GATEWAY TO THE FUTURE

GATE

GRADUATE AUTOMOTIVE TECHNOLOGY EDUCATION

CU ICAR

CLEMSON UNIVERSITY INTERNATIONAL CENTER FOR AUTOMOTIVE RESEARCH

DOE GATE Center of Excellence in Sustainable Vehicle Systems

Director and PI: Dr. Imtiaz Haque

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

Presenter Co-PI: Dr. Pierluigi Pisu

CLEMSON UNIVERSITY 1889

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Overview

Timeline

- Project start date: 10/1/2011
- Project end date: 09/30/2016
- Percent complete: 50.6%

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 FY13: $137,000
- Funding received for FY14: $266,453
- Total received: $ 810,873 (as of April 15th,2014)

Partners

- Many automotive OEMs and suppliers
- Project Lead: Clemson University

Project Objectives - Relevance

- DOE's VT Program Vision for GATE
  - Help overcome technology barriers in the design and development of high-energy efficiency and low environmental impact vehicle propulsion systems 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

FY13-14 Objectives-Relevance

- Continue recruit MS and Ph. D. students to populate the GATE program
- Establish application and selection procedures and advertise the opportunity provided by the GATE Center
- Complete GATE Powertrain Integration Laboratory
- Leverage industry, departmental and CU-ICAR facilities and partnerships
- Complete course upgrades
- Update and second offering of AuE 893-4: Hybrid Powertrain Control course
- Graduate first cohort of MS GATE students
- Issue a US DOE GATE Certificate of Excellence in Sustainable Vehicle Systems for completing the program.

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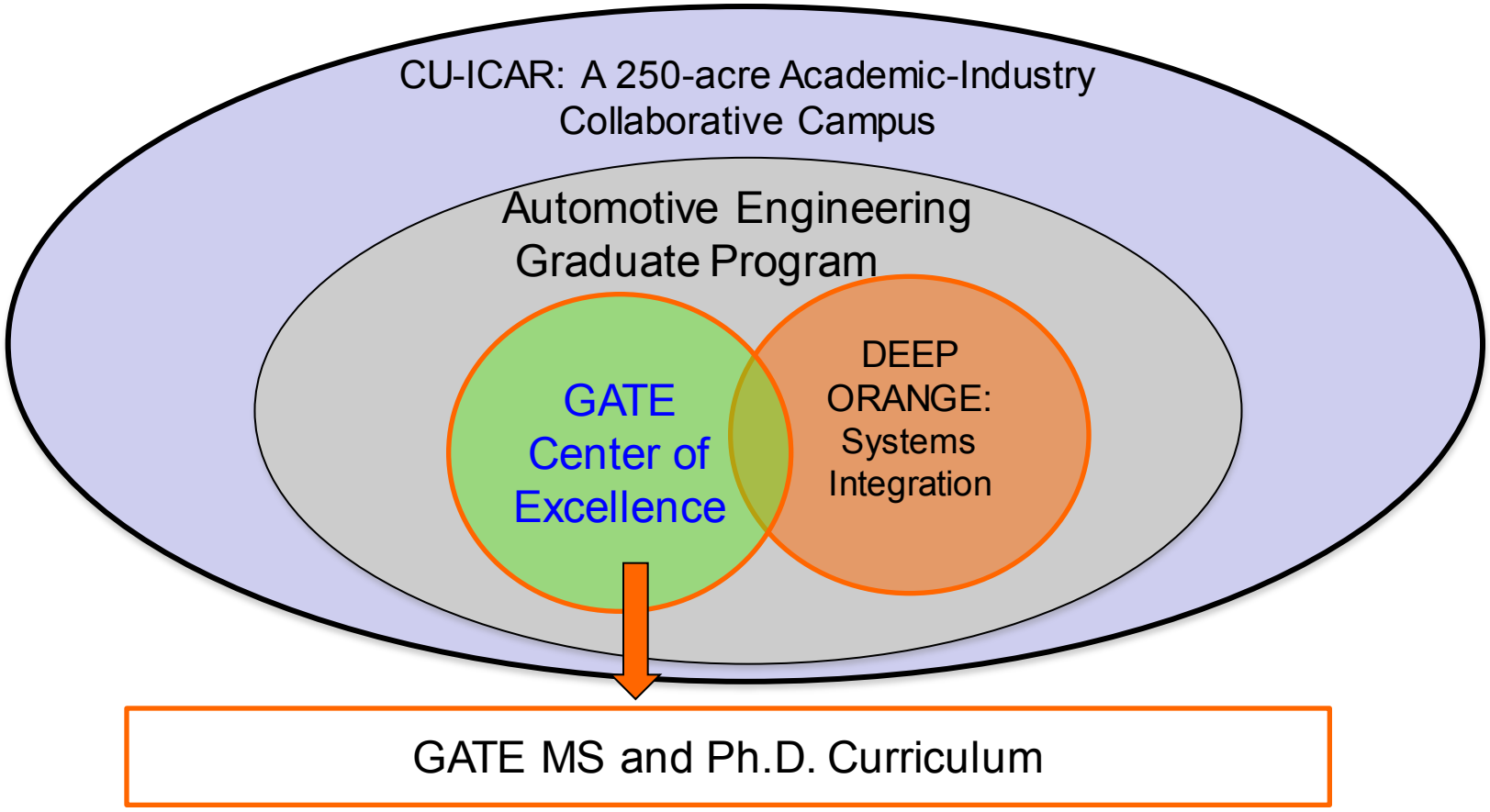
Milestones FY13 and FY14

- Milestone 2.2 - Advertised and Recruited third cohorts of PhD GATE fellows
- Milestone 5.1 - AuE 893-4: Hybrid Powertrain Control: Second offering Fall 2013 (next offering Fall 2014 – on Schedule)
- Milestones 5.2, 5.3 – Completed Course Development and Class Teaching Second Offering (next offerings – on Schedule)
  - AuE 817: Advanced Vehicle Propulsion Systems
  - AuE 827: Powertrain Control Systems
  - AuE 881: Automotive Systems Overview
- Milestone 3.5 - Vehicle Powertrain Integration Lab Development Completed
- Milestone 4.3 - Completed Review of GATE Center with DOE VTP Rep. (Oct. 2013)
- Milestone 7.1 – First MS cohort graduated, August 2013
- Milestone 8.2 – Submitted Semi-annual reports on April 2013, Oct 2013

Approach 1:
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 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.
- Milestone 2.2 - Recruit third cohorts of MS, PhD GATE fellows (Completed)

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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 (Revised on 12/05/13):
  - 13 Credits from 4 Core GATE courses plus a seminar (in Green)
  - 18 Credits from 6 support courses (current AuE/DO Core (in Blue))
  - 6 Credits of AuE 890 internship at industry location or at CU-ICAR
  - 6 Credits from GATE-designated electives (in Red)
  - Students not participating in Deep Orange may replace AuE 883 with another GATE-designated electives (in Red)

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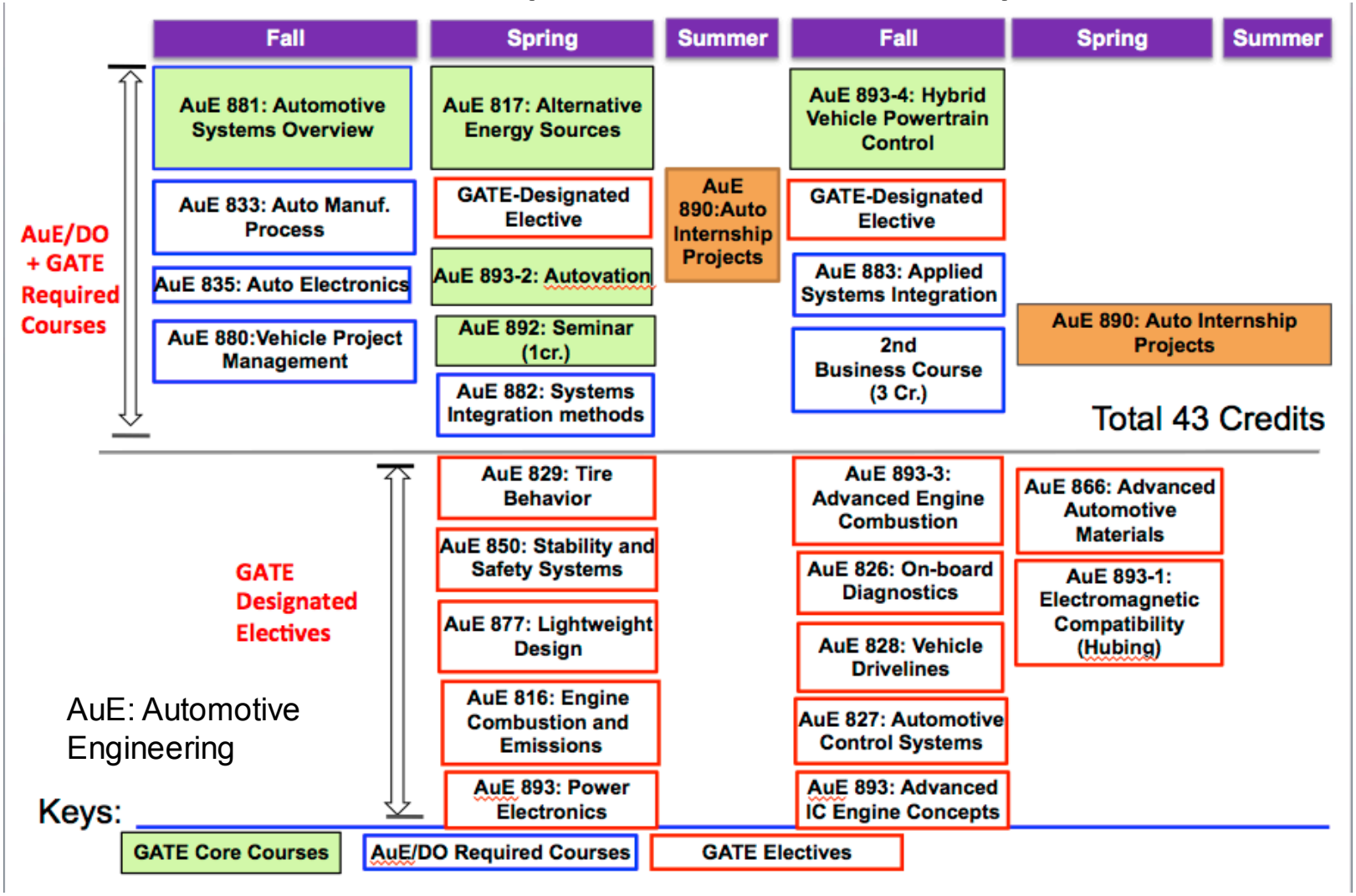
Approach 4:

MS GATE Course Plan (Revised on 12/05/13)



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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 (Revised on 12/05/13):
  - 13 Credits from 4 Core GATE courses plus a seminar (in Green)
  - Sustainability Minor (two courses minimum)
  - More courses as needed for specific research (minimum of 60 credits post BS)
  - Complete doctoral research dissertation in the GATE program specific area

- 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

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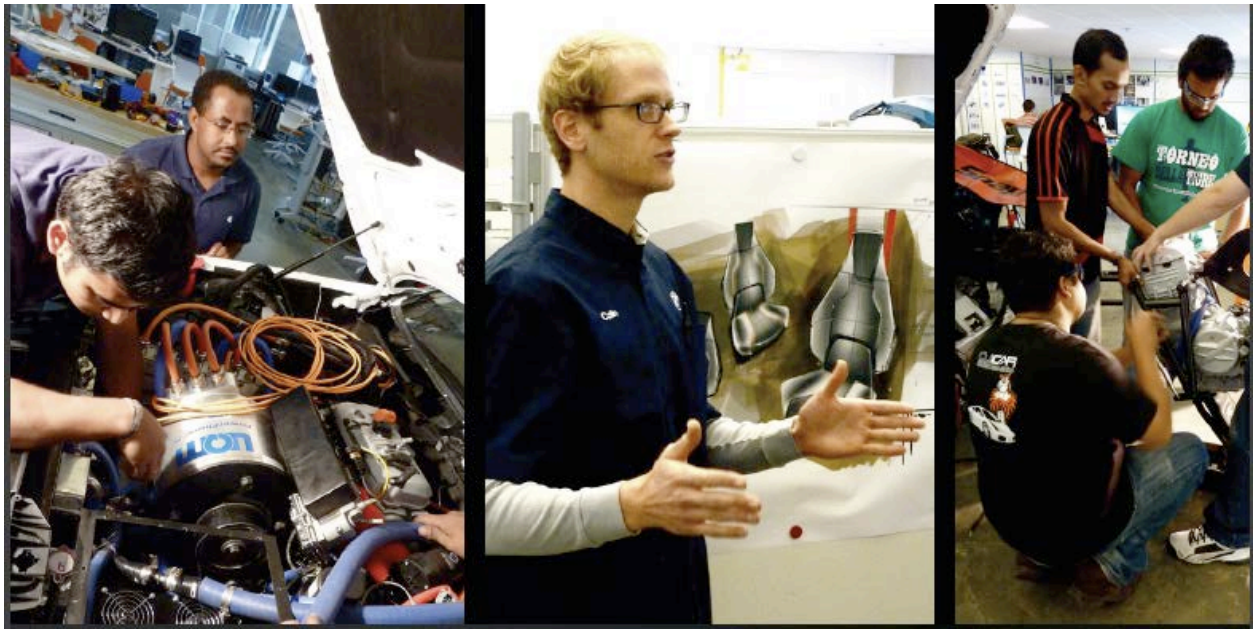
Approach 6:

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.



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Accomplishment 1:

Revised GATE MS and PhD Program

- Previous MS Program requirements:
  - 19 credits from 7-Core GATE courses plus a seminar (in Green)
  - 18 credits from 6 Support Courses for (AuE Core (in Blue))
  - 6 credits of internship at industry locations or at CU-ICAR
- Revised MS Program requirements:
  - 13 credits from 4 Core GATE courses plus a seminar (in Green)
  - 18 credits from 6 support courses (current AuE/DO Core (in Blue))
  - 6 credits from GATE-designated electives (in Red)
  - 6 credits of AuE 890 internship at industry location or at CU-ICAR
- Total number of required credits is unchanged, but now students have the choice of two GATE elective courses.
- Previous PhD Program requirements:
  - 19 credits from 7-Core GATE courses plus a seminar (in Green)
- Revised PhD Program requirements:
  - 13 credits from 4 Core GATE courses plus a seminar (in Green)
  - Other PhD Program requirements unchanged

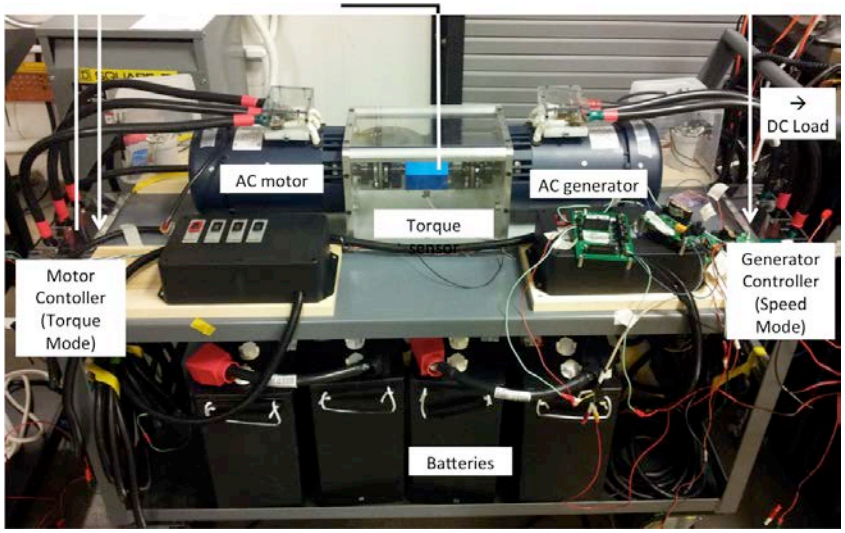
Accomplishment 2:

Offering of Course AuE 893-4: Hybrid Powertrain Laboratory

- Lab modules Include
  - Characterization of EV/HEV batteries
    - OCV curves
    - Pulse characterization and EIS
  - AC Motor/Generator: Control and Efficiency Mapping
  - EV Drive Cycle Emulation
  - Series/Parallel Drive
  - Fuel Cell Demo System
  - HEV Energy Management
- Second Offering in Fall 2013
- Next offering Fall 2014

NEW Modules developed:

- Active and Passive Battery Management/Control
- DC/DC buck converter implementation and testing
- Hybrid Golf Cart



EV Hardware-in-the-Loop Emulation Platform

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

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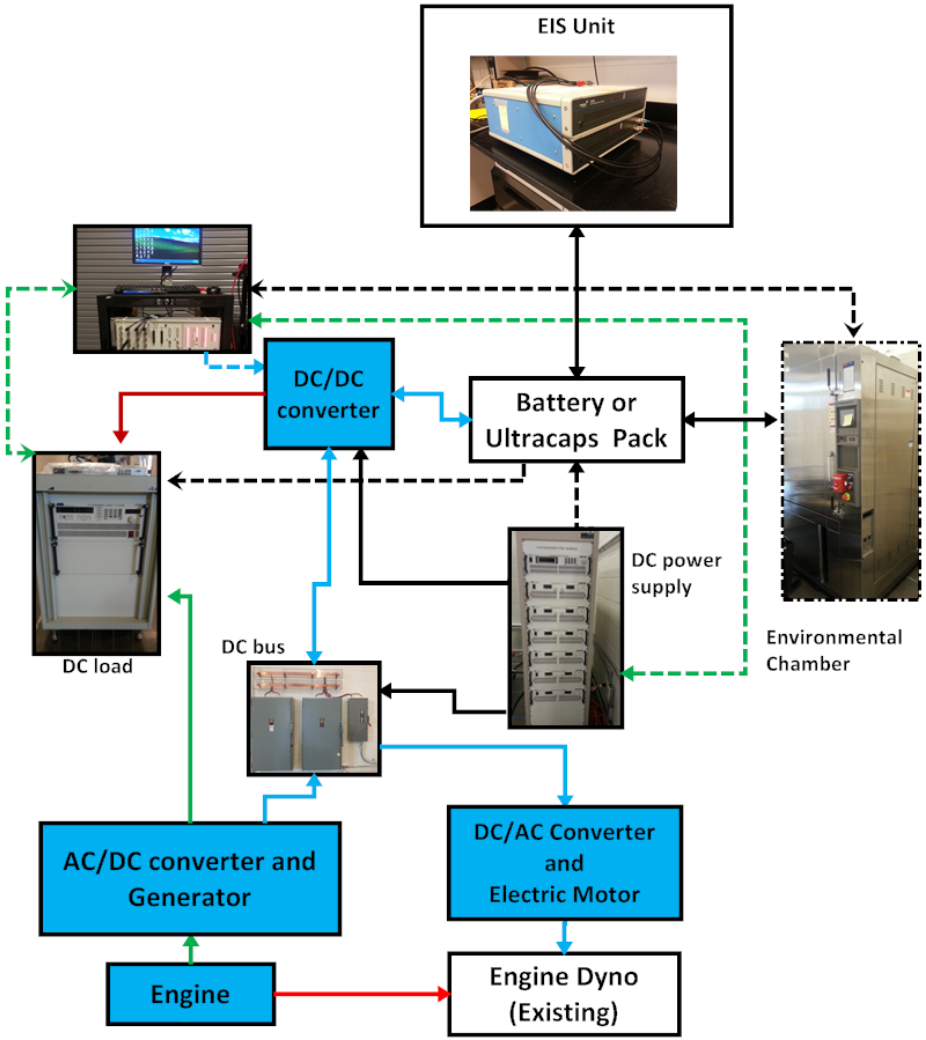
Accomplishment 3:

Completion of GATE Powertrain Integration Laboratory

HEV ECMS Energy Management Strategy



GATE Laboratory enables research and educational activities:

- AuE 893-4 course
- Characterization of electric and hybrid vehicle driveline components
- HIL testing of powertrain systems
- Advanced engine control research
- Fault diagnostics and prognostic algorithms for advanced hybrids

Accomplishment 4:

Offering 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 2013-2014:

- **Feb. 27, 2014 - Chrysler Powertrain Technologies: Meeting the 2025 Challenges,** Dr. Bob Lee, VP, Head of Engine & Electrified Propulsion Engineering Chrysler Group LLC, Powertrain Coordination - Group Executive Council Fiat S.p.A.
- **Nov. 14, 2013 – Personal Mobility – A Glimpse of What Lies Ahead**, Ray Hughes, Principle Engineer and Manager - Honda R&D America
- **Sep 11, 2013 - Sliding Mode Control in Automotive Applications,** Dr. Vadim Utkin, Professor, The Ohio State University.
- **Sep 30, 2013 – Development & Testing of a Hydraulic Hybrid Powertrain for Off-Highway Vehicles,** Lorenzo Serrao and Giulio Ornella, Senior System Engineers, Dana Holding Corporation
- **Oct. 25, 2013 - Current State and Development Trends of Conventional and Electrified Drivelines**, Jim Potter, Application Engineering Group - ZF Transmissions Group.
- **Nov. 6, 2013 - Multivariate Sensing and Computational Intelligence for Advanced Manufacturing,** Dr. Robert Gao, Professor, University of Connecticut.

Accomplishments 5:

New Course Developed: AuE 893-6: Power Electronics

- This course considers the design and control of power converters in electric drive vehicles. The course includes an overview of system architectures and covers system-level dynamic modeling and control using MATLAB/Simulink at levels appropriate to determine requirements and validate the performance of switched-mode power converters in the vehicle system. Analysis, modeling and design of switched-mode power converters in electric-drive vehicle systems are then covered, including battery DC-DC converters, battery management electronics, motor drive inverters and battery chargers.

- First offering in Spring 2014
- Students count: 14

Accomplishments 6:

Status of Recruiting and Enrollment (Year 3)

- Number of current GATE track student is 37:
  - 20 second year students and 17 first year students, exceeding the total of 25 for the 2nd year target
  - 26 MS students (including 3 female students)
  - 11 students pursuing Ph.D. degrees: Sara Mohon, Jacqueline Rios, Zholeika Abdollahi, Zhiyuan Du, Satadru Dey, Dave Anderson, Justin Callies, Thomas Schultz, Shuonan Xu, Zifan Liu, Ryan O'Donnell
    - 3 female Ph.D. students: Sara Mohon, Jacqueline Rios, Zholeika Abdollahi
- All Ph.D. GATE students are supported through research assistantships:
  - 3 by the direct DOE GATE Grant
  - 8 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!

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Accomplishment 7:

Impact of the GATE Curriculum on the existing AuE program

	Fall 2012	Spring 2013	Summer I	Summer II	Fall 2013	Spring 2014
COURSE NUMBER	STUDENT COUNT	STUDENT COUNT	STUDENT COUNT	STUDENT COUNT	STUDENT COUNT	STUDENT COUNT
AuE 893- Autovation	11	17			59	79
AuE 881- Automotive Systems Overview	80				96	
AuE 827- Automotive Control Systems	22				39	
AuE 816- Engine Combustion and Emissions		53			37	29
AuE 817- Alternative Energy Courses		37				40
AuE 892- GATE Seminar		17				31
AuE 893- Hybrid Powertrain Control Lab	13				17	
AuE 890- External Industry Internship	9	35	44	37	8	11
AuE 890- Internal Deep Orange Internship	14	13	23	23		16

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Accomplishment 8:

Example of Recent Research Publications by GATE Fellows and Faculty

- Mayyas, **R. Prucka, P. Pisu, I.Haque**,"Model-Based Automotive System Integration: Using Vehicle Hardware In-the-Loop Simulation for an Integration of Advanced Hybrid Electric Powertrain" In-Press, International Journal of Electric and Hybrid Vehicles.
- **S. Mohon**, A. Venkitakrishna, **B. Ayalew** and **P. Pisu** (2013), "Development of an Electric Vehicle Hardware-In-the-Loop Emulation Platform," 15th International Conference Advanced Automotive Technologies, ASME IDETC2013-12263, August 4-7, 2013, Portland, Oregon.
- **S. Dey** and **B. Ayalew** (2014) "Nonlinear Observers for State Estimation of Li-Ion Batteries," American Control Conference, June 4-6, Portland Oregon.
- **J. Rios**, and **P. Pisu** (2013) "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.
- **Rios, J.,** and **Pisu,** P, "An alternative approach for the equivalent consumption minimization strategy -ECMS". Submitted for evaluation at: 2013 ASME Dynamic Systems and Control Conference. Oct. 21-23,2013, Palo Alto, CA (submitted, in review)
- **P. Venhovens**, **P. Pisu**, **R. Prucka**, B. Makkar, P.Frommann, T. Sonavane and C. D'Amico, (2013) "Conceptualization and Implementation of an AWD Parallel Hybrid Powertrain Concept ", SAE paper number 2013-01-1448.

*Participating GATE faculty and students identified by bold face.

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Accomplishment 9:

Leveraging DOE GATE Funds FY13-14

- 3 Mazda GATE Fellowships $10,000 each ~ $30,000
- 1 FEV GATE Fellowship $10,000
- 18 GM Fellowships for Deep Orange 5, $1,000 each ~$18,000
- AuE Department additional cost share
  - One GATE Fellow support: $16,000+ plus tuition remission ($11,086) ~ $27,086
- Deep Orange 6: Youth-Oriented Utility Vehicle. Sponsored by Toyota, from January 2014 to December 2016, funded $500k.
- New faculty/staff hires in the topical areas of the GATE Center:
  - Dr. Simona Onori, Assistant Professor in power electronics (New Hire, 2013)
  - Dr. Srikanth Pilla , Assistant professor in biodegradable materials (New Hire, 2013)

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Accomplishment 10:

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

- "Thermal Barrier Coatings for the LTC Engine - Heat Loss, Combustion, Thermal vs. Catalytic Effects, Emissions, Exhaust Heat", *NSF/DoE Partnership on Advanced Combustion Engines*, PI Z. Filipi, Co-PI **R. Prucka**; 2013-2016, $1M
- "Synthetic Drive Cycle Generation to Support Studies on the Hybrid Electric Vehicle Battery Aging", PI A. Ivanco, Co-PI Z. Filipi, *Johnson Controls Power Solutions*, 2014-2015, $98K
- "Vehicle Modeling with Conventional and Novel Internal Combustion Engines", PI Z. Filipi, *General Motors R&D*, 2012-2014, $201K
- "Sensor-based In-Cylinder Mixture Composition Prediction", PI **R. Prucka**, Co-PIs Z. Filipi and M. Hoffman, *Fiat Chrysler Automobiles*, 2014-2016, $285K

Sub-total: $1,584M

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Accomplishment 10 (cont'd):

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

- "TIGER Grant Award: Clean, Connected and Efficient Vehicle" PI Z. Filipi, *Clemson University*, 2014, $18K
- "In-Vehicle Diesel-Assisted Natural Gas Operation for Compression Ignition Engines", PI Z. Filipi, Co-PI **R Prucka**, *EcoDual (Beaufort, SC)*, 2013-2014, $456K
- "Modeling & Optimization of Electrified Propulsion Systems", *DoD-US Army TARDEC* - Automotive Research Center Cooperative Agreement, PI Z. Filipi, 2012-2015, $276K
- "Energy Control Strategy for Driver Eco-Driving Enhancement, Feedback and Driving Style Assessment," PI J. Taiber, Co-PI **P. Pisu**, 2013, $74K
- "Wireless Power Transfer (WPT) and Charging of Plug-In Electric Vehicles," PI J. Taiber, Co-PI **T. Hubing**, 2014, $362K
- "Development of a Supervisory Optimal Controller for Hybrid Electric Vehicles Accounting for Battery Aging," S. Onori, 2014, $73K
- "International Connected Vehicle Testing Center (ICVTC)," PI J. Taiber, 2014, $454K

Sub-total: $1,713M

Accomplishment 11:

Internal Program Assessment

- AuE Faculty Retreat: September 21st, 2013; February 22n,2014
  - Discussion on how the GATE program fits Departmental Vision and Revision of Department Strategic Plan
- Employer Evaluation for FY 2013 (on internships and employment)
  - Technical background
  - Critical thinking
  - Taking initiative
  - Overall performance
- Student Self Evaluation FY 2013
- 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
- GATE MS Program requirements have been updated as result of assessment

FY 2013 Reviewers' Comments and Response

- Overall the review's comments were very positive
- Widespread agreement expressed that project supports overall DOE objectives, approach is good, well integrated with others, and appropriate technical barriers being addressed
  - "Clemson University (Clemson) GATE Center project was well-designed and had a good strategy for addressing technology barriers in the development of sustainable vehicles through an integrated education and research program for graduate students. Clemson had successfully integrated a number of related activities (e.g., Deep Orange) to provide an impressive array of opportunities for graduate students."
  - "Clemson seemed to have a fairly specific coursework plan for candidates. The identified approach was to follow vehicle development processes seen in the industry, developed through Clemson's relationship with industry partners."
  - RESPONSE: We will continue to expand our collaborative interaction with industry and academic partners as the program matures. We will work expanding the coursework and improve opportunities for candidates.

FY 2013 Reviewers' Comments and Response

- Technical accomplishments
  - "All the milestones for 2012 and 2013 had been met. The reviewer noted that the Clemson GATE project had made excellent initial progress in terms of establishment of the GATE Center and curriculum development; recruitment and support of graduate students, and elaborated that the project appeared to be well on the way to meeting enrollment goals, and development of the GATE powertrain laboratory. "
  - "Over the past year or so, Clemson completed the development of multiple courses and a vehicle integration laboratory. Clemson has 37 students to date in its GATE program, plus many other students taking selected courses within the GATE offerings. The reviewer noted that the original goal was to have 25 students in GATE. The expansion was largely made possible through industry funding, although many students are currently self-funded. "
  - RESPONSE: Generally positive comments, we will continue to look for funding to maintain or improve the current level of GATE students in the program.

FY 2013 Reviewers' Comments and Response

- Collaboration and coordination with other institutions
  - "Numerous seminar speakers are obtained from outside the program, particularly from the automotive industry. Clemson obtained additional GATE fellowships from the industry (Mazda and FEV), plus significant funding from the industry. The reviewer noted that the university also obtained related government or industry research project funding of over $4 million. The reviewer noted that Clemson specifically coordinates with other universities. The reviewer stated that the IAB provides feedback on program, as was specifically utilized to conduct an internal program assessment. Board membership includes automakers, suppliers, and others. In addition, according to the reviewer, Clemson also established employer evaluations (for internships and employment) to guide program improvements. "
  - RESPONSE: Generally positive comments, we will continue to expand out collaboration with industry partners to secure additional GATE fellowships. A new IAB meeting is scheduled for Spring 2014. We will continue to gather employer evaluations to guide program improvements and curriculum requirements.

Coordination and Collaborations with Other Institutions

- CU-ICAR hosted the SAE International Natural Gas Symposium, March 12-13, 2013.
- March 2013,"Characterizing Diesel Engine Transients and Real-time Models for Virtual Sensing", Faculty Seminar, University of Stuttgart, Germany, by Dr. Zoran Filipi
- Hosted the Workshop on IEEE SA Industry Connectivity on Electrical Vehicle Wireless Power Transfer
- June 2013, invited speaker, "Applying PHM Methods on Fuel Cells for Automotive Use," IEEE PHM Conference, by Dr. Pierluigi Pisu
- General Chair IEEE Vehicular Electronics Conference (VEC) / International Electric Vehicle Conference (IEVC) Leadership Forum and Expo 2013 held on October 23, 2013 in Santa Clara, CA, (J. Taiber)
- J. Taiber, Elected in 2013 to Chair of the Executive Committee of the IEEE-SA Industry Connection Activity Electrical Vehicle Wireless Power Transfer (EVWPT)

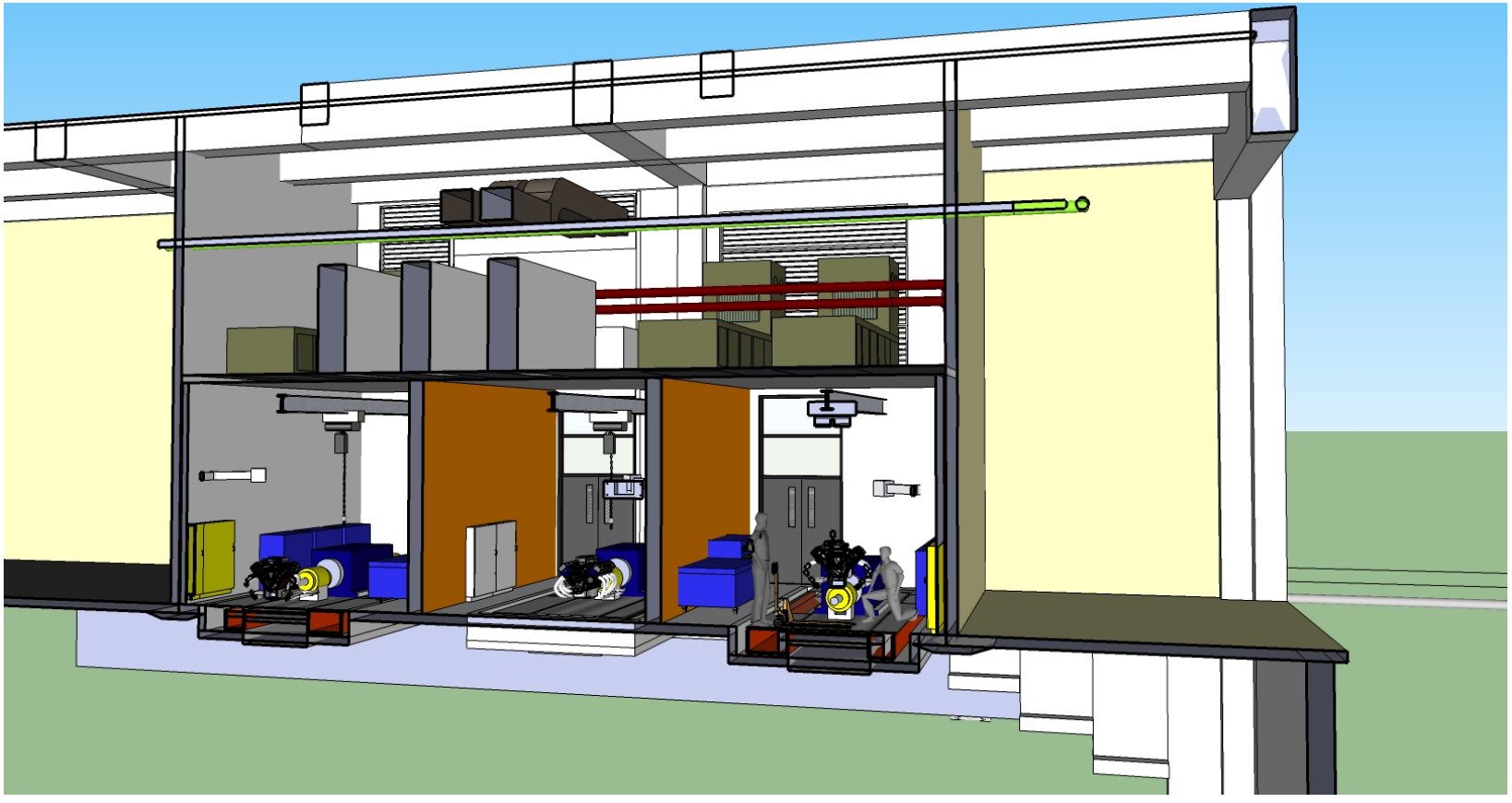
Proposed Future Activities (Year 4)

- Secure more fellowship and internship opportunities for the GATE Fellows
- Continue offering of newly developed courses and course content improvement
- 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 Campbell Center Advanced Powertrain Lab

Future Activities:

Campbell Center Advanced Powertrain Lab (APL) Layout

- Sectional view showing the three proposed test chambers and the mechanical mezzanine above



Summary

- Progress made on establishing Clemson's DOE GATE Center of Excellence in Sustainable Vehicle Systems
- Revised GATE MS Program requirements to create more flexibility by reducing the number of core GATE courses and increase the GATE electives.
- 37 MS and Ph.D. students in the program this FY.
- Curriculum outlined, new Power Electronic course being developed
- Completed 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 GATE Fellow support and for providing internships
- Collaborations/coordination initiated with other institutions on: curriculum materials, exchange lectures/seminars