2006-2010 GATE program at Ohio State University Center for Automotive Research

Modeling, control and system integration of advanced automotive propulsion systems

Yann Guezennec

Giorgio Rizzoni, Steve Yurkovich, Greg Washington, Ahmed Soliman and many others

DOE Program Review, February 28th, 2008

1998-2004 GATE Program

Hybrid Drivetrains and Control Systems

- Original funding from DOE: $550,000
  DOE GATE funding supported **22 Graduate-Student-years**.
- Additional funding at OSU-CAR during the GATE period of performance permitted supporting an additional **96 Graduate-Student-years**.
- Between 1999 and 2005, the GATE program at Ohio State graduated **38 M.S.** and **12 Ph.D.** students. **45 of these 50** professionals are now employed in the **automotive sector**.
-

Previous Program Outcomes

Year	M.S.	Ph.D.
1999	3	1
2000	2	0
2001	7	4
2002	8	1
2003	3	0
2004	6	3
2005	7	5
TOTAL	**36**	**14**

50

Company	Hires
DaimlerChrysler	2
Ford	7
General Motors	7
Hyundai	2
Caterpillar	8
Cummins	5
Oshkosh Truck	2
DDC	2
Bosch	1
Delphi	2
Ballard	1
OSU CAR	2
Battelle (fuel cells)	1
Army (USMA)	1
Other automotive	2
TOTAL	**45**

Previous Program Outcomes

Externally funded research programs totaling over $6 million in expenditures between ‘99 and ‘04 in:

a. Advanced engine combustion, sensing, actuation and control
b. Advanced electrochemical energy storage systems modeling and system integration
c. Fuel cell system modeling, design and control
d. Research in smart materials with application to sensing and actuation in automotive systems
e. Modeling, design, integration and control of light- and heavy-duty hybrid-electric vehicles

Partners:

Caterpillar, Cummins, DaimlerChrysler, Delphi, Denso, Ford, General Motors, Honda, Oshkosh Truck Corporation, NREL, U.S. Army TARDEC, NSF, U.S. DoT.

New GATE program

- The theme of the new program is ***System Integration***.
- Such integration is planned at various levels, including curricular integration, integration in teaching and experimental research; and integration in the use of academic, private and government resources.
- The DOE GATE program will continue to serve as a catalyst to leverage other resources and programs towards achieving the objective of educating a new generation of automotive system engineers
- The program focus is on:
  - *advanced combustion engines*,
  - *advanced energy storage systems*,
  - *fuel cell systems*,
  - *sensing and actuation technologies* and
  - *advanced hybrid propulsion and related control systems*,

  with a strong emphasis on the integration of such systems towards the development of new generation of automotive propulsion concepts.

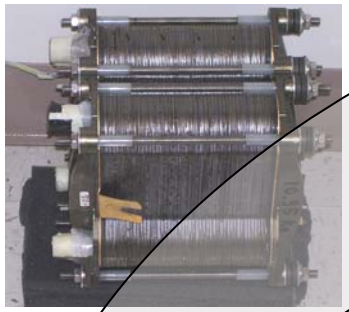
Current Program

- Contract signed on Sep. 21, 2005. Funding pledged in the amount of $670,000. The program began on Oct. 1, 2005.

Year 1	Year 2	Year 3	Year 4	Year 5
ME 787, full scale offering (Guezennec)		ME787 – permanent offering (Guezennec)		ME787 – permanent offering (Guezennec)
Define new System Integration project course (Rizzoni *et al.*)	System Integration project course – pilot (Rizzoni *et al.*)	System Integration project course – full scale offering	System Integration project course – permanent offering	System Integration project course – permanent offering
	ME 676 – pilot offering(Washington)	ME 875 – pilot offering (Dapino)	ME 676 – full scale offering(Washington)	ME 875 – full scale offering (Dapino)
CSE 768 Automotive case studies (Weide)	CSE 768 Automotive case studies (Weide)			
ME 632 – permanent offering (Soliman)	ME 632 – permanent offering (Soliman)	ME 632 – permanent offering (Soliman)	ME 632 – permanent offering (Soliman)	ME 632 – permanent offering (Soliman)
Year 1 Report to DOE and Industrial Advisory Board	Year 2 Report to DOE and Industrial Advisory Board	Year 3 Report to DOE and Industrial Advisory Board	Year 4 Report to DOE and Industrial Advisory Board	Final Report to DOE and Industrial Advisory Board

Program funding is significantly behind schedule on both the curriculum development funds and the fellowships – Out of money by the end of this quarter !

Advanced engines and energy storage systems
addressing societal needs



Emission reduction and efficient energy conversion

Society

"Well-to-wheel" technology assessment

Vehicle demonstrations

Control-oriented modeling

Real-time control

Hardware-in-the-loop implementation

Optimization of geometry, operating conditions, actuation

Sensor, actuator, hardware implementation

Multivariate optimization

Engine combustion models

Engine flow models, spray dynamics

Turbulent reacting flows

Experiments

Catalysis

Control theoretics, control policy, control structure

Experiments

Multi-dimensional simulations

Pollutant Formation, Energy Conversion Efficiency

Electrochemistry

Core Science

Product Engineering

Advanced sensing and actuation technology

Experiments

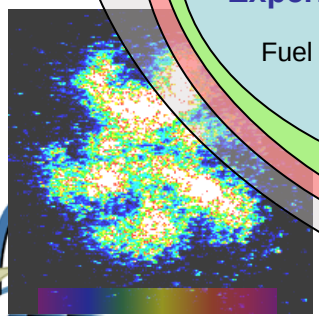
Chemical ki

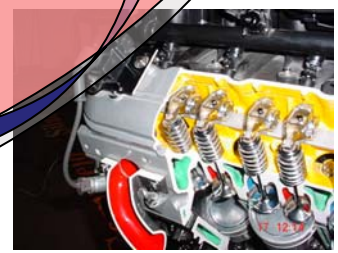
Fuel cell and battery modeling

Experiments

Engineering Science

Advanced Engine





Success metrics

- Number of graduates per year placed in auto industry
- Number of students in the program, including OSU graduate students and industry participants
- Auto companies participating in internship and recruitment programs
- Funded research programs leveraged from GATE
- Publications and patents
- Number of specialty courses developed and taught and number of team-taught courses
- Number of participating faculty
- Variety of courses across disciplines
- Outreach and societal impact
- International participation

Current DOE Fellows

Name: Edward T. Hillstrom
Major: Ph D in Mechanical Engineering
GPA: 3.81/4.00
Advisor: Prof. Giorgio Rizzoni
Title of thesis/subject of research project: Development of a high-performance fuel cell propulsion system for a land speed record vehicle
Expected graduation date: June 2009
Employment accepted: N/A

Name: Chris Suozzo
Major: M.S. in Electrical and Computer Engineering (ECE)
Advisor: Prof. Giorgio Rizzoni (ECE)
Title of thesis/subject of research project: Battery aging diagnostics and prognostics
(Expected) graduation date: March '09
Employment: N/A

Current DOE Fellows

Name: Leon Headings
Major: Ph.D. in Mechanical Engineering (ME)
GPA: 3.91/4.00
Advisor: Prof. Gregory Washington (ME)
Title of thesis/subject of research project: Modeling, design, and control of thermoelectric energy systems in hybrid vehicles.
(Expected) graduation date: June 2009
Employment accepted: N/A - Started technology transfer small company

Name: Jason Meyer
Major: MS in Mechanical Engineering (ME), PhD in Electrical Engineering (ECE)
Advisor: Prof. Guezennec (ME) and Yurkovich (ECE)
Title of thesis/subject of research project: Modeling and Calibration of Next Generation of Charge and Residuals Estimation in ICEs (MS)
Advanced control of transmissions for drivability (PhD)
(Expected) graduation date: June 2008 (MS) / June 2011 (PhD)
Employment accepted: N/A

Current DOE GATE Fellows

Name: Benjamin Sinsheimer
Major: M.S. in Electrical and Computer Engineering (ECE)
GPA: 3.60/4.00
Advisor: Prof. Giorgio Rizzoni (ECE)
Title of thesis/subject of research project: Development of a high-performance fuel cell propulsion system for a land speed record vehicle
(Expected) graduation date: March '08
Employment (accepted): A123

Past DOE Fellows

Name: Michael Arnett
Major: M.S. in Mechanical Engineering (ME)
GPA:3.87/4.00
Advisors: Profs. Giorgio Rizzoni and Eric Westervelt, (ME)
Title of thesis/subject of research project: Development and Implementation of an eAWD System for a Series-Parallel Hybrid Electric Vehicle
Graduation date: August 2007
Employment: General Motors (HEV group)

Name: Michael Flory
Major: Ph.D. in Mechanical Engineering (ME)
GPA: 3.87/4.00
Advisors: Prof. Giorgio Rizzoni and Yann Guezennec, (ME)
Title of thesis/subject of research project: Diesel HCCI Combustion and Control
(Expected) graduation date: 2009 – on leave
Employment: Hiltner Combustion Systems

Past DOE Fellows

Name: Kris Sevel
Major: M.S. in Mechanical Engineering (ME)
GPA: 3.80/4.00
Advisors: Profs. Yann Guezennec and Giorgio Rizzoni, (ME)
Title of thesis/subject of research project: Modeling and Control of Start/Stop of a Diesel engine in an HEV application
Graduation date: June 2007
Employment: General Motors – Hybrid Powertrain

Present Industry GATE Fellows

Name: Angelo Esposito
Major: Ph.D. in Mechanical Engineering (ME)
GPA: 3.61 /4.00
Advisors: Profs. Yann Guezennec, (ME) and Cesare Pianese, University of Salerno, Italy
Title of thesis/subject of research project: PEM Fuel Cell System modeling for automotive applications with emphasis on water transport dynamics – Dual PhD (co-advised) at UNISA (University of Salerno), Salerno, Italy
Expected graduation date: June 2010 (both degrees)
Employment accepted: N/A

Name: Yiran Hu
Major: Ph.D. in Electrical and Computer
GPA: 4.00/4.00
Advisors: Profs. Steve Yurkovich (ECE) and Yann Guezennec (ME)
Title of thesis/subject of research project: Modeling, control and optimization of engine processes using linear parameter varying modeling techniques and genetic algorithms
Expected graduation dates: December 2009
Employment accepted: N/A

Present Industry GATE Fellows

Name: Kerem Koprubasi
Major: Ph.D. in Mechanical Engineering (ME)
GPA: 3.89/4.00
Advisors: Profs Giorgio Rizzoni and Eric Westervelt, (ME)
Title of thesis/subject of research project: Extended Bump-less Transfer for Switched Hybrid Systems with Applications to Hybrid Electric Vehicle Control
(Expected) graduation date: September 2008
Employment accepted: N/A

Name: **Bruce Adcock**
Major: Ph.D. in Computer Science and Engineering (CSE)
GPA: 3.50/4.00
Advisor: Prof. Bruce Weide, CSE
Subject of research project: Media/data center for multiple CAR projects, Distance Education, and using genetic algorithms for optimization problems.
(Expected) graduation date: June 2009
Employment accepted: N/A

Present Industry GATE Fellows

Name: Kerem Koprubasi
Major: Ph.D. in Mechanical Engineering (ME)
GPA: 3.89/4.00
Advisors: Profs Giorgio Rizzoni and Eric Westervelt, (ME)
Title of thesis/subject of research project: Extended Bump-less Transfer for Switched Hybrid Systems with Applications to Hybrid Electric Vehicle Control
(Expected) graduation date: September 2008
Employment accepted: N/A

Name: Pinak Tulpule
Major: Ph.D. in Electrical Engineering (ECE)
Advisors: Prof Steve Yurkovich
Title of thesis/subject of research project: Modeling, Optimization and Control of Plug-in Hybrids
(Expected) graduation date: June 2010
Employment accepted: N/A

Present Industry GATE Fellows

Name: Kerem Bayar
Major: Ph.D. in Mechanical Engineering (ME)
Advisors: Prof Giorgio Rizzoni
Title of thesis/subject of research project: Hybrid Electric Vehicle Modeling and Control
(Expected) graduation date: June 2010
Employment accepted: N/A

Past Industry GATE Fellows

Name: Ta-Young “Gabriel” Choi
Major: Ph.D. in Mechanical Engineering (ME)
GPA: 3.97/4.00
Advisors: Prof. Yann Guezennec (ME)
Title of thesis/subject of research project: Modeling, Sizing, and Control of Plug-in Light Duty Fuel Cell Hybrid Electric Vehicle
Graduation date: March 2008
Employment: General Motors (Fuel Cell control group)

Name: Courtney Coburn
Major: M.S. in Mechanical Engineering (ME)
GPA: 3.70/4.00
Advisors: Profs. Giorgio Rizzoni andYann Guezennec (ME)
Title of thesis/subject of research project: Experimental Validation and Closed-loop Control of a Bifurcated Lean NOx Trap System with By-pass Regeneration
Graduation date: December 2006
Employment: Caterpillar, Inc.

GATE Course Offerings

Pilot version of the new course ME-794R "*Automotive System Integration*", Spring '07

Planned in '06 quarter and early '07, we developed a new Automotive System Integration course. In early '07, the proposed course was officially approved in the Mechanical Engineering and the College of Engineering and was offered in Spring quarter 2007 to 11 students (ME/ECE) by Prof. Guezennec (ME).

Group case study based on the system integration of an electric commuter vehicle

Interaction with virtual suppliers and vendors

Guest lectures by industry executives

Next offering scheduled for Fa '08

GATE Course Offerings

Pilot offering of the new course ME-794A, *"Modeling and Applications of Smart Materials"*, Winter '07

During the Fall '06 quarter, we continued the planning and course development for this new course. This new course correspond to the proposed offering of an "***Introduction to Sensor and Actuator Technology"*** course and has been re-titled to reflect content. This new course was offered in the Winter quarter 2007 by Prof. Dapino (ME)

Next offering scheduled for Wi '09

GATE Course Offerings

Incorporation of automotive case studies in the course ECE/CSE 668 "*Applied Software Engineering*", Winter '07

The course was offered during the Winter 2007 by Prof. Faruk Khan (ECE/CSE) to over 30 ECE/CSE and ME students. The course incorporated a new software engineering case study based on the ChallengeX program. Some DOE funds for curriculum development were devoted specifically for the support of GRA's for this course development. This two Graduate students did complete their MS in CSE in Wi '07 and Sp '07 with a thesis on related topics. Additionally, several of the GATE Fellows were assisted in developing the case study.

GATE Course Offerings

The course ME 788/794Y *"Fuel Cell Systems for Automotive Applications"*, Spring '08

The course will be offered during the Spring 2008 by Prof. Guezennec (ME/ECE) to over 20 ME and ECE students. This course was offered in a pilot offering form (ME 794Y) in Sp '06 as part of the GATE program course development. This course is also offered simultaneously via distance learning to over 20 engineers in the automotive industry (primarily GM).

GATE Course Offerings

Permanent offering of the course ME 631 "*Powertrain Instructional Laboratory*", Spring 2007

Significant effort went into the development of a new laboratory in the newly inaugurated Scott Laboratory, the new home of the Department of Mechanical Engineering. This (now permanent) yearly course was offered during the Spring '07 quarter by Dr. Soliman (ME/CAR) to 14 students (ME).

Next offering scheduled for Sp '08

GATE Course Offerings

Other GATE course offerings (not a stated deliverable, but *integral* part of the program):

The course ME 784 "*Energy modeling of hybrid Electric Vehicles*", was offered in Fall '07 by Prof. Guezennec (ME), with an enrollment of 14 OSU students (ME, ECE) and 15 GM distance learning students (Fall 2007 GM Outstanding Distance Learning Faculty Award).

The course ME 754 "*Optimization and control of Hybrid and Electric Vehicles*", is currently offered in Winter '08 by Profs. Guezennec (ME) and Yurkovich (ECE), with an enrollment of 12 OSU students (ME, ECE) and 4 GM distance learning students.

NOTE: ME 784 and ME 785 are courses developed under the previous GATE award, currently in their 6th offerings having impacted hundred of students at OSU and industry !

GATE Course Offerings

Other GATE course offerings (not a stated deliverable, but *Integral* part of the program):

The course ME 781 "*Powertrain Dynamics"* was offered during Autumn quarter 2006 by Prof.s Rizzoni (ME/ECE) and Srinivasan (ME), with an enrollment of 22 OSU students (ME and ECE) and 21 GM distance learning students.

The course ECE 753.01/ME 782D "*Powertrain Control"*, was offered during Winter quarter 2007 by Prof. Yurkovich (ECE), with an enrollment of 13 OSU students (ME and ECE) and 19 GM distance learning students.

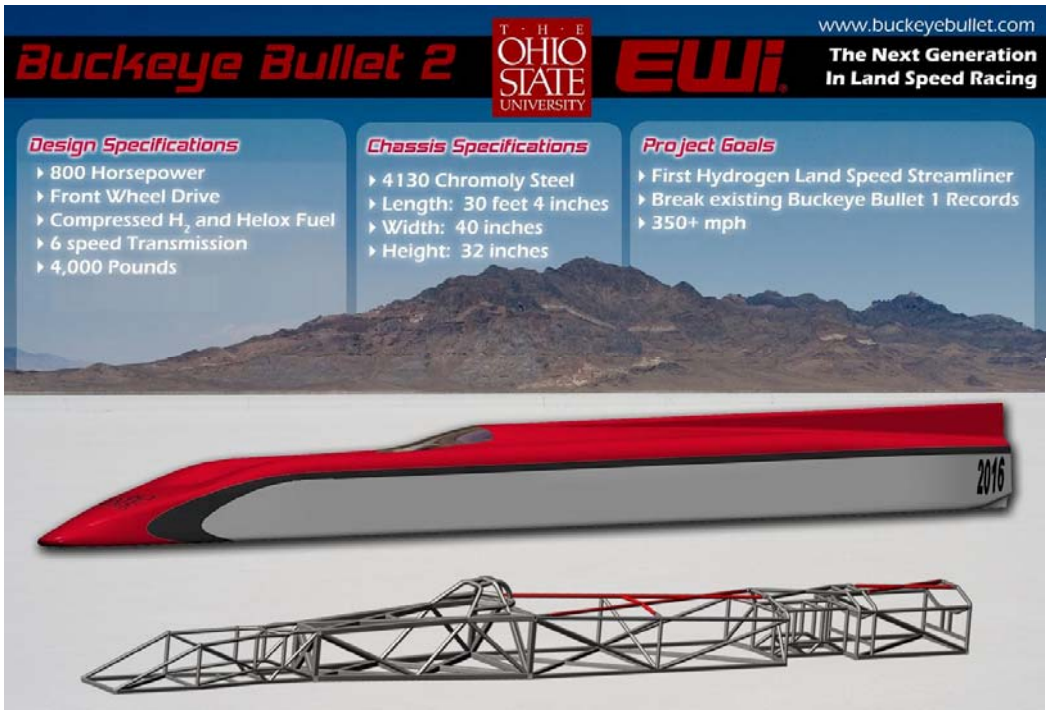
The course ME 730 "*IC Engine Modeling",* was offered in Spring quarter 2007 by Dr. Midlam-Mohler (a former GATE PhD graduate), with an enrollment of 8 OSU students (ME).

The course ME 874 "*Automotive System Diagnostics*" is currently being offered in Wi '08 by Prof. Rizzoni, with an enrollment of 12 OSU students (ME and ECE). Will be offered (time-delayed) to industry (GM, Chrysler)

+ many short courses (8-16 hours) developed and offered primarily to industry on specialized topics relevant to GATE program students (Electrical Energy Storage Systems for Traction Applications, Advanced Diesel Engines, Alternative Fuels, Fuel Cell Systems Control…) taught by OSU professors and researchers, with international participation (ETH Zurich, U. Stuttgart…)

A few accomplishments…

• Design and realization of a Land Speed Record vehicle powered by fuel cells, the BuckeBullett 2

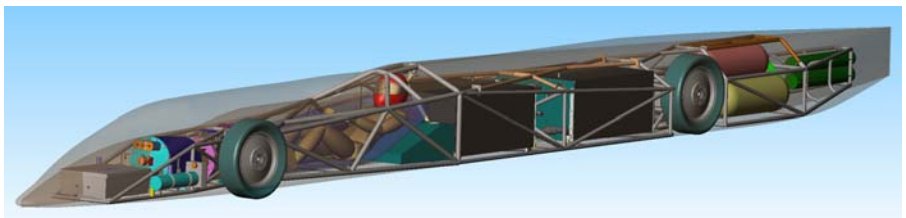


• Designed and built by students (ME, ECE and Aero), and leadership of two GATE fellows

• Strong partnership with Ford and Ballard and a host of other sponsors

• Made history at Bonneville Salt Flats in August and October ’07 with the fastest hydrogen-powered vehicle.

• Watch us in ’08… continuing to make history at Bonneville Salt Flats in August and October !



A few accomplishments…

The NEV FC Hybrid project

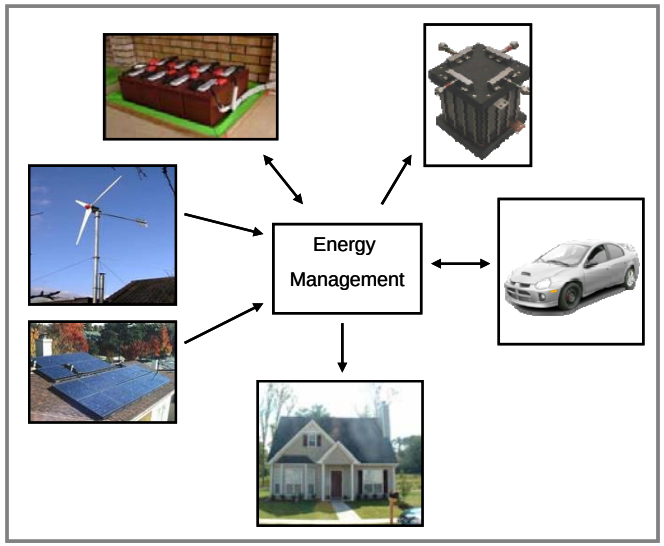
- Organized as a demonstration exercise / technology showcase / learning platform
- Focus on more efficient/sustainable local transportation
- Neighborhood Electric Vehicle (NEV) chosen because of cost constraints – Learning highly applicable to commuter vehicles
- Led by a GATE Fellow (currently employed by GM in fuel cell control group)
- High involvement of undergraduate students in the research
- Project used for special lecture in GATE class ME-794R *System Integration in Sp '07*

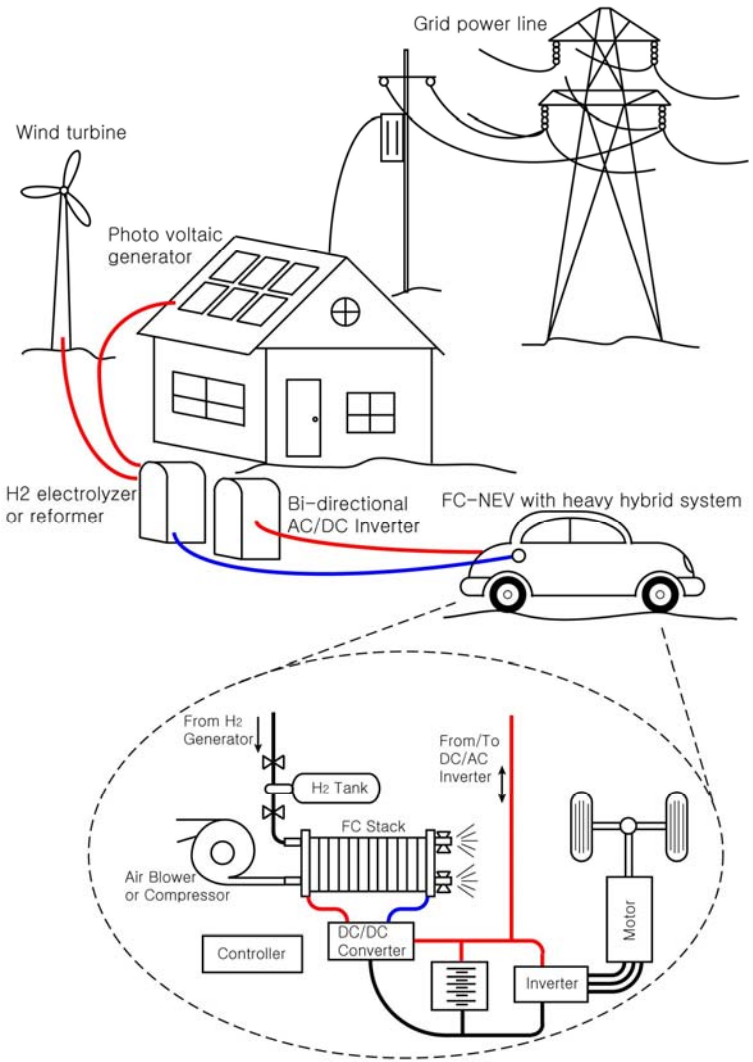
- Facets of the project:
  - Vehicle as part of a personal eco-system
  - Optimization of powertrain architecture and components
  - Component and sub-system testing
  - System integration:
    - Mechanical
    - Electrical
    - Controls
    - Electrical and H_2 Safety
    - Telematics and data acquisition
  - Realization

A few accomplishments…

The NEV FC Hybrid project

- Matlab-based “Personal Ecosystem” simulator
- Energy flows from/to different components
- Daily energy produced from renewables
- Excess energy management
  - Electrolyzer, until the initial condition of the H2 tank is restored (the daily hydrogen production equals the daily vehicle consumption)
  - Off-board battery, until the threshold SOC is reached
- When the vehicle is parked, the on-board battery can be:
  - recharged to a desired SOC (according to the driver schedule)
  - used as a backup energy provider for the residential load
- Work as led to multiple conference papers and theses





A few accomplishments…

ChallengeX competition – Leadership by GATE Fellows

4th Place overall

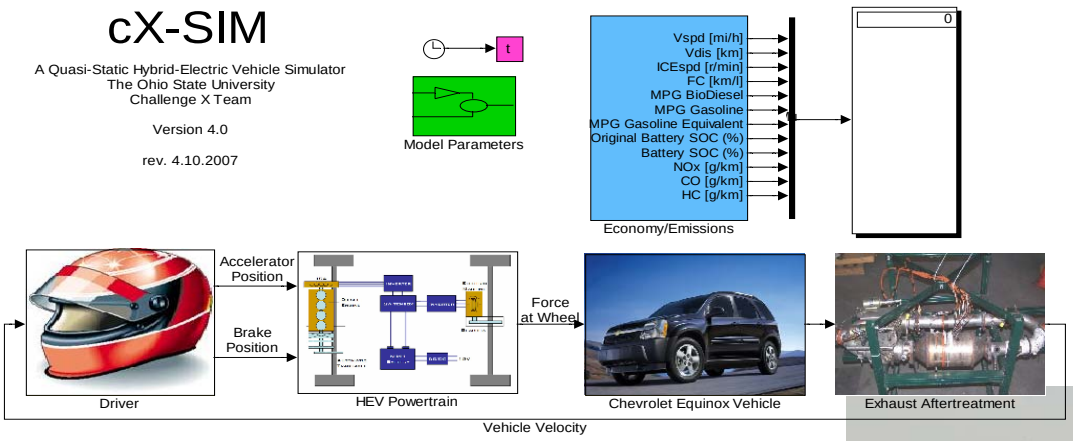
BEST NOISE (yes, with a Diesel engine!!! This is what control can do fc[illegible])

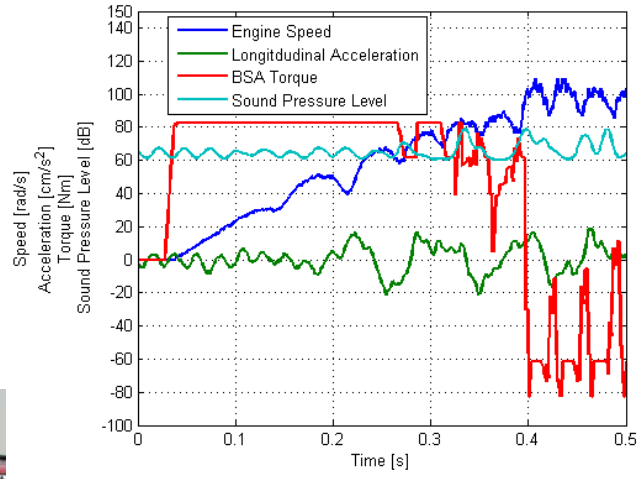
DYNAMIC DRIVE QUALITY AND CONSUMER ACCEPTABILITY (yes, with a Diesel engine!!! This is what control can do for you…)

2nd PLACE, MATHWORKS: CROSSOVER TO MODEL BASED DESIGN AWARD

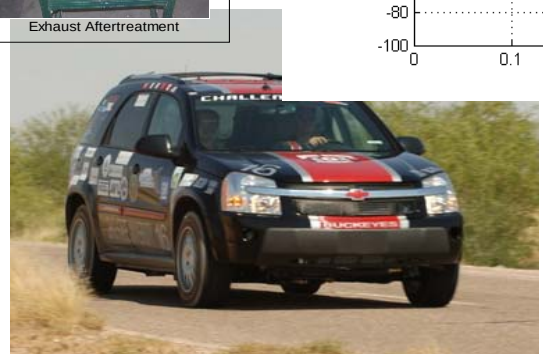
OUTREACH AWARD FOR BEST SPONSORED EVENTS

NSF OUSTANDING FACULTY ADVISOR AWARD (Rizzoni et al.)





➔ **Multiple papers and theses from this work**



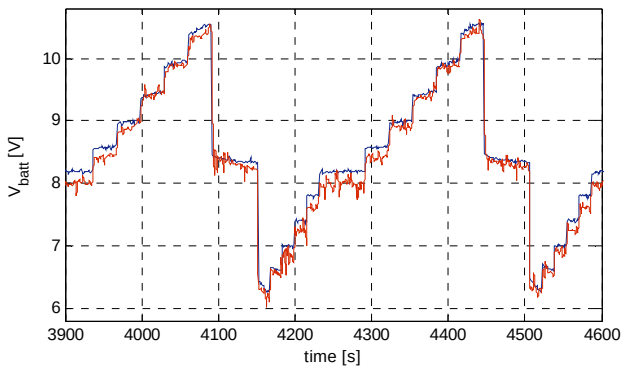
A few accomplishments…

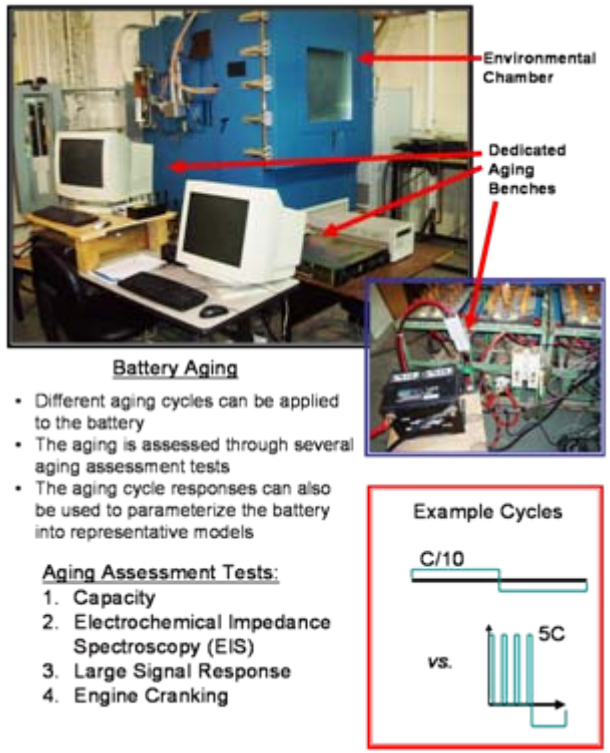
Battery electro-thermal battery characterization

- HITL battery system evaluation (few hundred W up to 75 kW)
- Multiple battery cell and module test facilities
- 2 environmental chambers
- Battery aging
- Modeling capabilities
- In-vehicle validation and data collection

Activities

- Electro-thermal dynamic battery odel development and validation
- Development and validation of SoC estimators
- Various chemistries: advanced PbA, NiMH, Li-ion





A few accomplishments…

New Battery Aging Lab (7 stations, 24/7 operation)

- Multiple battery aging cyclers comprised of:
  - Programmable loads and supplies
  - Environmental chamber and/or Peltier junctions to control cell/module temperature
  - Individual PC-based, Labview individual data acquisition system and Phytec MPC-555 microprocessor system controller for each cycler
  - Designed for accelerated aging and aging assessment of NiMH and Li-ion cells modules
- Architecture mimicking parallel computer cluster
  - Multiple cyclers in parallel for accelerated testing
  - Overall system architecture designed for 24/7 safe operation with redundant control systems
  - All cyclers connected by dedicated Ethernet to supervisory safety controller and data archiver computer, with emergency operator paging system and accessible through VPN via the Web.
- Used for characterization of aging of batteries in HEV applications and End of Life (EOL) determination
- Electrochemical Impedance Spectroscopy (EIS) capabilities for non-intrusive damage assessment and prognostics

A few accomplishments…

Recent Fuel Cell Research activities:

- **Consortium**:
  - **Construction of single channel passive fuel cell with optical access with microscope imaging –** Used for experimental characterization of single water droplet formation, coalescence and migration on GDL in fuel cell channels; liquid film dynamics and removal in fuel cell channels; interfacial model development and validation of water/air/GDL

- **Modeling and testing of a Diesel-fueled reformer and PEM fuel cell APU** for with Battelle Memorial Institute/TACOM

- **BuckeyeBullett II – A fuel cell powered land speed record vehicle**

- **Technical and user evaluation of Ford Focus FCV**
  - One of Ford FCV has been on loan to CAR in early ’07 (enabled by the presence of a hydrogen refueling station at CAR inaugurated Sp ‘06)
  - Ford engineers provided a ‘deep-dive’ training into the vehicle architecture and full access to all data and diagnostics

Summary

- The GATE program at Ohio State is on track with the SOPO
- DOE funds are significantly leveraged by industry $$
- The program has already graduated 4 MS students placed in the automotive industry (2 more MS + 1 PhD in Wi/Sp ’08)
- New courses have been developed and offered at OSU and the automotive industry with significant enrollment

- Program is leveraged with significant industry-sponsored research

- GATE students play a significant leadership role in student competitions (cX, Eco-car) and highly visible high technology vehicle demonstrations (BuckeyeBullett 2, NEV, etc…)

- The GATE program leverages very extensive research experimental facilities