



DOE GATE Center of Excellence in Sustainable Vehicle Systems

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Co-director and co-PI: Dr. Beshah Ayalew



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Project ID # TI024

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Overview

Timeline

- Project start date: 10/1/2011
- Project end date: 09/30/2016
- Percent complete: 9.1%

Budget

- Total project funding:
 - DOE share: \$1,000,000
 - CU share: \$250,000
- Funding received FY 2011: \$222,420
- Percent complete: 9.1%

Barriers

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

Partners

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

Involved Personnel and Expertise

- Dr. Beshah Ayalew, Co-PI: Control systems, electric and hydraulic hybrid powertrains, vehicle dynamics, process control
- Dr. Imtiaz Haque, PI: Modeling and simulation tools for advanced transmission concepts
- Dr. Todd Hubing, Co-PI: Vehicular electronics, electromagnetic compatibility for EVs, HEVs
- Dr. Mohammed Omar, Co-PI: Thermal modeling, non-contact measurement, automotive materials and manufacturing
- Dr. Pierluigi Pisu, Co-PI: System fault diagnosis and failure prognosis, hybrid electric vehicle energy management, battery life prediction
- Dr. Rob Prucka, Co-PI: Advanced engine concepts, multi-fuel engines
- Dr. Paul Venhovens, Co-PI: Systems integration challenges via Deep Orange Projects; Packaging, manufacturability, market viability, light-weight design
- Mr. Michael Messman: Research engineer, test equipment and lab management.

Project Objectives - Relevance

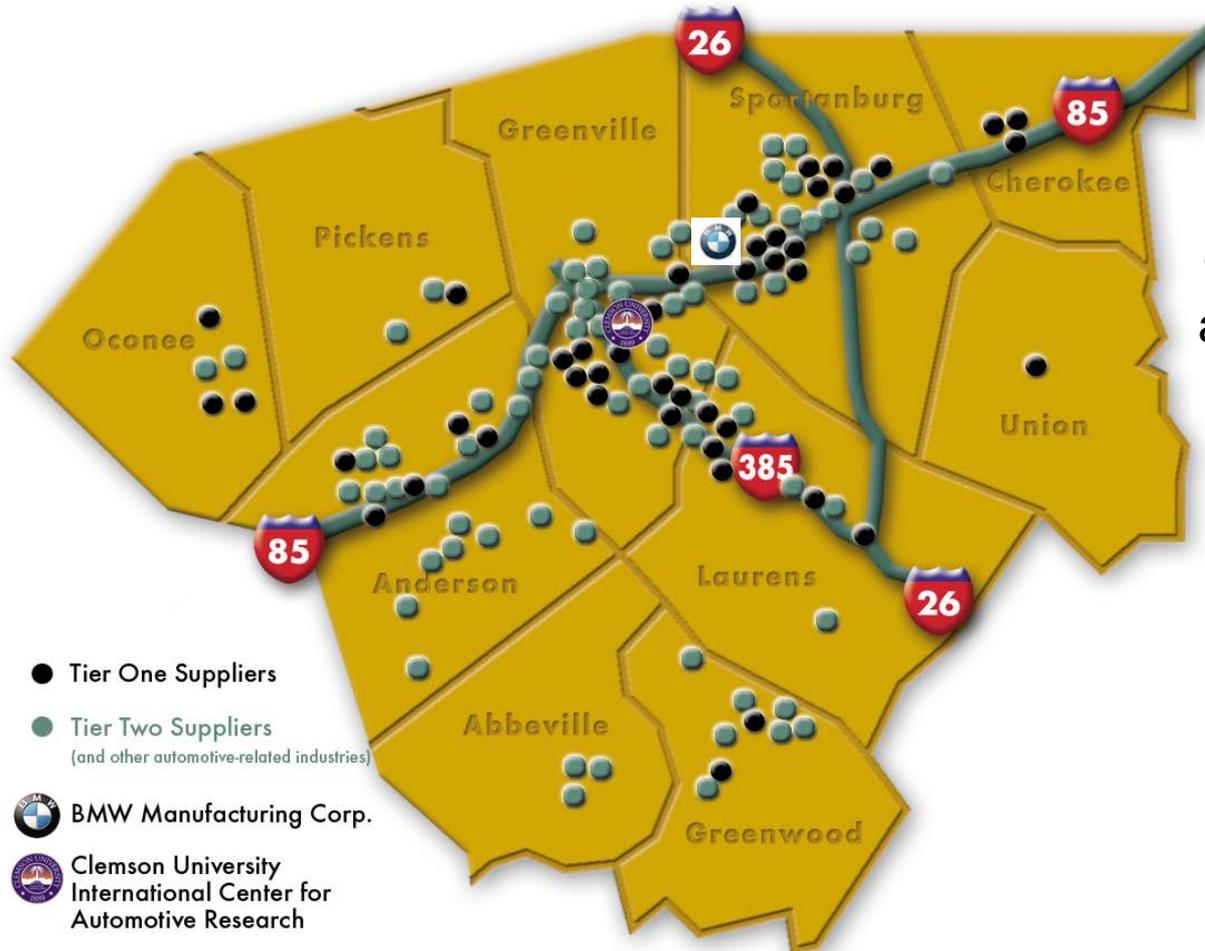
- DOE's VT Program Vision for GATE
 - Help overcome technology barriers in the design and development of cost effective, high-energy efficiency vehicles for the US market through an integrated research and education graduate program
- Clemson GATE Center's Specific Goal: Establish a GATE Center of Excellence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

Year 1 Objectives

- 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
- Recruit MS and Ph. D. students to populate the GATE program
- Commence work on the GATE Powertrain Integration Laboratory
- Leverage industry, departmental and CU-ICAR facilities and partnerships
- Commence work on upgrading existing courses and developing the proposed new lab course
- Set up internal assessment process

CU-ICAR's Strategic Location

- Upstate South Carolina Regional Automotive Cluster

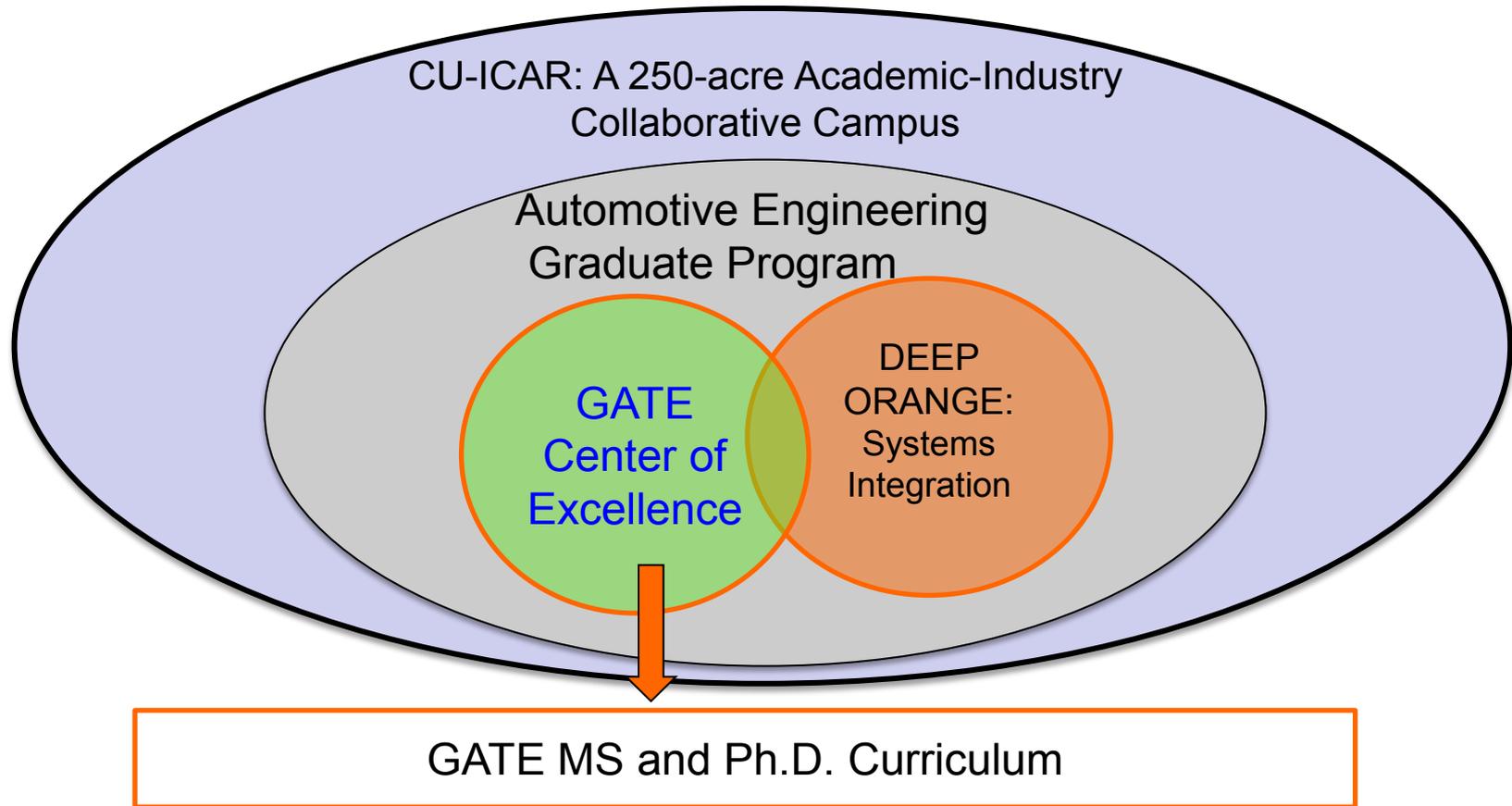


125 automotive suppliers and related companies in 10-county region

CU-ICAR: Setting for the DOE GATE Center

- **Unique public/private partnership** for single-theme (Automotive/Motorsports) research and educational campus with more than \$200 Million in investments
- Endowed Chairs in four key areas – **Systems Integration, Design & Development, Manufacturing, and Vehicular Electronics**
- Currently 137 Masters and PhD students (**first PhD in Automotive Engineering Program in U.S.**) – program at max capacity
- **Industry involvement** in curriculum development/teaching, research direction/projects
- Main objectives are to: 1) Provide the international automotive industry with exceptional master's and doctoral graduates 2) Conduct leading-edge fundamental and applied research to meet current and future automotive industry challenges in a collaborative and innovative environment 3) Transfer strategically-relevant technology and knowledge to industry

Deployment of the Clemson DOE GATE Center



- ✓ 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:

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.

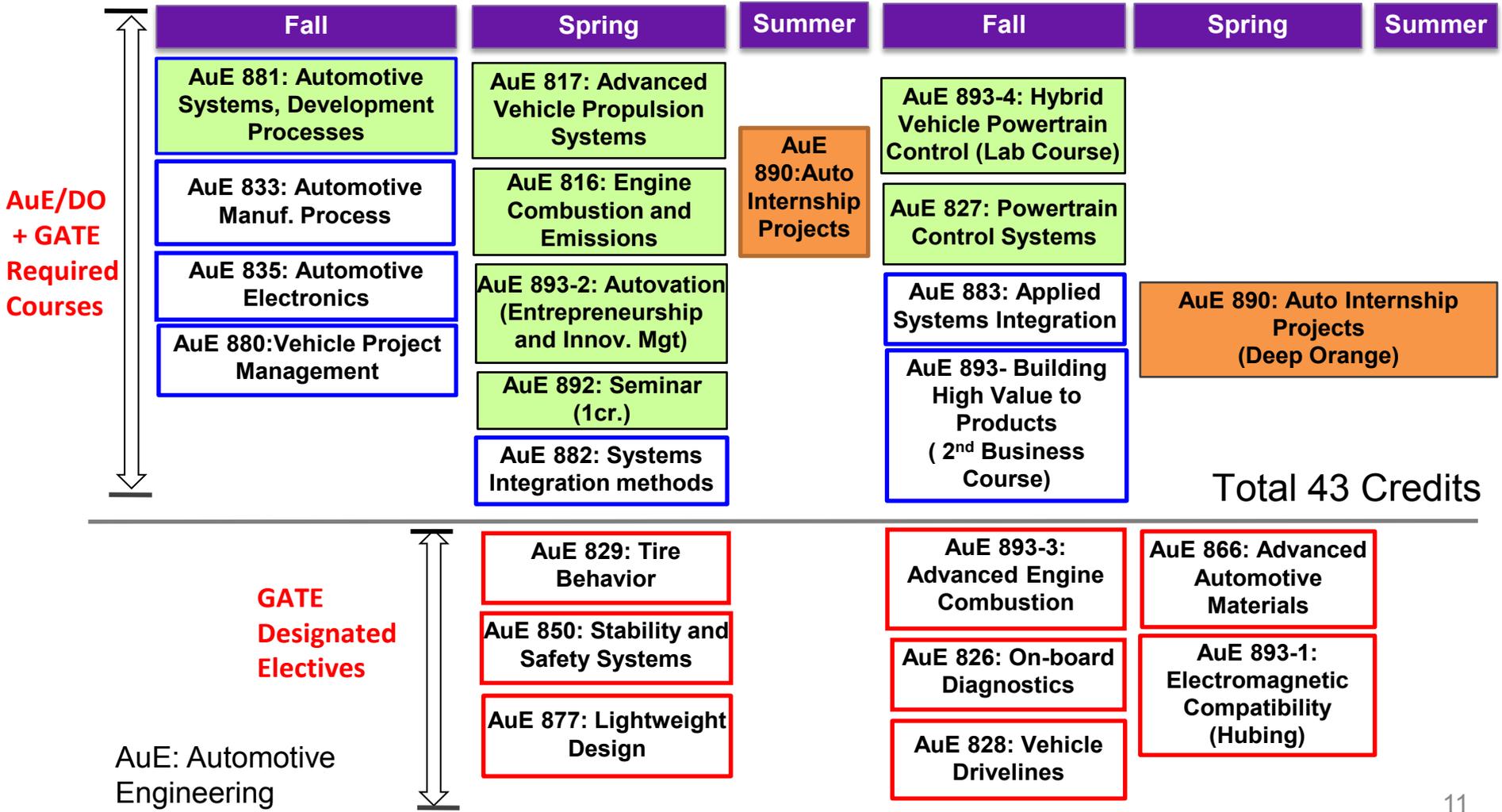
Approach:

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

Approach:

Curriculum Details (MS)



Approach:

GATE Ph.D. Program

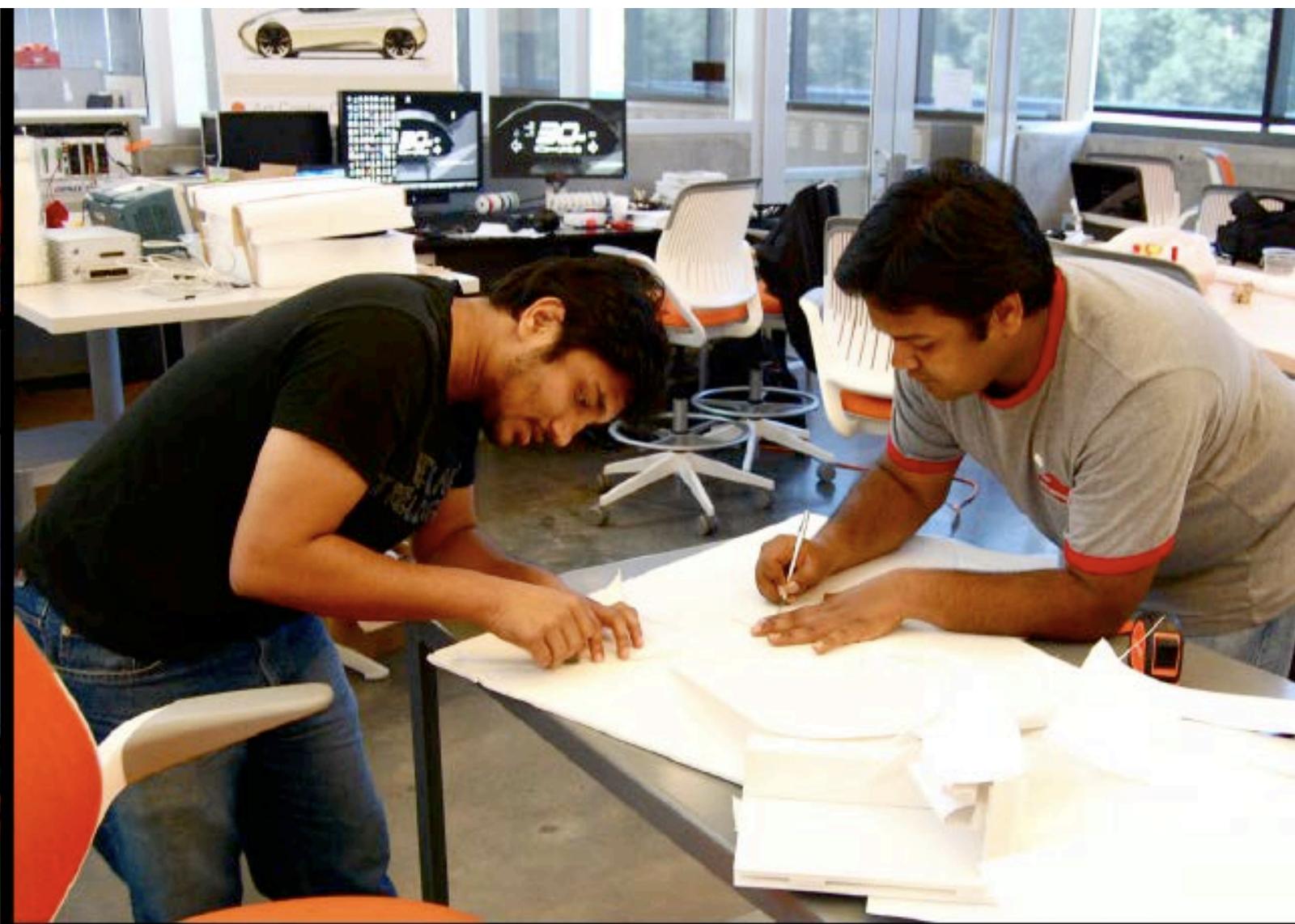
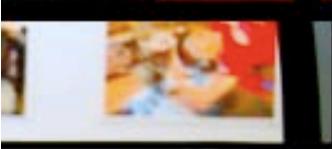
- Goal of Program:
 - To train technical experts at the Ph.D. level who act as thought and innovation leaders with an understanding of the broader challenges and opportunities for the automotive sector from the perspectives of energy resource economics, life-cycle impact and public policy
- For technical 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:

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.







Deep Orange 1 Industry Partners



INDUSTRIAL ORIGAMI®



Altair Engineering



Approach/Accomplishment: Creation of AuE 893-4: A New Lab Course

- Lab modules Include
 - Real-time Data Acquisition
 - Characterization of EV/HEV batteries (uses DC Load, HPS, dSPACE, thermocouples, 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 Emulation
 - Hybrid/EV Vehicle Energy Management
 - Battery Management Systems (BMS)
- Some of these lab modules have already been worked out in detail.
 - First offering is Fall 2012.



BMS for the Deep Orange 1 Vehicle

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

Other Key Facilities for GATE Center Research & Education

- 4x4 Independently Controllable 500 hp Chassis Dynamometer
 - Energy use and emissions evaluation under different driving cycles (UDDS, FTP, etc...)
 - In a semi-anechoic chamber: for driveline NVH analysis



- ETS Lindgren Electromagnetic Compatibility (EMC) Chamber
 - Premium high-performance RF-shield
 - Immunity testing up to 100V/m
 - EMC testing of components/electronic subsystems and full vehicle systems
 - Power bus transient testing

- MTS 7-Post Shaker and Wiess Environmental Chamber
 - Durability testing and evaluation
 - Simulating operation in a wide range of climates.
 - Temperature -40 to 85 C; Humidity 15 to 95%



Accomplishments:

Status of Recruiting and Enrollment (Year 1)

- A total of 17 students were admitted to the GATE track in the Fall 2011
 - 5 students pursuing Ph.D. degrees: Sara Mohon, Jacqueline Rios, Dave Anderson, Justin Callies, Thomas Schultz
 - 2 female students: Sara Mohon and Jacqueline Rios
 - 12 students pursuing M.S. degrees
 - 1 female
- All Ph.D. GATE students are supported through research assistantships:
 - 2 by the direct DOE GATE Grant
 - 3 by other sponsored research in the focus area of the GATE Center
- 3 MS GATE students received MAZDA-GATE Fellowships (\$10,000 each)
- Most MS students in the program are self-supported!

- The Center has the target of increasing enrollment to 25 GATE students by the end of the second year (August 2013) of the program.

Accomplishments:

Recent Research Publications by Select GATE Fellows and Faculty (early in program)

- Patent disclosures:
 - **S. Mohon, P. Pisu, P. Venhovens**, and J. Streit, “Method and Apparatus to Determine Damage Level of a Battery”
 - J. Sill and **B. Ayalew**, “ Predictive Tire Force Saturation Management for Vehicle Stability Control”, with special application to independent electric/hybrid drives
- **J. Rios, P. Pisu**, M. Chowdhuri, “ A comparative analysis of energy control strategies for plug-in hybrid electric vehicles,” submitted to 51 st IEEE Control and Decision Conference, Dec 10-13, 2012, Maui, HI.
- 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*, Dec. 2011.
- J. Sill and **B. Ayalew**, “Vehicle Stability Control Through Predictive and Optimal Tire Saturation Management”, Submitted to 14th *International Conference on Vehicle Technologies*, 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)
- Xiao, B., **Prucka, R.**, “A Virtual Laminar Flame Speed Sensing Strategy for Multi-Fuel Adaptive Internal Combustion SI Engines using Cylinder Pressure Feedback,” in preparation for the *International Journal of Powertrains*, March 2012.

*GATE faculty and students identified by bold face.

Accomplishments:

Leveraging DOE GATE Funds (so far, in 6 months)

- 3 Mazda GATE Fellowships \$10,000/year each ~ \$30,000/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
- Additional internship commitments (still early for our GATE students to go on internships)

FEV	BMW	ORNL	Proterra
SEMA	Sturman Industries	SIMPACT	Michelin
- 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
 - 3 faculty searches underway in power electronics, automotive software engineering, and sustainable materials
 - GATE Program Coordinator

Accomplishment/Approach: 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

Coordination and Collaborations with Other Institutions

- 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
 - Informal contacts made with other GATE centers and institutions working in different aspects of EV technology.
- In subsequent years, the plan is to foster collaboration on:
 - GATE curriculum materials
 - Remote lectures (CU and Penn State have done this before)
 - Research forums and workshops



Proposed Future Activities (Year 2)

- Complete the GATE Powertrain Integration Laboratory
- 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
 - AuE 817: Advanced Propulsion Systems: coordinated with the new lab course
 - AuE 893-4: Hybrid Powertrain Control: New lab course planned for Fall 2012
- Ramp up recruitment efforts, to reach enrollment target of 25 GATE Fellows
- Secure more fellowship and internship opportunities for the GATE Fellows
- New faculty hired January 2012 will expand research, course, and equipment capability which contributes directly to the focus of GATE Center
 - e.g. single-cylinder and multi-cylinder engine test cells are being worked out
- 3 more faculty searches underway in the areas of
 - Power electronics, automotive software engineering, and sustainable materials

Summary

- Progress made on establishing Clemson's DOE GATE Center of Excellence in Sustainable Vehicle Systems
- 17 MS and Ph.D. students in the program this FY.
- Curriculum outlined, new course being developed, others being upgraded
- New GATE Powertrain laboratory under development: most equipment acquired
- 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