cycle



UDDS EV Capable PHEV Using an ‘Engine Optimum’ Control Strategy

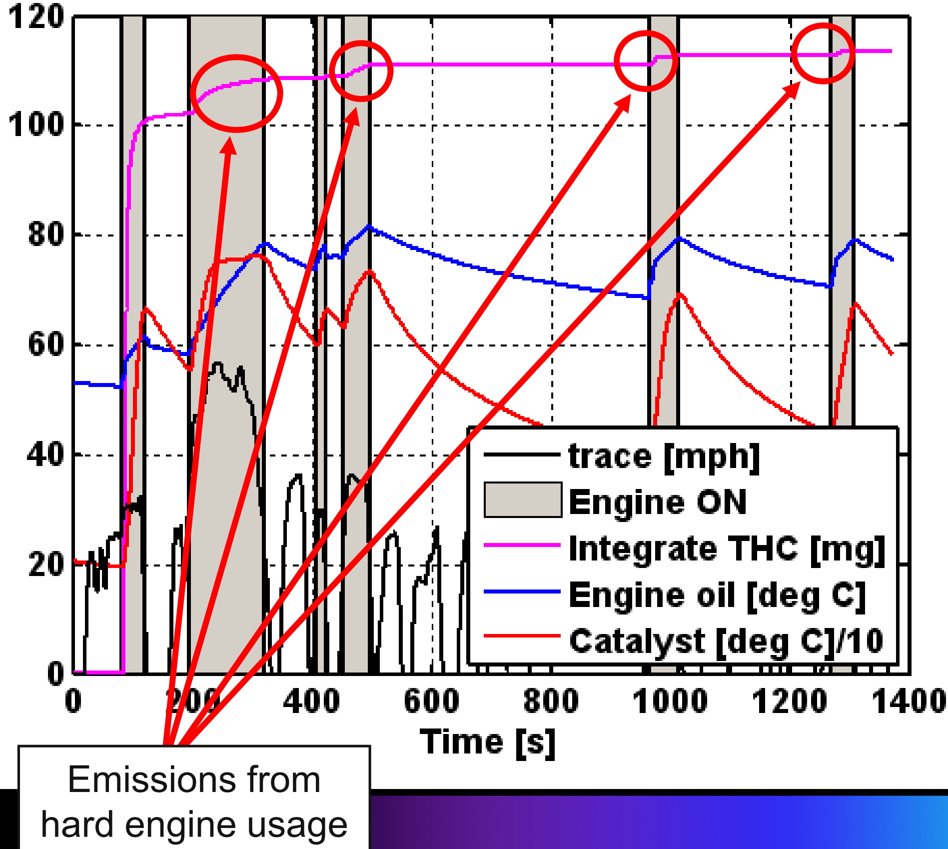
PHEV
Phase 1 data



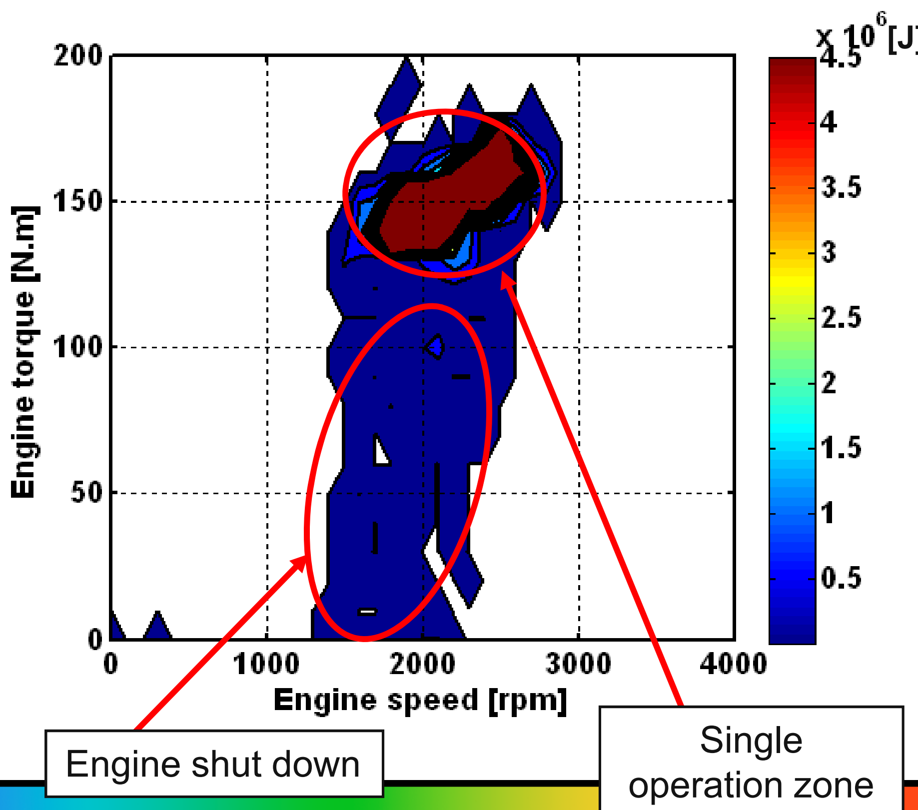
In this extreme hybrid case, the engine is run at high loads to improve efficiency when used, but this also causes higher emissions.

- UDDS EV Capable PHEV using an 'Engine Optimum' Control Strategy – Results from the last UDDS (hot).

Temperature and emission data

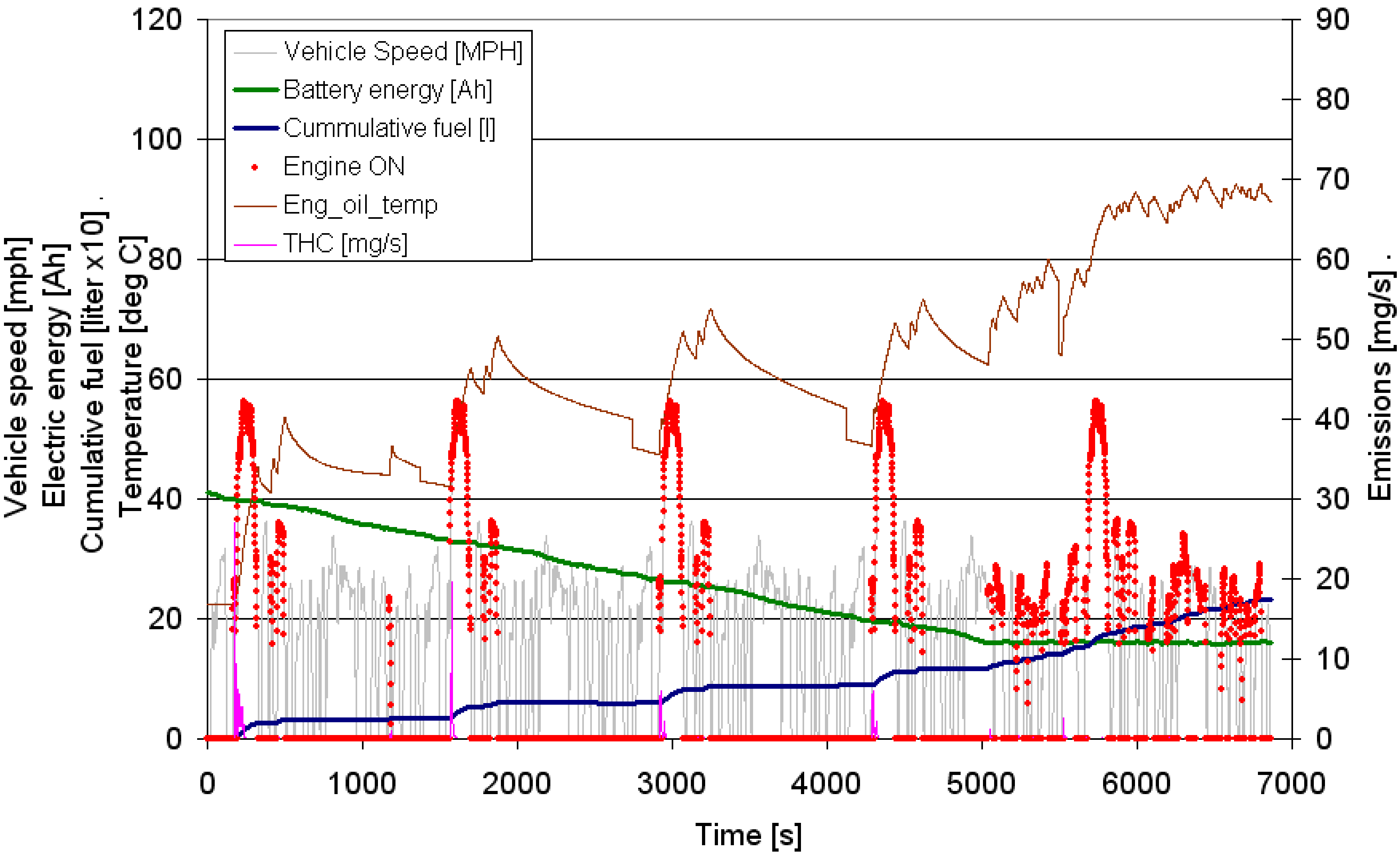


Fuel energy used over the cycle



Blended PHEV Using a 'Load Following' Control Strategy

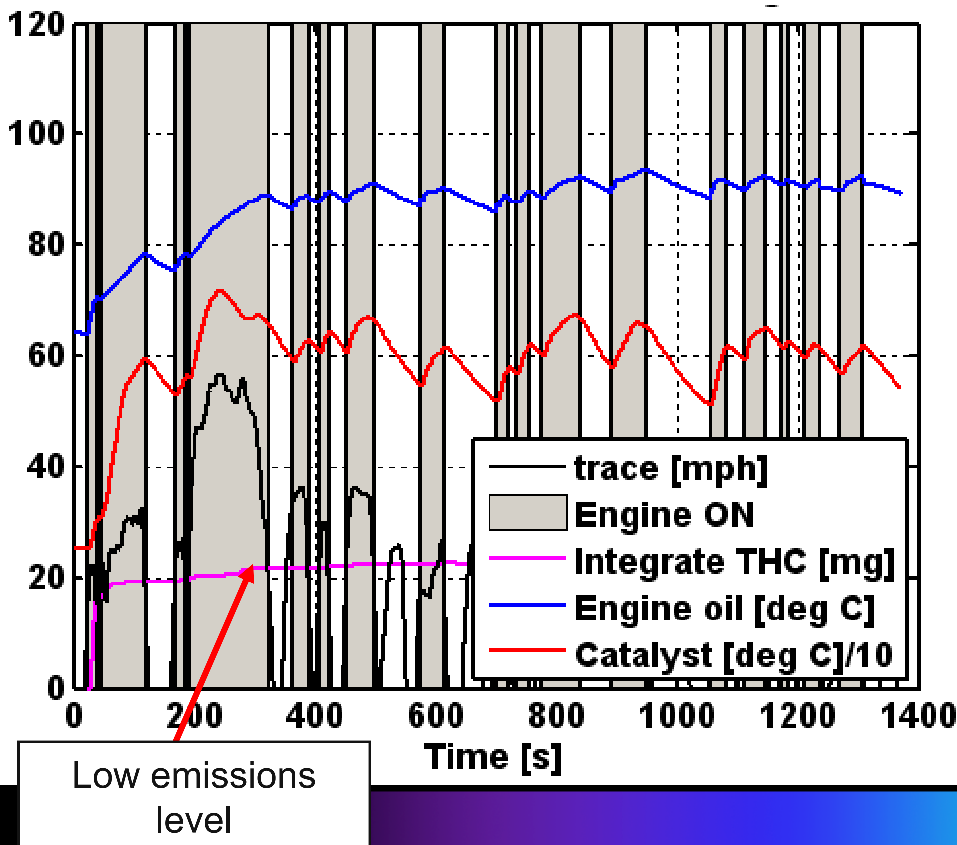
PHEV
Phase 1 data



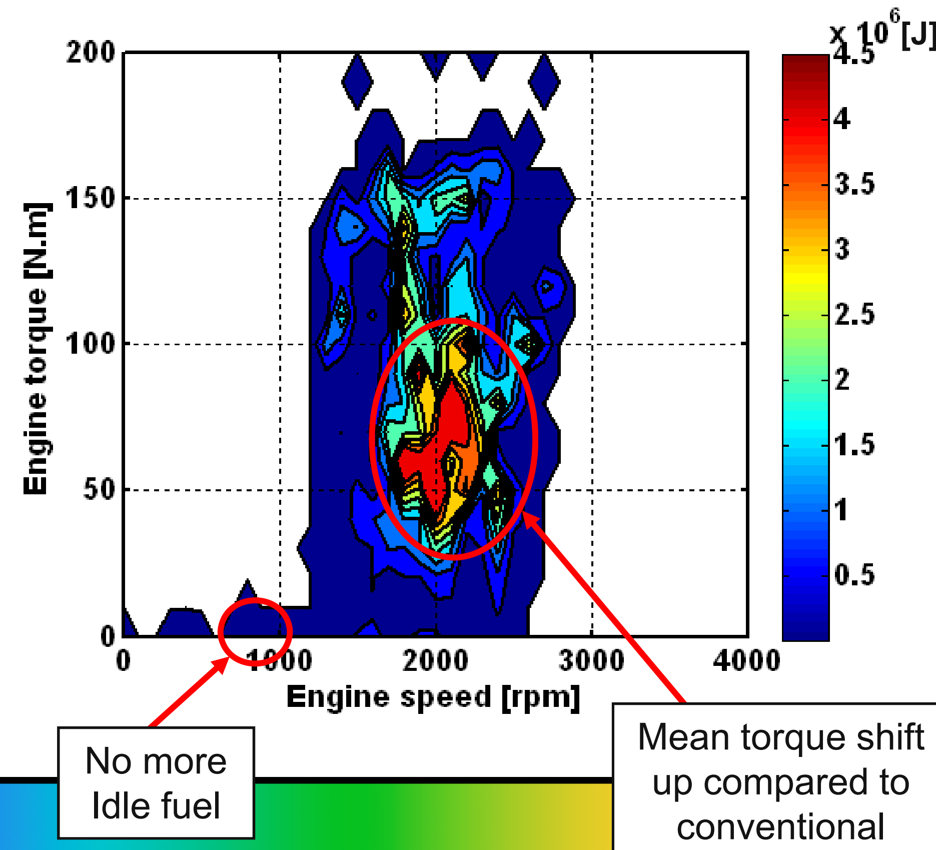
The 'load following' strategy improves the emissions significantly but the engine operation is not located in the high efficiency area.

- Blended PHEV using a 'Load Following' Control Strategy – Results from the last UDDS (hot)

Temperature and emission data

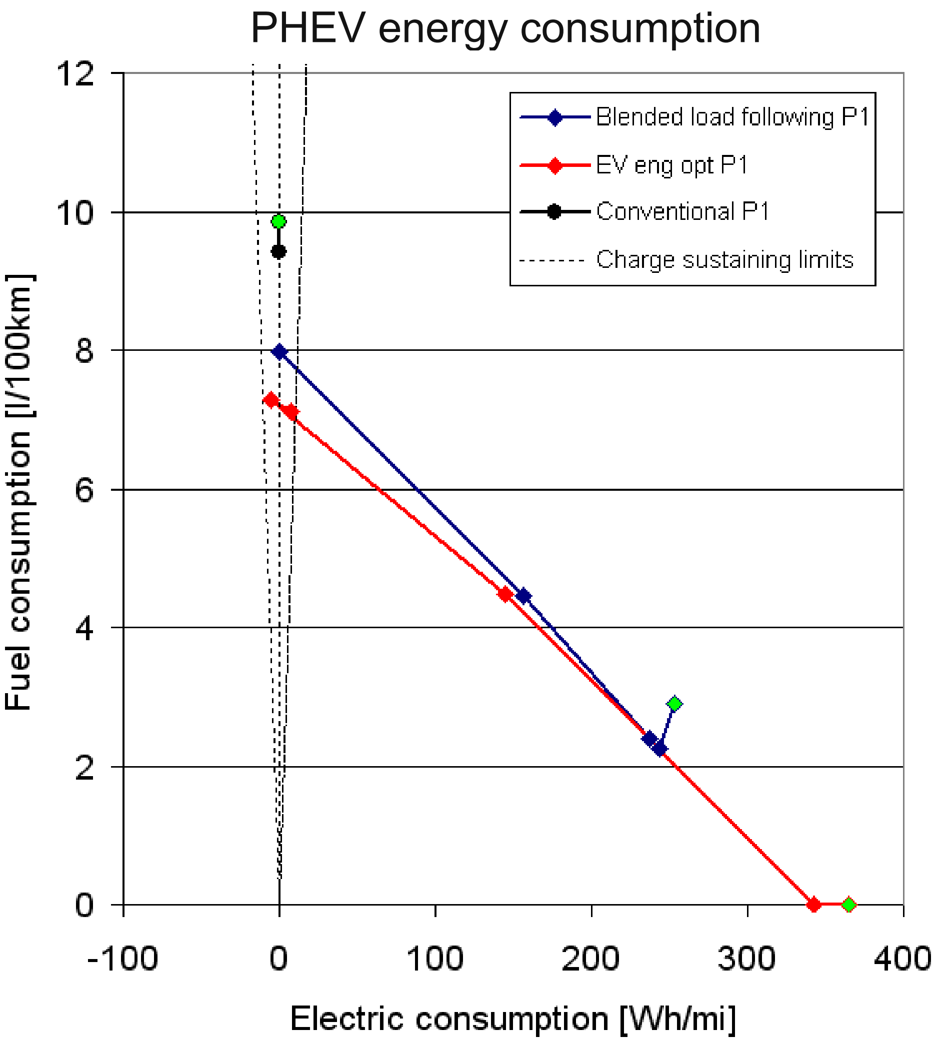


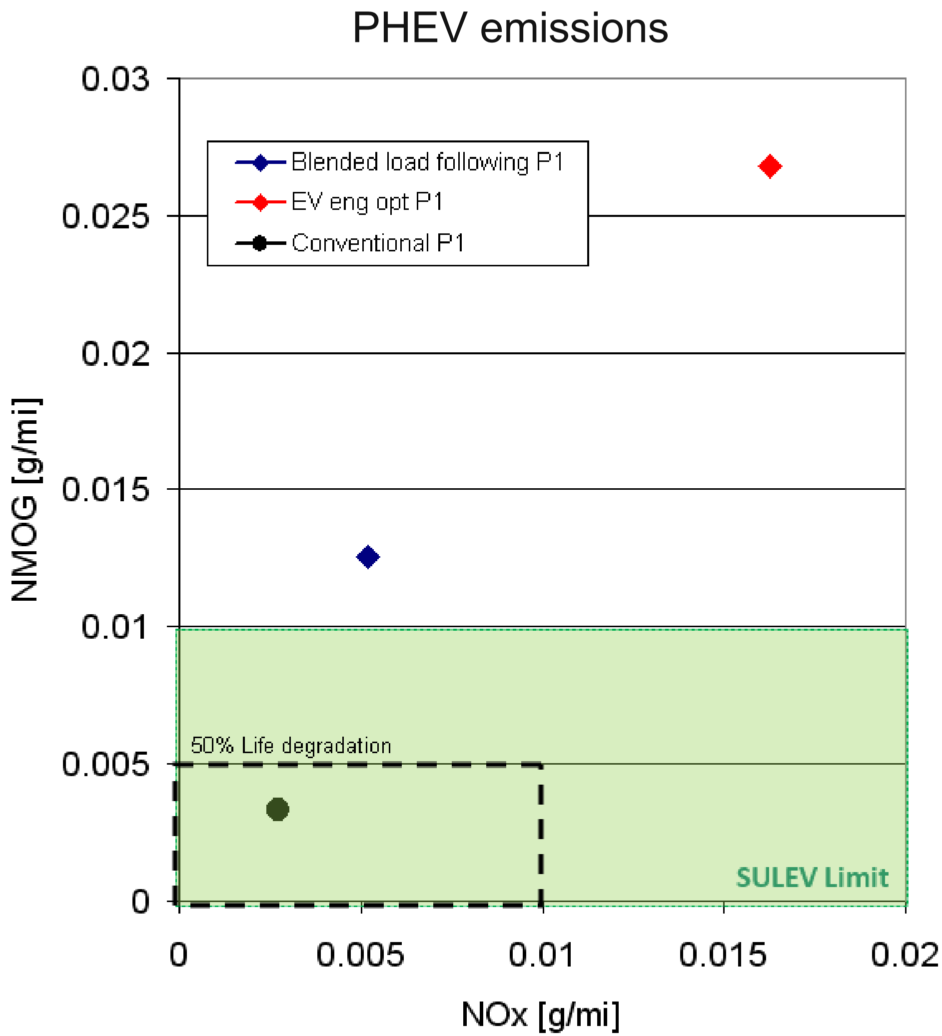
Fuel energy used over the cycle



The EV capable 'engine optimum' achieves the Highest Petroleum Displacement at the expense of emissions.

PHEV
Phase 1 data





Conclusion: Lessons Learned on Fuel Economy and Emissions for PHEV as well as the Basic Phase 2 Concepts

PHEV
Phase 1 data

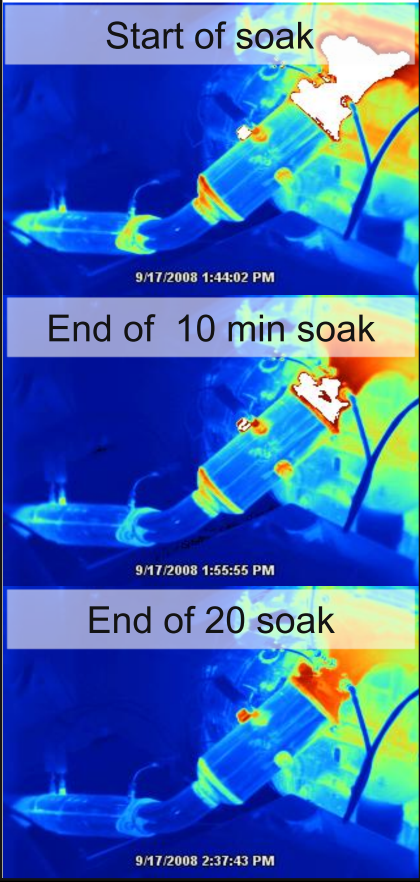
- The conclusions of Phase 1 are:
  - Emissions:
    - *Aggressive engine loads are detrimental to emissions*
    - *Long engine off periods can cool the catalytic converter down significantly*
    - *First cold engine start produces the most emissions until the catalytic converter reaches light off temperature*
  - Fuel Economy:
    - *Hybridization can improve Fuel Economy by up to 20% in charge sustaining*
- The concepts for Phase 2 are:
  - Engine warm up period
    - *Limit torque to 10% during a set period of time for 'easy' warm up*
    - *Ramp maximum torque up based on engine energy output*
  - Engine forced restart
    - *If catalytic converter temperature is below a target temperature*

PHEV Soak

MATT's PHEV capabilities were used to investigate soak time sensitivity on plug-in testing for J1711.

- What:
  - What is the impact of time between tests on fuel economy and emissions?
  - MATT's virtual battery pack, the SOC, is reset to the same level before every test. Therefore, the same test can be repeated over and over with different soak times.
- Importance:
  - The PHEV test procedure is composed of a series of urban cycles in a row. The time to recalibrate the emissions equipment varies from test facility to test facility.
- Results:
  - The Fuel Economy impact is measurable but insignificant within a 30 minute window. The closer the cycle is run to the previous cycle, the more energy efficient the vehicle is.
  - On the emissions the difference is not measurable.

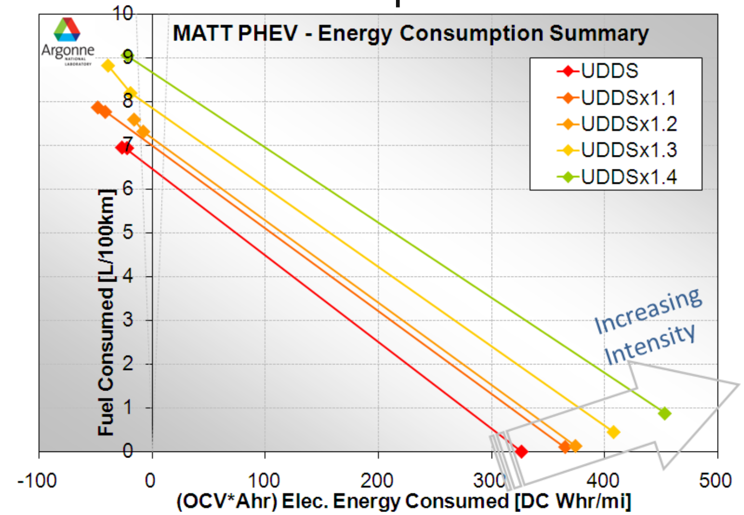
Thermal imagines of the exhaust system help under stand the soak time impact



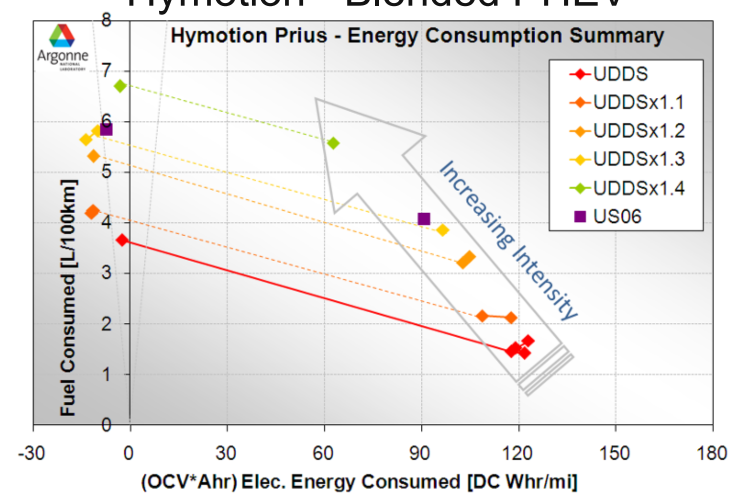
MATT provided the only UDDS EV capable PHEV data for the drive cycle intensity study.

- What:
  - How does driver aggressiveness translate into extra fuel and/or battery energy used for the different types of PHEVs?
- Importance:
  - Past study shows that fuel economy in hybrid vehicles is more sensitive to driver aggressiveness than conventional vehicles.
  - PHEV fuel economies can vary from X [mpg] to infinite [mpg].
- Results:
  - For a UDDS EV capable PHEV as driving intensity increases, fuel consumption and electrical energy consumption increases
  - Further information is in the ANL presentation vss_04_carlson by Richard Carlson

MATT - EV capable PHEV



Hymotion - Blended PHEV

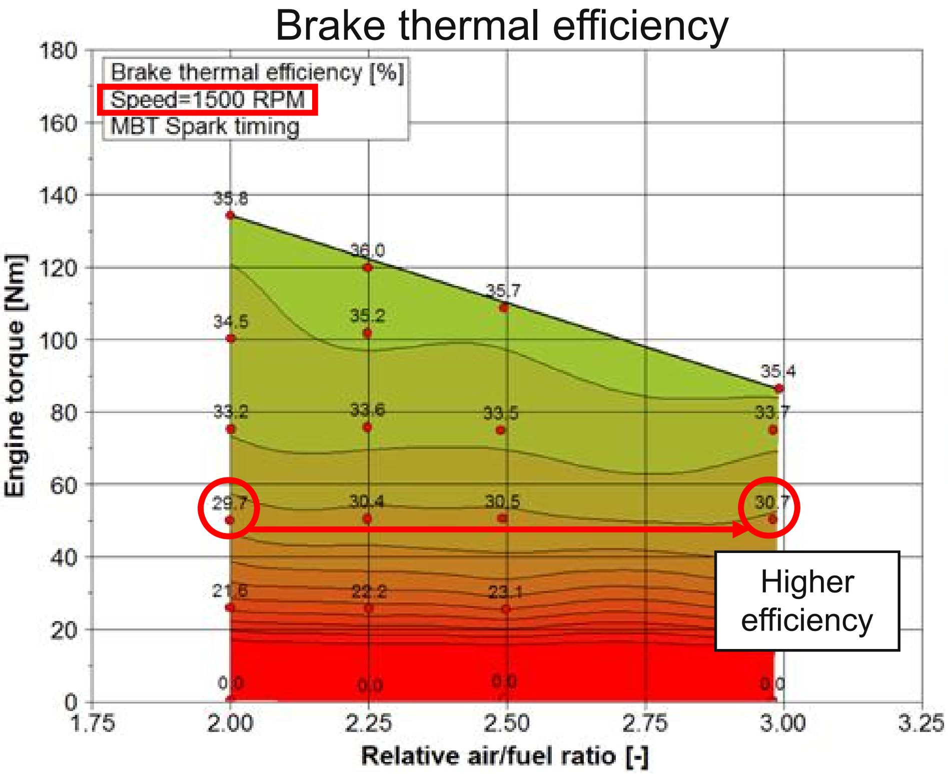


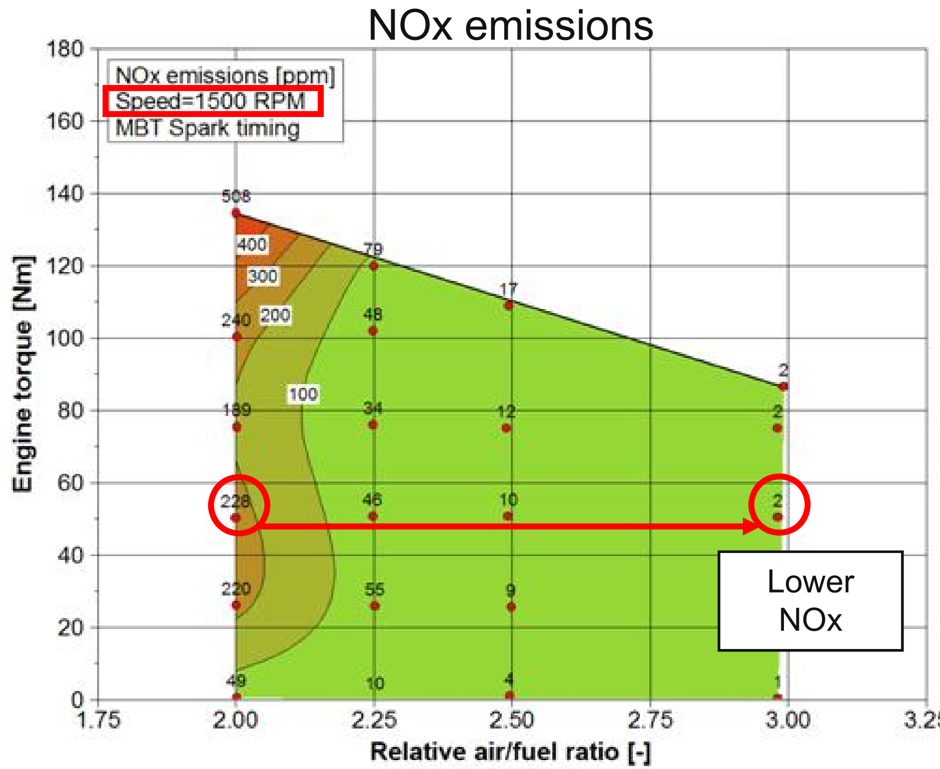
Evaluating the Hydrogen Internal Combustion Engine as a Bridging Technology to the Hydrogen Economy

- Why:
  - Part of DOE's mission is to evaluate new technology components from a vehicle system perspective
  - Integration of DOE calibrated hydrogen engine
- Importance:
  - Provides direct comparison to gasoline engine
  - Underlines the technical viability of hydrogen internal combustion engines
- Results:
  - SULEV emissions level possible with no exhaust after-treatment (NO_x<0.02 g/mi)
  - Innovative variable air-fuel ratio hydrogen combustion strategy proven as most efficient in transient operation while keeping emissions at ULEV levels

Hydrogen Engine Dynamometer Data for Brake Thermal Efficiency and Emissions as a Function of Air Fuel Ratio

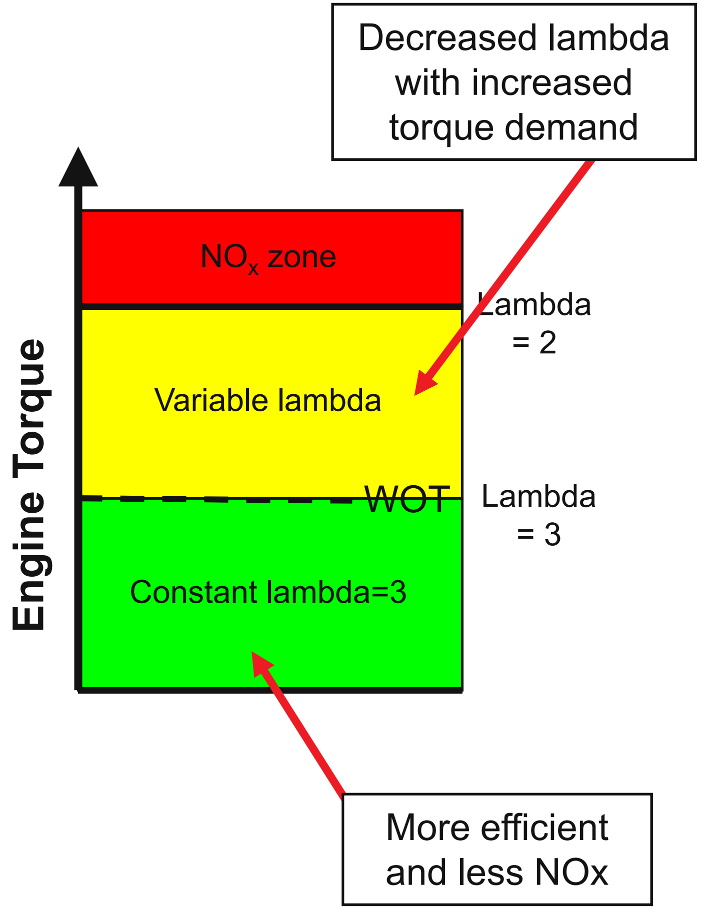
- For the same engine torque speed point, the leaner combustions are more efficient and produce less NOx, but they also show a dramatic reduction in power. The peak efficiencies are higher as the air-fuel ratio increases.



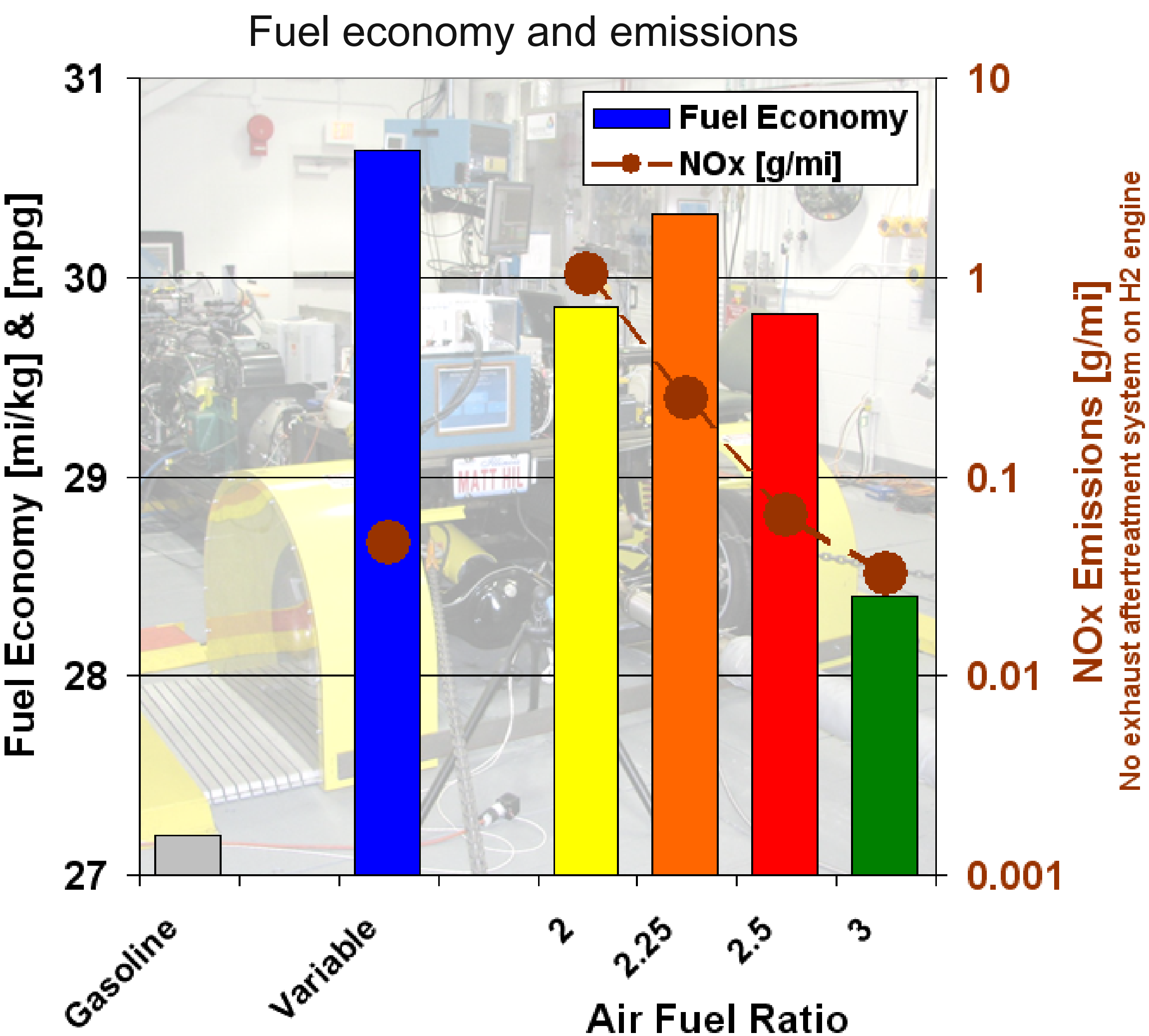


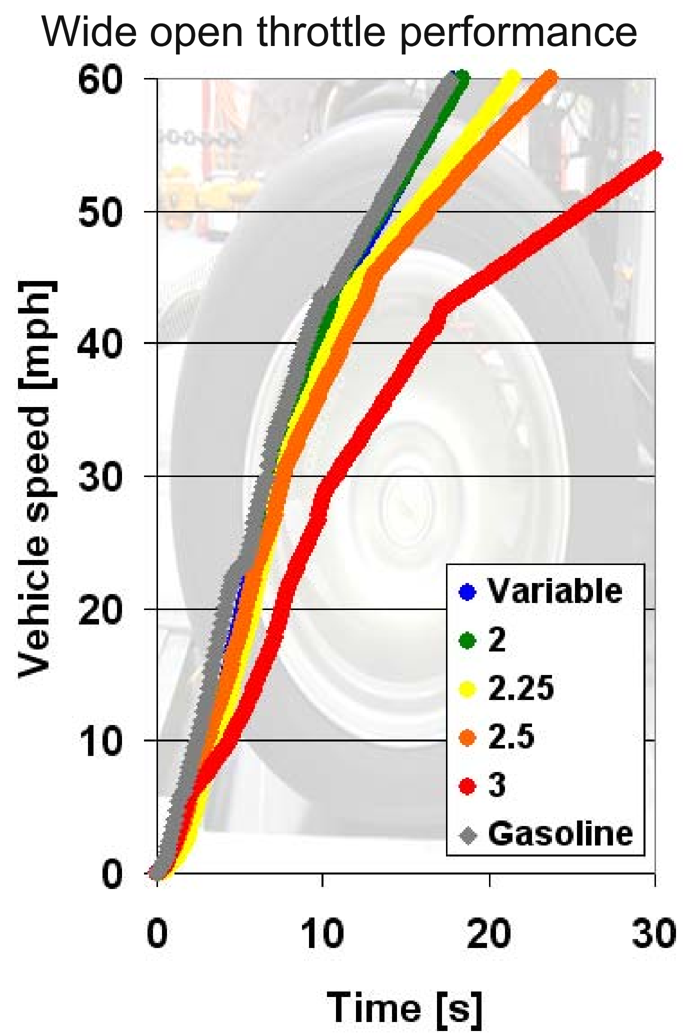
Variable Air-Fuel Ratio Combustion Strategy to Improve Efficiency and Emissions for Transient Operation

- Two categories of combustion strategies:
  - Classic constant lambda fueling maps:
    - *2, 2.25, 2.5 and 3.*
  - Variable lambda
    - *Idle and lower load: lambda 3*
    - *Medium load: Wide open throttle with variable lambda*
    - *Maximum load: lambda 2 (depending on emissions goal)*
- Predictions
  - The variable air-fuel ratio should have the best fuel economy
  - The lambda 3 strategy should have the lowest emissions



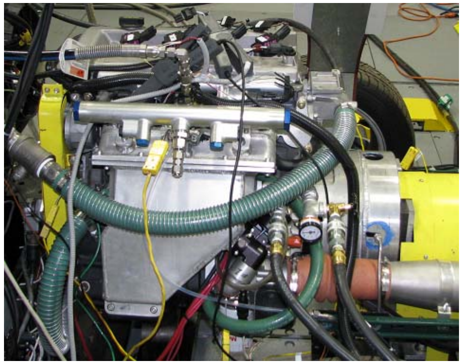
Fuel Economy and Emissions Results on Hot Start UDDS for a Mid-Sized Sedan as well as Performance Pesults



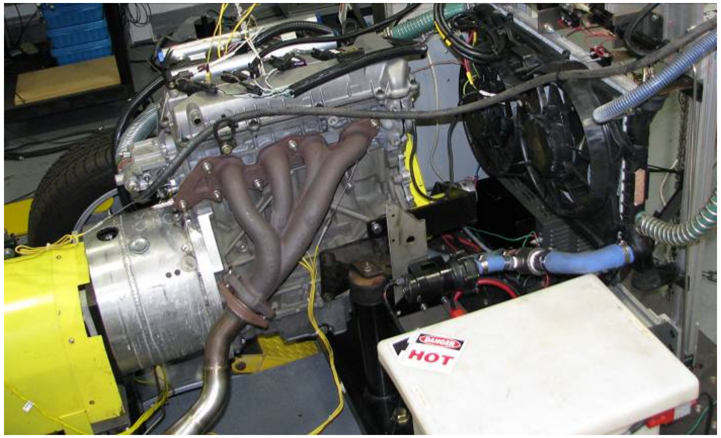


Conclusion: The Variable Air-Fuel Ratio Combustion Strategy provides the best fuel economy and lowest emissions while maintaining performance on a hydrogen engine.

- Argonne calibrated a supercharged engine in the hydrogen test cell and evaluated it on standard drive cycles in a vehicle system environment.
- The reasons for the success of the variable air-fuel ratio strategy:
  - Acceleration: higher torque, higher efficiency
  - Cruise: higher efficiency at lower torque
  - Better shift schedule: lower speed & higher torque

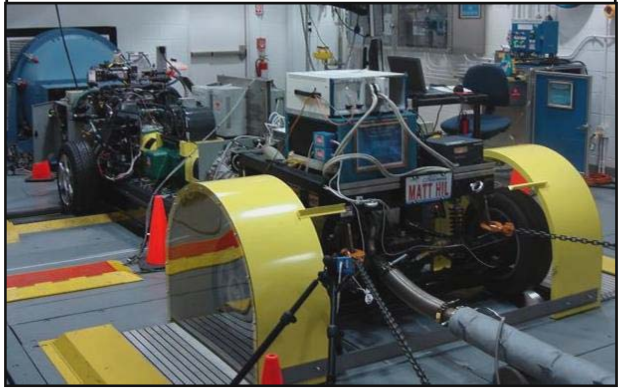


- Future Work:
  - Evaluate the hydrogen engine in a HEV/PHEV environment
  - Evaluate an advanced hydrogen engine with direct injection operation



Future work

"MATT" Platform as PHEV



- HEV and PHEV
  - Fuel Economy and Emissions Trade-offs
    - *Finish Phase 2*
    - *Data analysis*
    - *Possibly investigate other control philosophies and their impact on emissions behavior*
  - Further support J1711 PHEV test procedure development
  - Investigate the added hybrid freedom with an integrated starter / alternator
- Hydrogen engine evaluation
  - Hydrogen engine evaluation in hybrid vehicle environment
  - Data analysis
- Other DOE technology testing in vehicle system environment
  - Example: alternative fuel engine

Summary: MATT is used a tool to evaluate components as well as to generate fuel economy and emissions data for PHEV tests.

- A supercharged hydrogen engine was evaluated in a vehicle environment using MATT:
  - The variable combustion strategy was proven to provide the best fuel economy while maintaining low emissions and maintaining vehicle performance.
- In the fuel economy and emissions trade-off study the baseline PHEV cases are completed:
  - Emissions are generated by a cold engine and then an exhaust after-treatment system cannot convert them.
  - In Phase 2, the hybrid system will be used to help reduce the emissions.
  - Possible further work is planned using different control philosophies
- MATT was also useful in other studies such as:
  - Soak time sensitivity
  - PHEV drive cycle sensitivity
- MATT is generating hardware-based data for a wide range of very specific studies