PENN STATE DOE *GRADUATE AUTOMOTIVE TECHNOLOGY EDUCATION (GATE)* PROGRAM FOR IN-VEHICLE, HIGH-POWER ENERGY STORAGE SYSTEMS

Joel Anstrom, Director of GATE Program
The Pennsylvania State University
DOE Merit Review, June 16, 2014

Project ID#
TI025

"This presentation does not contain any proprietary or confidential information"

Overview
PSU GATE Program

- Timeline
  - Start Oct 2011
  - End Oct 2016
- Budget
  - Awarded: $944,753
  - PSU Match: $374,672
  - Obligated: $287,412
  - Expended: $268,858
  - Expended match: $43,494

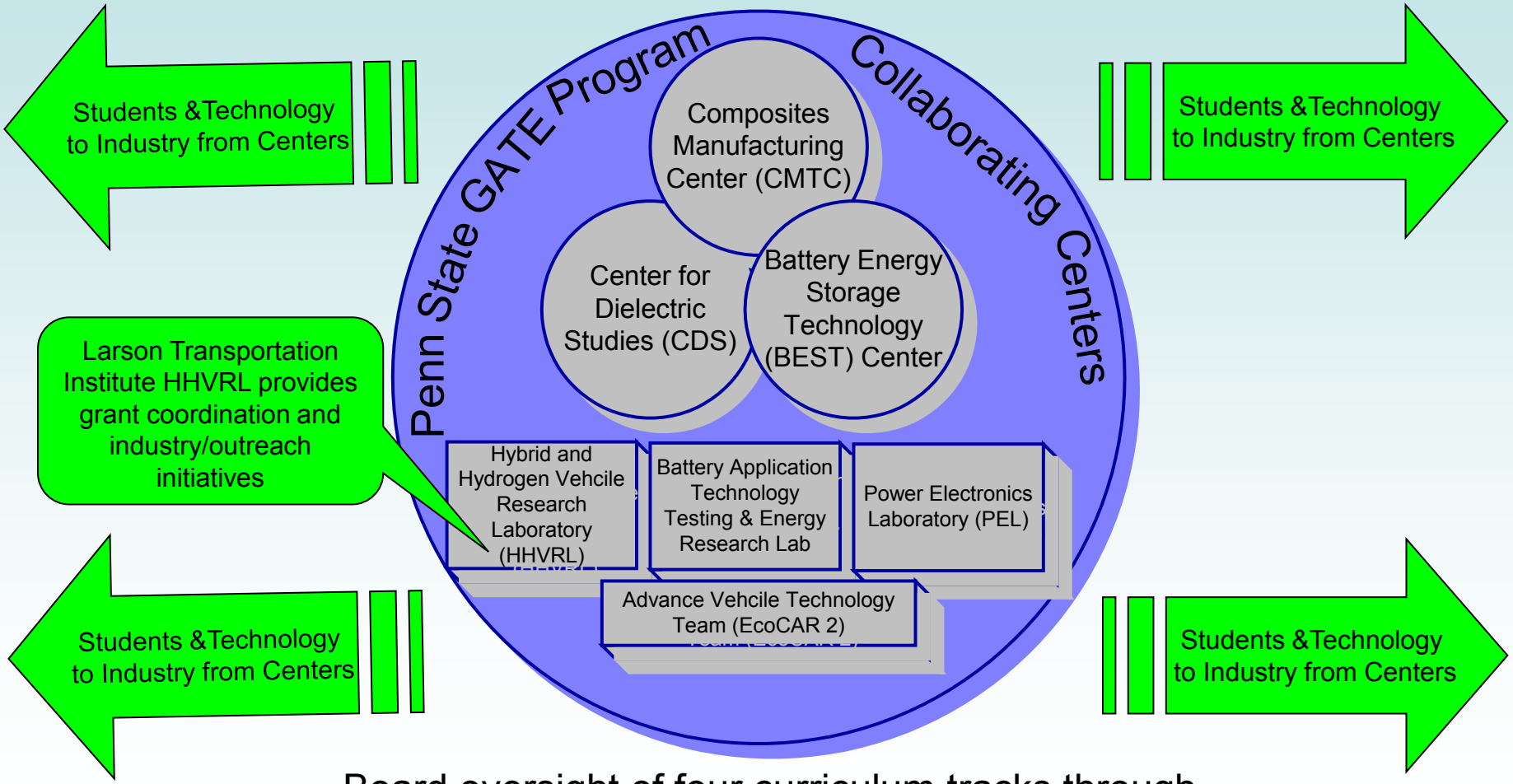
- Barriers
  - Energy storage cost and durability
  - Public Acceptance of electric drive (cost)
  - Engineering workforce
- Partners
  - US DOE and GM via EcoCAR 2
  - Clemson University
  - The Mathworks

Relevance
Goals and Objectives

- Provide graduate curriculum focused on high-power in-vehicle energy storage for hybrid electric and fuel cell vehicles covering the fundamental science and models for electrical energy storage technologies: ***batteries, capacitors, flywheels*** and their combinations


- Touch on system topics related to energy storage curriculum to prepare students for the engineering workforce including:
  - battery management systems
  - electric and hybrid vehicle configurations
  - fuel cells
  - power electronics
  - controls
  - hydraulic hybrids
  - vehicle modeling (Autonomie)
  - Hardware in the Loop (HIL) techniques
  - combustion
  - alternative fuels
- Develop relationships between GATE students, faculty, industry, researchers, and employers to enable US fleet fuel efficiency goals via a trained engineering workforce in advanced vehicle technology

Approach
Structure and Principles

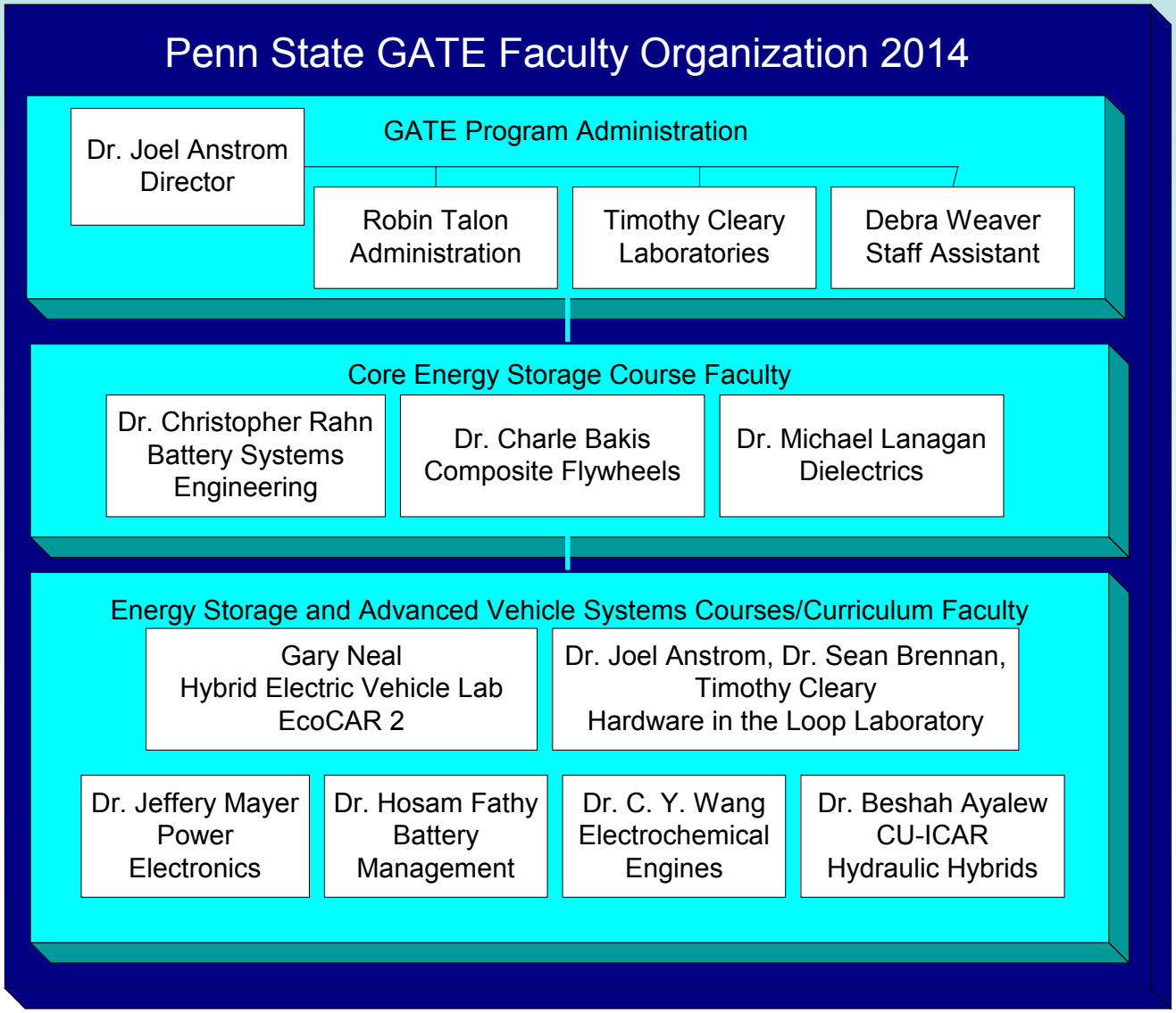


Board oversight of four curriculum tracks through individual centers BEST, CDS, CMTC, and HHVRL

Approach
Structure and Principles

- Team planning and teaching of GATE courses
- Research within individual centers by technology
- HHVRL coordinates GATE grant reporting and industry outreach
- GATE Fellows follow curriculum and pursue energy storage thesis topics
- Any student in GATE curriculum is considered a GATE Student
- Synergy with DOE AVTC Team (EcoCAR 2)
- Provide dedicated “focus vehicle” platforms for GATE student research
- Hardware in the Loop Benches for each lab where beneficial
- GATE graduates advance energy storage targets

Approach
Structure and Principles



Approach (continued)

Penn State GATE Curriculum 2014

Group I Prerequisites - Nine Credits Required

- Select from Department Math Requirement (3)
- Select Numerical Methods Course (3)
- Select Advanced Track Course (3)

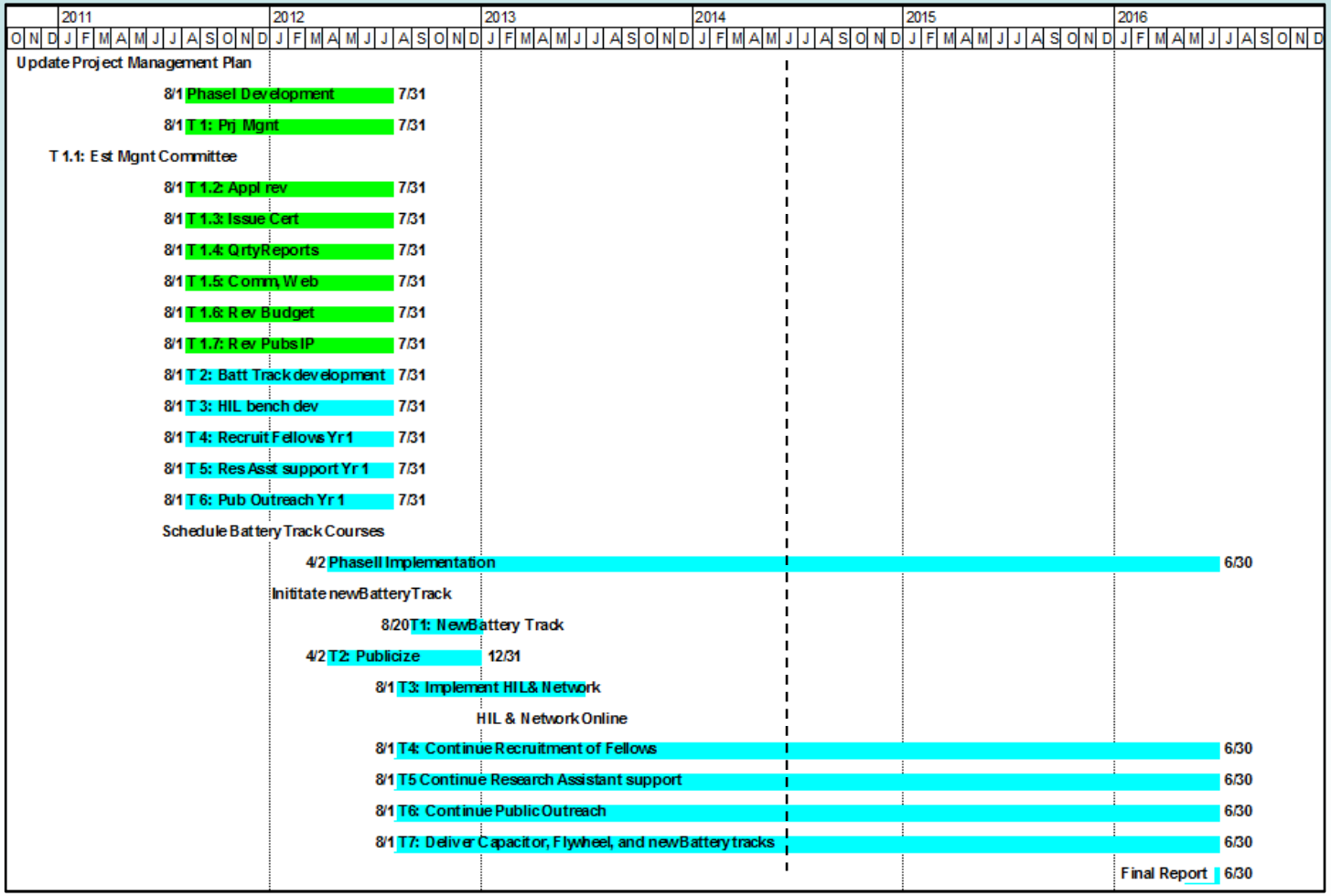
Group II GATE Track Coordinator, Board, and Required Course - Three Credits

Battery Track C. Rahn - BEST	Capacitor Track M. Lanagan- CDS	Flywheel Track C. Bakis - CMTC	System Track J. Anstrom - HHVRL
ME 597C Battery Sys Eng C. Rahn	ME/E Sc 551 Energy Storage Faculty Team	ME/E Sc 551 Energy Storage Faculty Team	ME/E Sc 551 Energy Storage Faculty Team

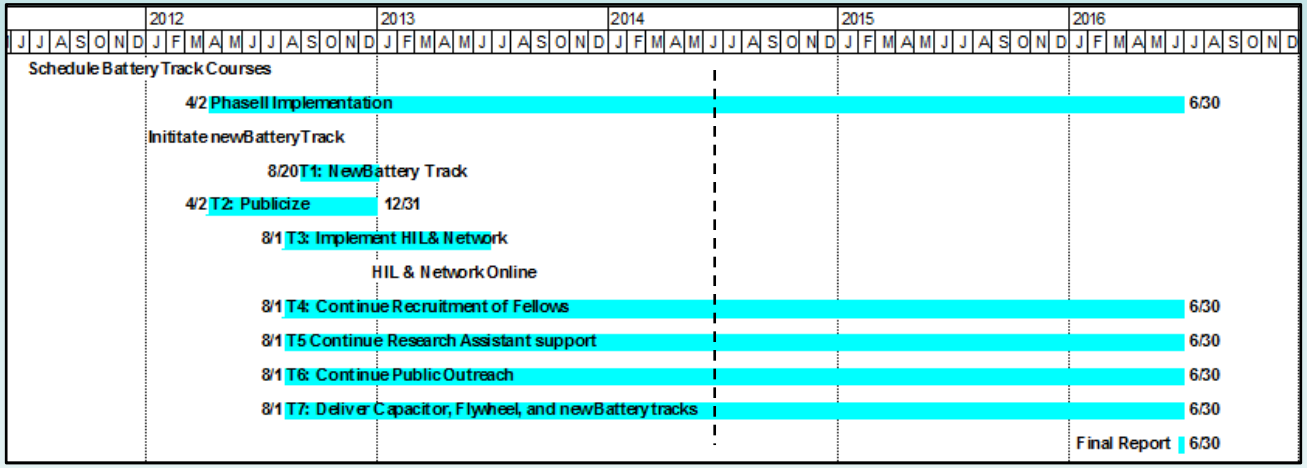
Group III Elective Courses - Six Credits

Take...	Take...	Take...	Take...
ME597B Op Cnt Engy Sys H. Fathy	ESci 597A/MatSc 597D MicroWave Proc. of Materials	EMech 471 Engr. Composite Materials	ME 597F HIL for Auto Development
And	And either...	And either...	And
ME597A Elec Chem Eng C. Wang	ME 442W&443W Adv. Veh. Design I&II	ME 442W&443W Adv. Veh. Design I&II	ME 442W&443W Adv. Veh. Design I&II
	Or	Or	
	ME 597F HIL for Auto Development	ME 597F HIL for Auto Development	

Progress
Project Schedule



Progress
Phase II Tasks 1-7



- T1: Battery Track initiated with two new courses (ME 597 B & C) and published textbook
- T3: HIL platform delayed over licensing terms - supporting undergraduate (potential Systems Fellow) on GM gift money to accelerate implementation

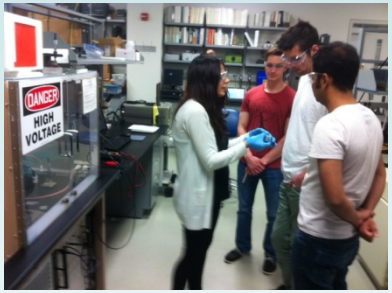
Tasks T4&5: Recruitment of GATE Fellows and Support of RA's

GATE Track	GATE Fellowship Years Goal/To Date	Research Assistantship Years Goal/To Date
Battery Track	8/3.5	16/6+
Capacitor Track	4/0.5 (+1.5 S15)	4/2.0
Flywheel Track	4/3	4/0
Systems Track	2/0 (+1.5 S15)	8/3.5

- T6: Outreach is in progress through website, EcoCAR 2, and 21st CAC event
- T7: GATE course interest and attendance continues to be good

Accomplishments
Required Courses

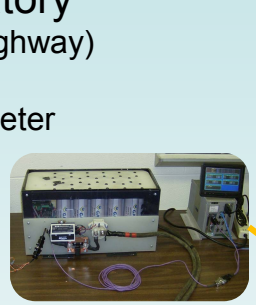
- **ME/E Sc 551 - High Power In-Vehicle Energy Storage**
  - Fundamental science of energy storage team taught by six GATE faculty
    - Batteries: Lithium, NiMh, PbA electrochemistry, labs
    - Capacitors: single and double layer, labs
    - Flywheels: composite rotor design and motors
  - Introduction to energy storage models
  - Vehicle road loads, vehicle platform demos
  - *Online pilot S13, planning distance ed. format S15*

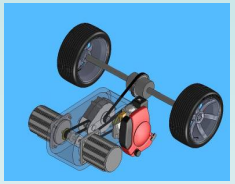


- **ME 442W/443W HEV Laboratory (EcoCAR 2 Team)**
  - ***Placed 1st overall in 2013 EcoCAR 2 Competition!***
  - Develop **DOE AVTC** Competition Vehicles
    - 1999-2004 FutureTruck – Lithium Tech cells
    - 2005-2008 Challenge X – Lithium Tech cells
    - 2008-2011 EcoCAR – A123 modules and BMS
    - 2012-2013 EcoCAR 2 – A123 modules and BMS
  - *Funded faculty support of HIL effort if EcoCAR 3 awarded*
  - Senior capstone for ME, EE, Chemical Engineering
  - GATE faculty, fellows and RA's bring energy storage expertise

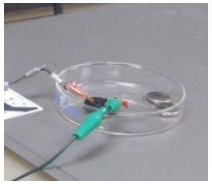
Accomplishments
Electives and Initiatives

- ME 597F “HEV HIL” Adv. Automotive Hardware-in-the-Loop (HIL) Techniques
  - PHEV10 developed as rolling HIL laboratory
    - Two Mode PHEV series (urban) and parallel (highway)
    - Onboard engine HIL lab with dynamometer
    - Onboard induction motor HIL lab with dynamometer
    - 48V Li-ion battery pack with BMS
    - Control strategy optimization
    - On track fuel economy lab





  - Li-ion and Capacitor modeling & lab
  - Mathworks donated licenses and hardware
  - ANL donated PSAT/Autonomie licenses
  - Transitioning to newly donated Pi Innovo ECU software and hardware platform
  - Moved from spring to fall semester to better support EcoCAR HIL deliverables
- Extending HIL capability to other GATE Energy Storage Centers/Labs
  - Piloting HIL for capacitor and battery button cell voltammetry in CDS Lab
  - Demonstrate full system HIL using scaled sample
  - Extend HIL to other labs where beneficial
  - Leverage as GATE course laboratory exercises
  - Piloting Pi Innovo ECU as HIL target
  - Future plans to network HIL labs



Accomplishments
GATE Students

Current GATE Fellowships

- Daniel Marple – Battery Track
  - Advisor Dr. Christopher Rahn
  - High temperature effects on Li-ion battery life
- Kamiar Salehi – Battery Track
  - Advisor Dr. Christopher Rahn
  - Low temperature and abuse effects on Li-ion battery life

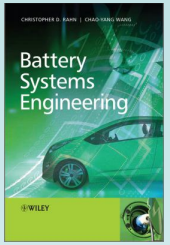
Noteworthy GATE Student Success

- Harshad Kunte – Systems Track
  - MSME S14 – Tesla Motors
  - Advisor Dr. Christopher Rahn and Timothy Cleary
  - Improved lithium battery SOC estimate for transit bus battery pack under thermal load using extended Kalman filter

Accomplishments Summary 1999-2014

- Current and previous GATE Programs (1999-2013) accomplishments:
  - 5 GATE fellows have been funded under current GATE program
  - 18 funded as GATE Fellows with previous DOE funding
  - ~50-70 funded as GATE Students with other funding
  - 6 PhD graduates supported as GATE Fellows
  - ~550 student-semesters of HEV Lab
  - Other GATE research and students funded by:
    - DOE, NSF, DARPA, ARPA-E, DOT, DOS, NASA, PA-DEP, PA-DCED
    - GM, Ford, Volvo, Cummins, GE, Norfolk Southern, Air Products
  - Hundreds of K-12 students enriched by NSF outreach focused on advanced transportation and 21st Century Auto Challenge
  - PSU GATE Graduates placed in FCV/HEV development and testing at Ford, GM, Chrysler, Nissan, Tesla, NREL, INL, Oakridge NL, Mack Volvo, Aberdeen Proving Grounds

Accomplishments
Sample Publications



Textbooks:

Christopher D. Rahn, Chao-Yang Wang, Battery Systems Engineering, ISBN: 978-1-119-97950-0, 250 pages, February 2013, Wiley.

Conference, Journal, and Thesis publications:

Berbano, Seth S., Mehdi Mirsaneh, Michael T. Lanagan, and Clive A. Randall. "Lithium Thiophosphate Glasses and Glass–Ceramics as Solid Electrolytes: Processing, Microstructure, and Properties." International Journal of Applied Glass Science 4, no. 4 (2013): 414-425.

Y. Shi, C. Ferone, and C. Rahn, “Identification and Remediation of Sulfation in Lead-Acid Batteries Using Cell Voltage and Pressure Sensing,” Journal of Power Sources, Vol. 221, pp. 177 -185, January 2013.

G. Zhang, C. Shaffer, C.-Y. Wang, and C. Rahn, “In-Situ Measurement of Current Distribution in a Li-ion Cell,” Journal of The Electrochemical Society, Vol. 160, No. 4, pp. A610-A615, 2013.

* Sawlsville, Julie, “Battery Safety: A Systematic Study of Battery Perfromance Under Extreme Conditions,” MSE Thesis in Mechanical Engineering, The Pennsylvania State University, May 2013.

* Ripepi, M. J., "Transverse Mechanical Properties of Uni-directionally Reinforced Hybrid Fiber Composites, " MS thesis in Engineering Mechanics, The Pennsylvania State University, Aug. 2013.

* Ross, J. W., "On the Optimization of Composite Flywheel Rotors," Ph.D. Thesis in Engineering Science and Mechanics, The Pennsylvania State University, Aug. 2013.

** Kunte, Harshad S., “Development of Control Oriented Electrical and Thermal Models of an Electric Transit Bus Battery System,” MSE Thesis in Mechanical Engineering, The Pennsylvania State University, May 2014.

*** Aglione, Daniel, “Design, Modeling, and Simulation of Battery Pack Suspensions for Off-Road Electric Vehicles,” MSE Thesis in Mechanical Engineering, The Pennsylvania State University, May 2014.

Research funded by: * US DOE GATE Program, ** Mineta Transportation Institute, *** General Electric Transportation Division

Accomplishments
Outreach

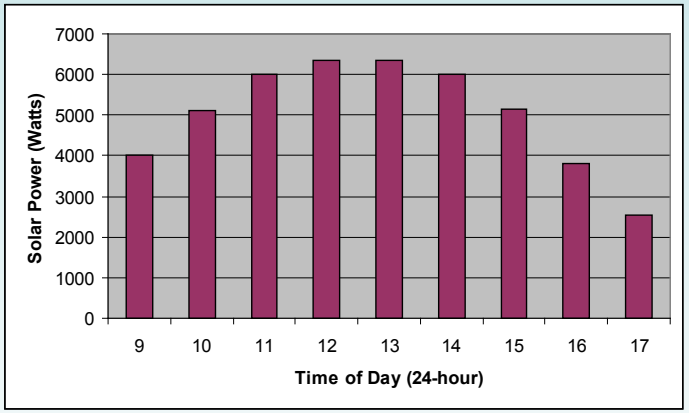
GATE Students and Alumni Help Organize and Host 21st Century Automotive Challenge 2009-2014

Competition Divisions by Market Segment Rather than Technology

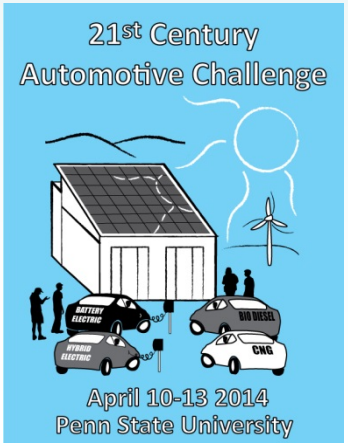
- Production / Independent
- Light Duty / Heavy Duty
- Local / Local and Highway
- Passenger accommodation: 1-2, 3-5, 6+
- EV, HEV, PHEV, bio-diesel, CNG, ethanol

April date during Blue White scrimmage exposed 50-70 thousand fans to ~15 alternative fuel vehicles including Penn State EcoCAR and EcoMarathon teams

Carbon footprint score includes solar fraction of EV charging from PSU Solar Decathlon home



http://www.larson.psu.edu/21st%20CAC



Pluggable vehicles can participate in simulated Vehicle to Grid (V2G) connection during peak and off peak

Collaboration & Coordination Government and Industry

- Volvo Preferred Academic Partner for research and education
- General Electric research and education partnership
- Mathworks campus licensing agreement
- ANL Autonomie license arrangement for GATE classes
- GM annual gift to GATE Program
- Pi Innovo donating five M211F OpenECU controllers and software
- ARPA-E reconfigurable BMS project
- GE Underground mining vehicle battery pack suspension project
- 21st Century Automotive Challenge Event
  - Eastern Electric Vehicle Club collaboration
  - Sustainability Institute collaboration for solar home venue and outreach
  - Mineta Transportation Institute sponsorship of alternative fuel seminar
  - FTA Bus Test Center provides facilities and sponsorship
  - Penn State Office of Physical Plant sponsorship

Collaboration & Coordination Academic

- Penn State DOE AVTC EcoCAR 2 Team
- Penn State Center for Sustainability and 2007 DOE Solar Decathlon home
- Penn State Applied Research Lab
- IQS Barcelona (Spain) Industrial Engineering visiting scholars
- Chalmers, Sweden and Institut National des Sciences Appliquées de Lyon (France) through the Volvo Preferred Academic Partnership
- Clemson University GATE Program
  - GATE Seminar at Greenville SC February 2012
  - Co-chair ASME IDETC AVT 5 sessions
- Pennsylvania College of Technology Advanced Automotive Technology Program support of hybrid vehicle curriculum
- Central Pennsylvania Institute for Science and Technology Automotive Program Board

Addressing 2013 Reviewer Feedback

- Reviewers recommended more Advisory Board input
  - Q2: Accomplishments "…The reviewer advised that it may be useful to get advisory input from the systems perspective to help guide the focus areas."
  - Q3: Collaboration "…reviewer noted that Penn State tried to develop an IAB,…reviewer advised that it still might try to resurrect some form of this idea, to assist in monitoring and improving Penn State's program.
  - Individual battery, capacitor and flywheel centers will review respective energy storage tracks with their IABs for feedback and comment. HHVRL will review systems track by survey of automotive systems industrial partners.
- Reviewer concerned focus too broad and/or too academic
  - Q1: Approach "The reviewer observed limited industry partnering, and cautioned that the program appeared to be too academic focused."
  - Q1: "…For this reviewer, a potential concern is that this program does cover so much territory that care must be taken to maintain focus to ensure progress. "
  - By design, required courses provide academic focus while electives allow flexibility and provide exposure to a broader technology focus for a balanced energy storage engineering education. While the program is broad, students complete only one of four energy storage curriculum tracks, each advised by a separate group of faulty within their particular energy storage industry.

Addressing 2013 Reviewer Feedback

- Reviewers concerned program maintaining status quo, not demonstrating continual improvement
  - Q1: Approach "…According to this reviewer, the project team is just continuing to do what the project was doing with current collaborators."
  - Q2. Accomplishments "The reviewer commented that it was hard to identify the progress achieved on this project, and most of the discussion was on past efforts."
  - The program is following the proposed schedule which includes development of new tracks and continual improvement of energy storage curriculum as the technology evolves. Hardware in the Loop techniques are being deployed to integrate energy storage theory with applied system practice and as a means to expose students to all types of energy storage technology. Students receive exposure to industry partners though their respective centers. GATE students also help to host the annual 21st Century Automotive Challenge which exposes them to the latest alternative fuel vehicles in a real world scenario. Notable evidence of continual improvement and innovation includes publication of an energy storage text book, development of two new battery courses, winning the 2013 EcoCAR 2 challenge, and development of online course content with plans for distance education to reach industry.

Future Work

- Continual improvement GATE curriculum and labs
- Continue offering four GATE tracks
- Expand HIL capability to all GATE labs for scaled testing where beneficial
- Continue DOE EcoCAR participation with faculty support of HIL deliverables
- Expand industry involvement, sponsorship, and projects
  - Continue recruitment of GATE partners
  - Annual vehicle competitions outreach to public
- Expand online courses towards offering distance education GATE certificate with progress made during 2013-14
- Continue focus vehicle use for GATE student thesis work:
  - EV1 based fuel cell vehicle with Li-ion
  - Two-mode PHEV with $LiFePO_4$ pack
  - Range extending series PHEV with Li-Ion pack and active yaw control
  - Neighborhood EV with $LiFePO_4$ pack and solar array

Summary

- Relevance
  - Strong record of placement into automotive industry and research organizations
  - Strong outreach component
- Approach
  - Alignment of various centers and labs into a unified yet diverse program
  - Curriculum tracks specific to particular technologies for electrical energy storage
  - Students learn from a large team of interdisciplinary faculty
- Technical Accomplishments
  - Penn State GATE Program funding has been highly leveraged to support many students with other funding sources
  - Good progress in energy storage centered curriculum development with system background
  - Strong record of publication
- Collaborations
  - Good progress in obtaining projects and collaborations with industry
  - Broad array of academic collaborations
- Future work
  - Develop online and distance education versions of energy storage curriculum to reach a larger body of students in industry and research careers
  - Continual improvement of course content as technologies evolve
  - Expand HIL capability to all GATE labs for scaled testing where beneficial
  - Recruit additional partners and sponsors for GATE related education and research

Contact Information

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