GATEWAY TO THE FUTURE

GATE

GRADUATE AUTOMOTIVE TECHNOLOGY EDUCATION

CUICAR

CLEMSON UNIVERSITY INTERNATIONAL CENTER FOR AUTOMOTIVE RESEARCH

DOE GATE Center of Excellence in Sustainable Vehicle Systems

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CLEMSON UNIVERSITY 1889

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Overview

Timeline

- Project start date: 10/1/2011
- Project end date: 09/30/2016
- Percent complete: 28.7%

Barriers

- Graduate engineering workforce
- Technology barriers addressed:
  - System Cost
  - Reliability and life
  - Performance

Budget

- Total project funding: $1,250,000
  - DOE share: $1,000,000
  - CU share: $250,000
- Funding received in FY12: $348,873
- Funding received for FY13: $137,000
- Percent completed: 28.7%

Partners

- Many automotive OEMs and suppliers
- Project Lead: CU-ICAR

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Project Objectives - Relevance

- DOE's VT Program Vision for GATE
  - Help overcome technology barriers in the design and development of cost effective, high-energy efficiency vehicles for the US market through an integrated research and education graduate program

- Clemson GATE Center's Specific Goal: Establish a GATE Center of Excellence in Sustainable Vehicle Systems that trains graduate Fellows at the MS and Ph.D. level by:
  - Creating a dedicated GATE Curriculum
  - Establishing a new Advanced Powertrain Integration Laboratory by leveraging state-of-the art equipment at CU-ICAR and acquiring new equipment
  - Engaging in graduate research endeavors that address specific technical challenges in the area of sustainable vehicle systems

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FY12-13 Objectives

- Recruit MS and Ph. D. students to populate the GATE program
- Establish the GATE Center curriculum within the Automotive Engineering graduate program
- Establish application and selection procedures and advertise the opportunity provided by the GATE Center
- Develop GATE Powertrain Integration Laboratory
- Leverage industry, departmental and CU-ICAR facilities and partnerships
- Upgrade existing courses and develop and offer the proposed new lab course
- Set up internal assessment process

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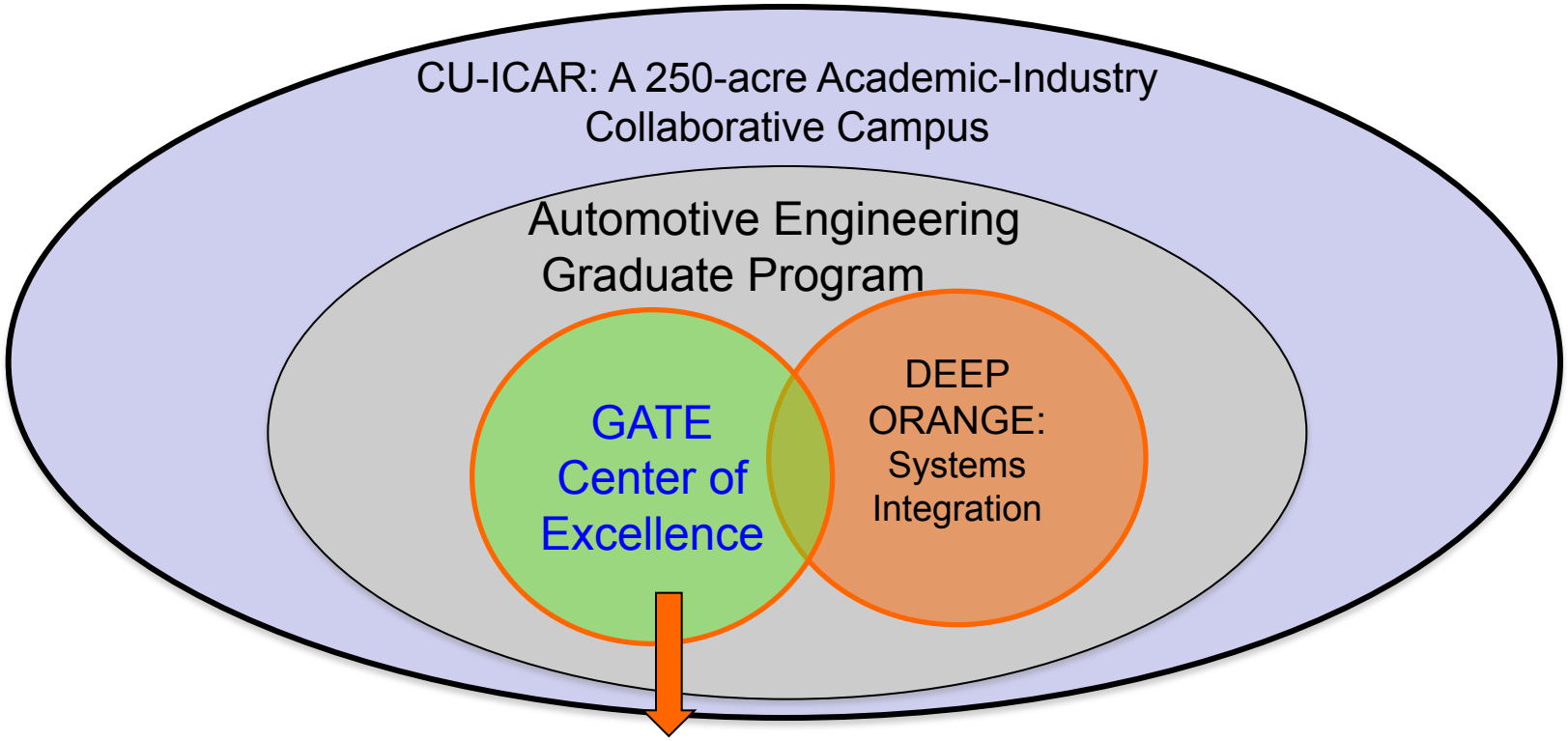
Milestones FY12 and FY13

- Milestone 2.2 - Advertised and Recruited second cohorts of PhD GATE fellows
- Milestone 3.1, 5.1 - New Course Developed and Taught in Fall 2012: AuE 893-4: Hybrid Powertrain Control.
- Milestone 3.2 - Completed Upgrade of AuE 881: Automotive Systems and Development
- Milestones 3.4, 5.2, 5.3 - Upgraded Courses AuE 817: Advanced Vehicle Propulsion Systems and AuE 827: Powertrain Control Systems; completed class teaching first offering.
- Milestone 3.5 - Vehicle Powertrain Integration Lab Development Completed
- Milestone 4.3 - Completed Review of GATE Center with AuE Industrial Advisory Board, VTP Reps, DOE Labs, GATE Fellows, Faculty, graduate research committee (Feb 2012)
- Milestone 8.2 – Submitted Semi-annual reports on April 2012, Oct 2012

Approach 1:
Deployment of the Clemson DOE GATE Center



GATE MS and Ph.D. Curriculum

- ✓ Core GATE Automotive Engineering courses
- ✓ GATE-designated electives
- ✓ Sustainability minor for Ph.D. GATE Fellows
- ✓ 6-month internship for MS GATE Fellows
- ✓ Graduate Seminars

Approach 2:

Application and Selection of GATE Fellows

- Candidates must satisfy admission requirements to the Automotive Engineering graduate program at Clemson University, including the following:
  - BS degree in an engineering or applied science discipline
  - GPA above 3.5 in the last degree attained
  - Preferably two years of post BS work experience
  - Exceptional GRE scores
  - Research plan essays for Ph.D. candidates
  - At least three recommendation letters
  - If deemed necessary, interview with selection committee
- Fellowships
  - Merit-based paid fellowships ranging from $10k-$18k/year with possible remission of tuition to the top candidates, subject to availability of funding.
  - Select candidates may also be supported independently through research grants, awards, scholarships and other means.

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Approach 3:

GATE MS Program

- Goals of Program:
  - To train the highly skilled automotive engineering workforce with the technical depth and breadth needed to address applied system integration challenges with sustainable vehicle systems including:
    - Design, control and integration of advanced powertrain concepts
    - Component and system diagnostics and reliability
    - Light-weight design and manufacturing
    - Business perspectives and market viability of ideas/products
- Current Requirements:
  - 7-Core GATE courses plus a seminar for 19 credits (in Green)
  - 6 Support Courses for 18 credits (AuE Core (in Blue))
  - 6 Credits of internship at industry locations or participating in the Deep Orange vehicle prototyping project at CU-ICAR
  - GATE-designated electives (in Red) allowed by substitutions
- Some constraints are still being worked out by the AuE faculty

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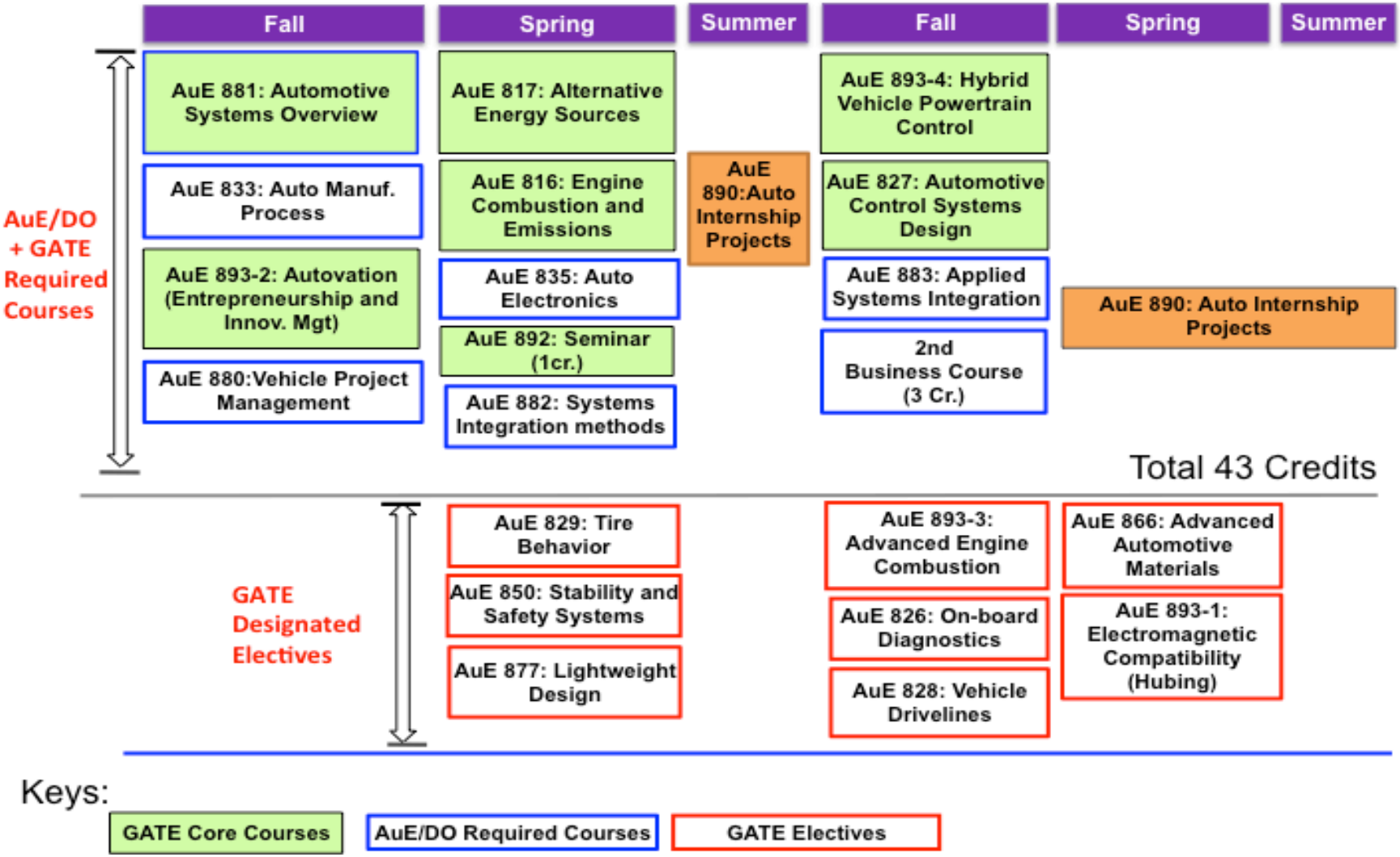
Approach 4:

Curriculum Details (MS)



Approach 5:

GATE Ph.D. Program

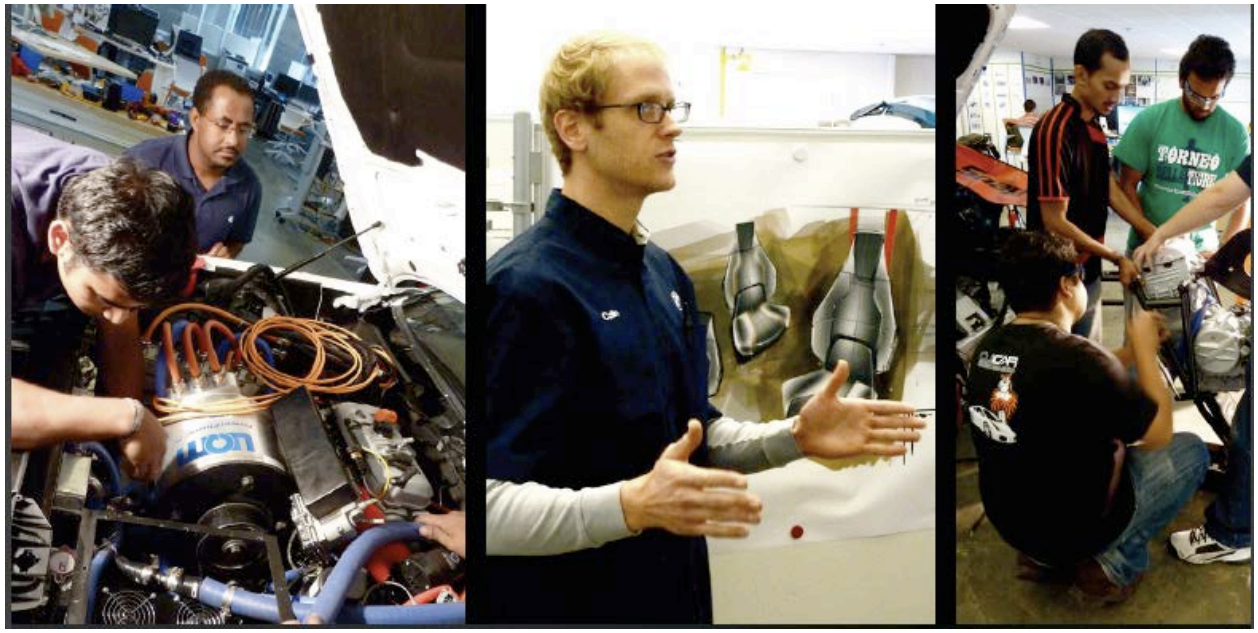
- Goal of Program:
  - To train technical experts at the Ph.D. level who act as thought and innovation leaders with an understanding of the broader challenges and opportunities for the automotive sector from the perspectives of energy resource economics, life-cycle impact and public policy
  - For technical expertise:
  - 7-Core GATE courses plus a seminar for 19 credits (in Green)
  - Sustainability Minor
  - More courses as needed for specific research (minimum of 60 credits post BS)
  - Complete doctoral dissertation in the area of sustainable vehicle systems

- Sustainability Minor: Select 2 courses from those identified by the CU President's Commission on Sustainability. Examples:
  - AP EC 657 Natural Resource Use, Technology and Policy
  - EN SP 671 Man and his Environment
  - EN SP 400 Studies in Environmental Science
  - ME 620 Energy Sources and their Utilization

Approach 6:

Deep Orange - Mimicking OEM Vehicle Development Processes in 2-Yr Graduate Education

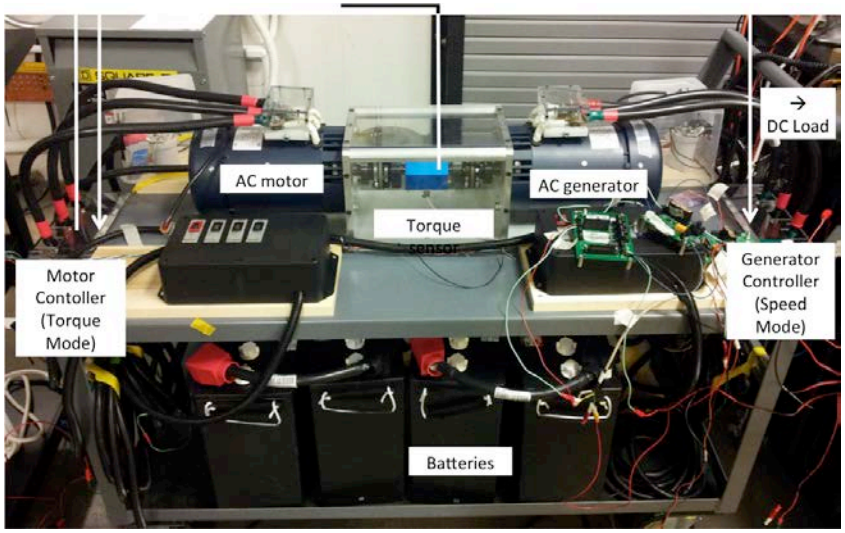
Deep Orange is a framework that immerses graduate AuE students into the world of a future OEM and/or supplier. Working collaboratively, students, multi-disciplinary faculty, and participating industry partners focus on producing a new vehicle prototype each year. Each project incorporates integrating breakthrough product innovations and new processes, providing the AuE students with hands-on experience in vehicle design, engineering, prototyping and production from the time they enter into the academic program until graduation.



Accomplishment 1:

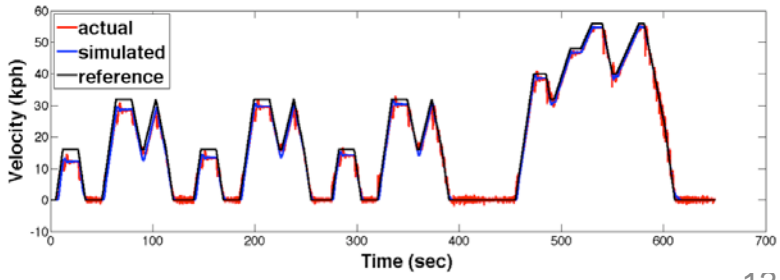
Creation of Course AuE 893-4: Hybrid Powertrain Laboratory

- Lab modules Include
  - Real-time Data Acquisition
  - Characterization of EV/HEV batteries (uses DC Load, HPS, dSPACE, thermo-couples, environmental chamber)
  - AC Motor/Generator: Control and Efficiency Mapping
  - EV Drive Cycle Emulation: BEV, Motor under feedback torque control
  - Series/Parallel Drive: APU to DC-load plus battery
  - Fuel Cell control and energy management
  - Hybrid/EV Vehicle Energy Management
  - Battery Management Systems (BMS)
- Course was offered in Fall 2012 for the first time.



EV Hardware-in-the-Loop Emulation Platform

- Motor, inverter and battery in hardware
- Vehicle and driver simulated in software



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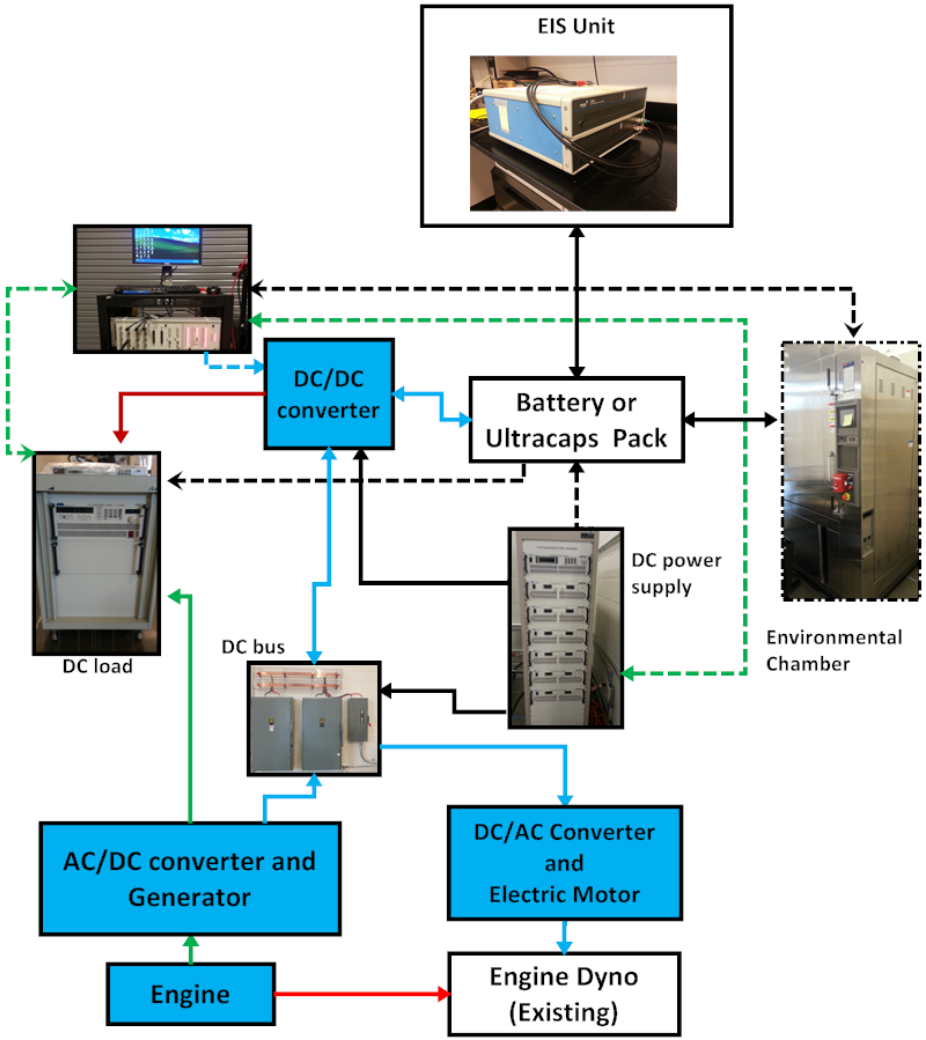
Accomplishment 2:

Creation of GATE Powertrain Integration Laboratory

Working volume for HEV battery pack

HEV ECMS Energy Management Strategy



Accomplishment 3:

Specific Research and Educational Activities Enabled by the GATE Laboratory

- Characterization of electric and hybrid vehicle driveline components
  - Impedance characterization of batteries, supercapacitors, fuel cells
  - Temperature and humidity controlled environmental chamber
    - Battery life prediction models: degradation, ageing, failure modeling
  - Efficiency mapping of electric motors and generators
  - Testing of power electronics: motor controllers, BMS, etc
- Hardware-in-the-loop (HIL) testing of powertrain systems
  - Energy management strategies for EV, series, parallel hybrid architectures
  - Integrated energy efficiency and vehicle dynamics
- Advanced engine control research
  - Validation of novel control algorithms for multi-fuel engine operation
- Fault diagnostics and prognostic algorithms for advanced hybrids
  - Analyzing component and system behavior under fault injection in simulated experimental environments
  - Methodologies for automatic calibration of diagnostic thresholds for fault detection and isolation, for characterization of failure evolution, failure propagation and identification of fault features

Accomplishment 4:

Creation of Course AuE 892 Seminar

- Seminar series on topics of interest to automotive engineers in the area of leadership, and sustainable and networked mobility.

Sample of seminar speakers FY 2012:

- **9/27/12 - The Future of Personal Transportation,** Dr. J. Gary Smyth, Executive Director, North American Science Labs,GM Global Research and Development
- **11/13/12** - **Control of NOx Aftertreatment for US Diesel Powertrains** Michiel Van Nieuwstadt , Diesel Controls and Diagnostics, Ford Motor Company, Research and Advanced Powertrain Controls
- **12/14/12** - **Internal Combustion Engines of the Future: Clean and Efficient Use of Alternative Fuels**, Dr. Carrie M. Hall, Purdue University

FY 2013 External Speakers (Spring 2013)

- **Creating Sustainable GreenVillages**, Fred Payne, Greenville County Council
- **IEEE Transportation Electrification**, Dr. Lee Stogner, Chair of IEEE Transportation Electrification Initiative
- **Innovation through Technology Convergence**, Dr. Y. Eugene Pak, Director of Convergence Research Division, AICT, Seoul National University

Accomplishments 5:

Creation of Course AuE 893-3: Advanced IC Engines Concepts

- This course covers novel modes of combustion in IC engines, in-depth study of the underlying phenomena, and advanced engine systems required to translate the novel combustion concept into a viable technology. The course will prepare students for contributing to future advanced efforts in the research and development setting, at either the university or the industry R&D facility.

  The impact of powertrain integration, such as the potential synergy between the advanced engine concepts and various hybrid propulsion architectures, will provide the perspective regarding possible future directions.
- First Time offer in Fall 2012
- Students count: 10

Accomplishments 6:

Status of Recruiting and Enrollment (Year 2)

- Number of current GATE track student is 37:
  - 17 second year students and 20 first year students, exceeding the total of 25 for the 2nd year target
  - 28 MS students (including 3 female students)
  - 9 students pursuing Ph.D. degrees: Sara Mohon, Jacqueline Rios, Satadru Dey, Dave Anderson, Justin Callies, Thomas Schultz, Shuonan Xu, Zifan Liu, Ryan O'Donnell
    - 2 female Ph.D. students: Sara Mohon and Jacqueline Rios
- All Ph.D. GATE students are supported through research assistantships:
  - 2 by the direct DOE GATE Grant
  - 7 by other sponsored research in the focus area of the GATE Center
- 6 MS GATE students received MAZDA-GATE Fellowships ($10,000 each)
- Most MS students in the program are self-supported!

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Accomplishment 7:

Impact of the GATE Curriculum on the existing AuE program

	Fall 2011	Spring 2012	Summer I	Summer II	Fall 2012	Spring 2013
COURSE NUMBER	STUDENT COUNT	STUDENT COUNT	STUDENT COUNT	STUDENT COUNT	STUDENT COUNT	STUDENT COUNT
AuE 893- Autovation	15		7		11	17
AuE 881- Automotive Systems Overview	56				80	
AuE 827- Automotive Control Systems	18				22	
AuE 816- Engine Combustion and Emissions		38				53
AuE 817- Alternative Energy Courses		29				37
AuE 892- GATE Seminar		17			12	17
AuE 893- Hybrid Powertrain Control Lab					13	
AuE 890- External Industry Internship	4	27	30	31	9	35
AuE 890- Internal Deep Orange Internship		13	15	14		7

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Accomplishment 8:

Example of Recent Research Publications by GATE Fellows and Faculty

- Patent disclosures:
  - **S. Mohon, P. Pisu, P. Venhovens**, and J. Streit, "System and Method to Determine the Condition of a Battery"
  - J. Sill and **B. Ayalew**, " Predictive Tire Force Saturation Management for Vehicle Stability Control", with special application to independent electirc/hybrid drives
- **J. Rios**, and **P. Pisu**. "A Comparative Analysis of Optimization Strategies for a Power-Split Powertrain Hybrid Electric Vehicle," In *Proceedings. of the FISITA 2012 World Automotive Congress*, Lectures Notes in Electrical Engineering, 191, pp. 541-550, 2013.
- S**. Mohon**, A. Venkitakrishna, B**. Ayalew** and **P. Pisu**, "Development of an Electric Vehicle Hardware-in-the-Loop Emulation Platform**,**" ASME IDETC2013-12263*, International Conference on Advanced Vehicle Technologies, IDETC/CIE 2013* August 4-7, 2013, Portland, Oregon, USA.
- X. Zhang, and **P. Pisu**. "An Unscented Kalman Filter Based Approach for the Health-Monitoring and Prognostics of a PEM Fuel Cell," In *Proceedings of the Prognostics and Health Management Conference 2012,* Minneapolis, MN, Sep. 23-27, 2012.
- Y. He, **J. Rios**, M. Chowdhury, **P. Pisu**, and P. Bhavsar. "Forward Power-Train Energy Management Modeling for Assessing Benefits of Integrating Predictive Traffic Data into Plug-in-Hybrid Electric Vehicles," *Transportation Research Part D Journal,* **17**(3), pp.201-207, May 2012.
- J. Sill and **B. Ayalew**, "Vehicle Stability Control Through Predictive and Optimal Tire Saturation Management", 14th ASME *International Conference on Vehicle Technologies*, *IDETC/CIE 2012.* August 12-15, 2012, Chicago, IL.
- A. Mayyas, **M. A. Omar**, **P. Pisu**, A. Mayyas, A. Al-Ahmer, C. Montes and S. Dongri, "Thermal modeling of power-split hybrid powertrain packaging using battery cell-based model" *Journal of Power Sources*, **196**(15), 6588-6594 (2011).

*Participating GATE faculty and students identified by bold face.

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Accomplishment 9:

Leveraging DOE GATE Funds

- 6 Mazda GATE Fellowships $10,000/year each ~ $60,000/year
- 1 FEV GATE Fellowship $10,000/year
- Freescale Semiconductor: Internships 2/year with total cost of $20,000
  - Evaluation modules, development kits and software tools, valued at $5,000
- AuE Department additional cost share
  - Contribution to purchase of environmental chamber: $15,000
  - One GATE Fellow support: $18,000+ plus tuition remission ($11,086) ~ $29,086
  - New GATE Laboratory utilities and enclosures: $30,000
- Equipment in-kind contributions:
  - TM4 (electric motor and inverter) $6,000
  - E-Z-Go and Curtis Instruments (electric motors and controllers) $5000
- GM/Chevrolet to sponsor Deep Orange 5. Commitment of $300K. (2020 urban vehicle for GenY/Z living in U.S. Megacities; purpose built car sharing vehicle with limited autonomous driving). Includes Powertrain
- New faculty/staff hires in the topical areas of the GATE Center:
  - Dr. Zoran Filipi, Professor and endowed chair in advanced powertrain systems
  - Dr. Fadi Abu-Farha, Assistant professor in lightweight materials
  - Dr. David Smith, Assistant professor in automotive software engineering (New Hire, 2012)
  - 2 faculty searches underway in power electronics, and sustainable materials
  - GATE Program Coordinator (New Hire, 2012)

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Accomplishment 10:

New Projects in last 12 Months from Leveraging DOE GATE Laboratory and Funds

- Vehicle Modeling with Conventional and Novel Internal Combustion Engines, $201K, General Motors R&D ~ Filipi
- Modeling and Optimization of Electrified Propulsion Systems – Series HEV Truck with in-wheel motors, DoD (TARDEC) $199K ~ Filipi
- Fault Tolerant Hydraulic Hybrid, DoD (TARDEC)- $190K ~ Filipi, Ayalew
- Diesel-Assisted Natural Gas Operation for Compression Ignition Engines, EcoDual, growth company based in Beaufort, SC, $456K ~ Filipi, Prucka
- Thermal Barrier Coatings for Low Temperature Combustion Engines, NSF-DoE $1M ~ Filipi, Prucka

Sub-total: $2,046M

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Accomplishment 10 (cont'd):

New Projects in last 12 Months from Leveraging DOE GATE Laboratory and Funds

- Model-based Spark Control of Gasoline Engines, Chrysler, $266K ~ Prucka
- Developing a HiL/MiL Simulation and Control Model of a 9-Speed Automatic Transmission using Interlocking Dog Clutches, Chrysler, $120K ~ Venhovens, Prucka
- Ensuring Compliance while Developing Clean, Safe, and High Quality Aftermarket Performance Products," Sponsored by the Specialty Equipment Market Association (SEMA), Total: $998,284.00. Approved by SEMA Board. In final contract negotiations. ~ Venhovens, Prucka
- NSF CAREER Award. NSF. $450K for 3 years ~ Fadi-Abu Farha
- *USDOE* "Integrated Computational Materials Engineering (ICME) Development of Advanced Steel for Lightweight Vehicles", $325K ~ Fadi Abu-Farha

Sub-total: $2,159M

Accomplishment 11:

Internal Program Assessment

- Industrial Advisory Board Meeting, February 3,2012
  - Represented companies: BMW, Mazda, FEV, Michelin, Proterra, ZF Lemforder, Okuma, Koyo Bearings, Timken, SEMA
  - Discussion of overall graduate and GATE program, and industry feedback
- AuE Faculty Retreat: February 10, 2012
  - Discussion on how the GATE program fits in the current AuE curriculum
- Employer Evaluation (on internships and employment)
  - Technical background
  - Critical thinking
  - Taking initiative
  - Overall performance
- Student Self Evaluation
- A process has been set up to use the feedback for continuous improvement of the GATE Center and its integration in the AuE graduate program

Accomplishment 12:

Coordination and Collaborations with Other Institutions

- CU-ICAR hosted the SAE International Natural Gas Symposium, March 12-13, 2013.
- Exchange seminar on “Penn State DOE GATE Program for In-Vehicle High Power Energy Storage” and visit by Dr. Joel Anstrom from Penn State to CU-ICAR (February 22, 2012)
  - Exchanged GATE center implementation and experience
  - Particularly, on providing educational hands-on experience
- Course seminar on “Robust Drivetrain System Diagnostics” and visit by Dr. Pierluigi Pisu from CU-ICAR to Ohio State (March 2, 2012)
- GATE course seminar at CU-ICAR on EV Drives and Controllers by Prof. Dan Hammerstrom, Portland State University, Portland, OR.
  - Remote delivery, spring 2012
- CU-ICAR hosted the IEEE International Electric Vehicle Conference (IEVC) on March 4-7, 2012
  - Informal contacts made with other GATE centers and institutions working in different aspects of EV technology.

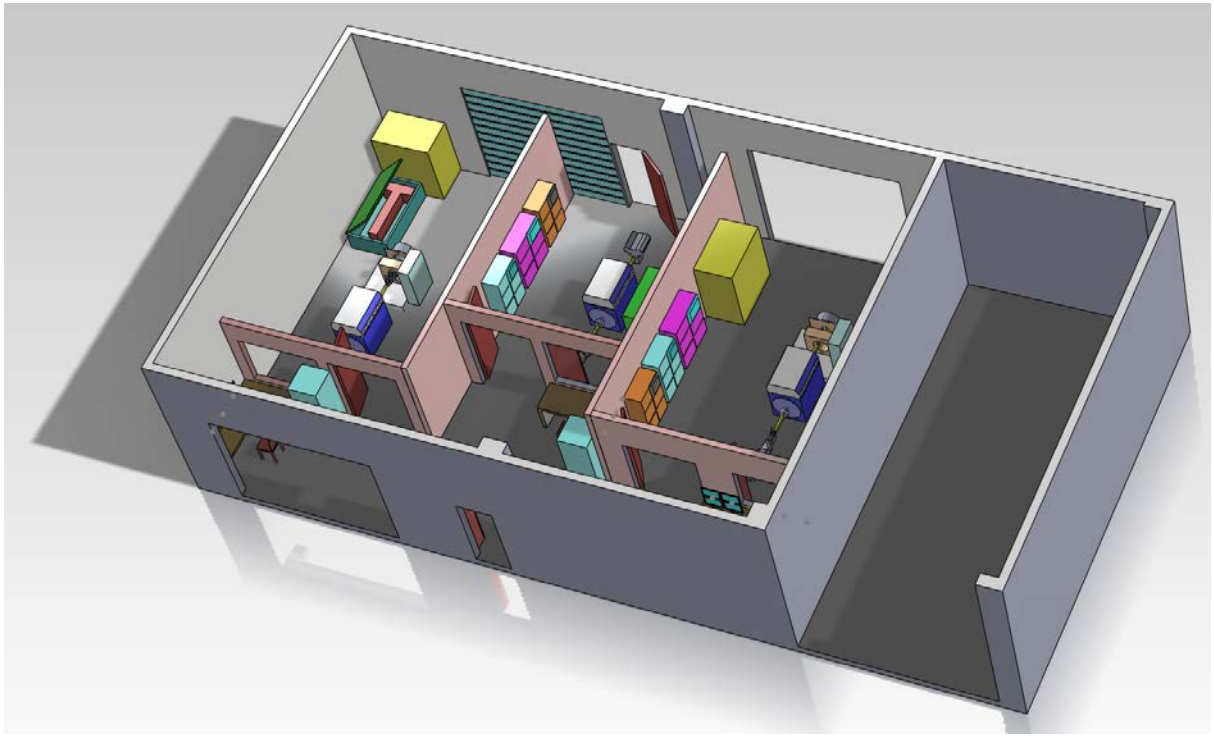
Proposed Future Activities (Year 3)

- Complete upgrades and new course offering
  - AuE 881: Automotive Systems and Development Processes: upgrade with emerging sustainability topics
  - AuE 827: Powertrain Control Systems: upgrade with lab demonstrations
- Secure more fellowship and internship opportunities for the GATE Fellows
- Hire two more faculty in the areas of power electronics and sustainable materials
- Foster additional collaboration with remote lectures, research forums and workshops
- Host workshops, conferences and events in the area of sustainable Vehicle Systems
- Initiate construction of New Advanced Experimental Facility

Future Activities:

New Advanced Powertrain Experimental Facility

- Emphasize flexible engine and powertrain system test capabilities



Summary

- Progress made on establishing Clemson's DOE GATE Center of Excellence in Sustainable Vehicle Systems
- 37 MS and Ph.D. students in the program this FY.
- Curriculum outlined, new course being developed, others being upgraded
- Developed GATE Powertrain laboratory
- GATE Faculty and Fellows engaged in specific research and publishing work in topical areas of the GATE Center
- GATE Center curriculum integrated with Deep Orange Project
- Good progress on leveraging funds for more GATE Fellow support and for providing internships
- Collaborations/coordination initiated with other GATE Centers and institutions on: curriculum materials, exchange lectures/seminars