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 9, 2015

Project ID#
TI025

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview
PSU GATE Program

- Timeline
  - Start Oct 2011
  - End Oct 2016
  - 70% complete
- Budget
  - Awarded: $944,753
  - PSU match: $374,672
  - Obligated: $944,753
  - Expended: $442,447
  - Expended match: $286,483

- Barriers
  - Energy storage cost and durability
  - Public acceptance of electric drive (cost)
  - Engineering workforce
- Partners
  - US DOE & GM via EcoCAR 3
  - Clemson GATE
  - Pi Innovo

Relevance
Goals and Objectives

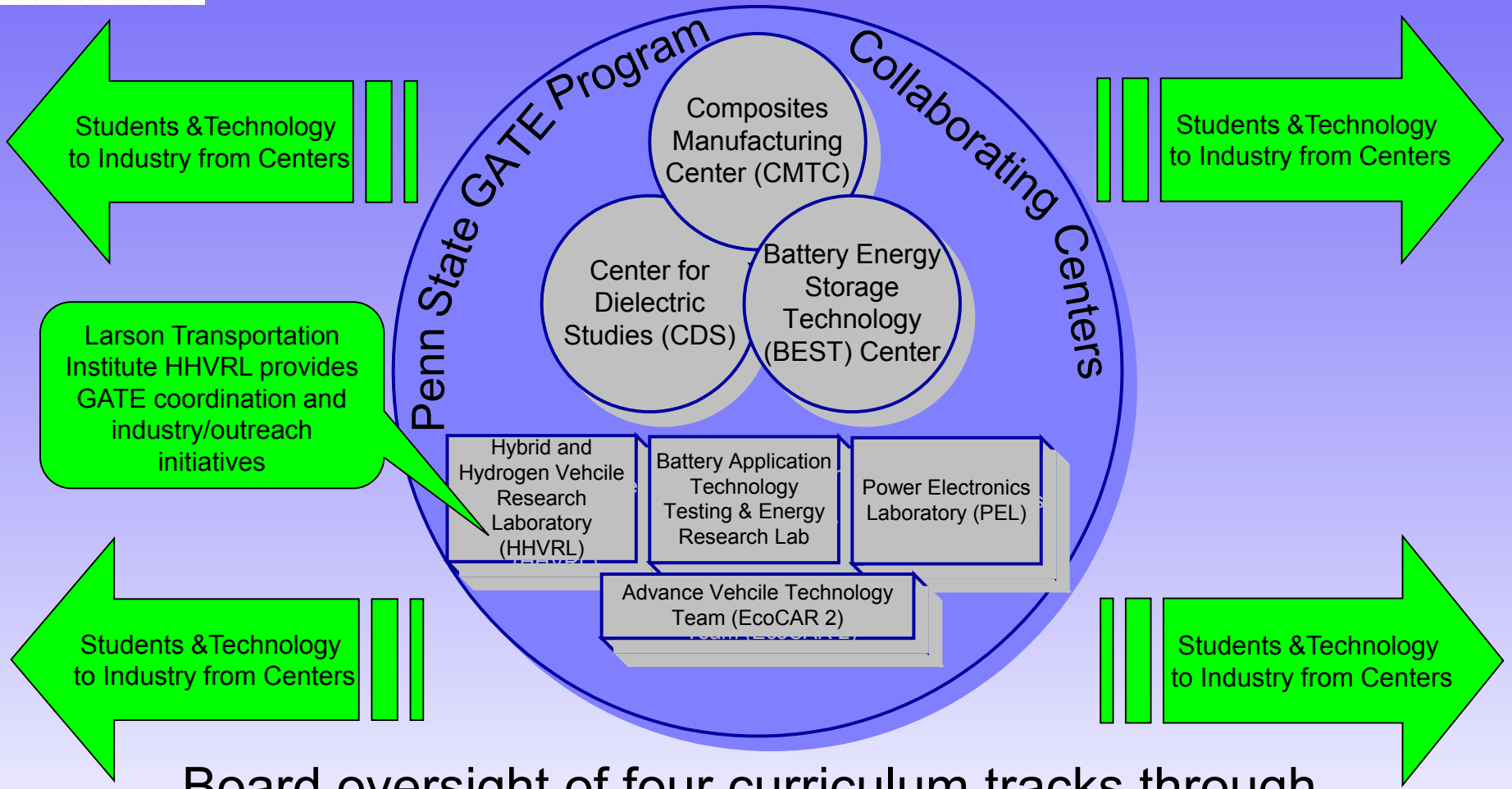
- Provide graduate curriculum focused on high-power in-vehicle energy storage for hybrid electric and fuel cell vehicles covering the fundamental science and models for electrical energy storage technologies: ***batteries, capacitors, flywheels*** and their combinations


- Provide a broad overview of 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/software/component in loop
  - 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

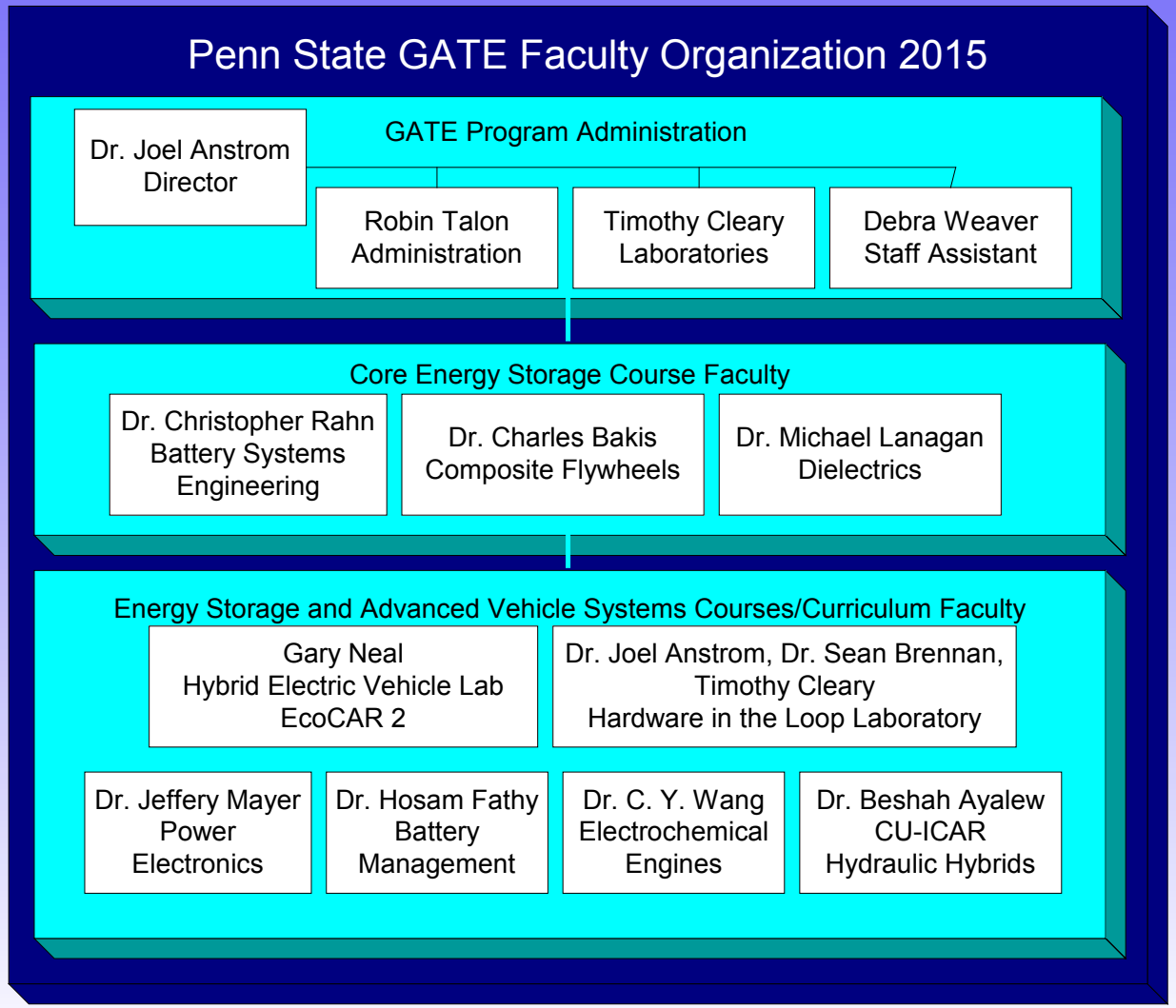
- Team planning and teaching of GATE courses
- Research within individual centers by technology
- HHVRL coordinates GATE grant reporting and industry outreach
- GATE Fellows follow curriculum and pursue energy storage thesis topics
- Any student in GATE curriculum is considered a GATE Student
- Synergy with DOE AVTC Team (EcoCAR 3)
- GATE graduates advance energy storage targets
- Provide dedicated “focus vehicle” platforms for GATE student research
- Component in the Loop Benches for each lab where beneficial

Approach
Structure and Principles



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

Approach
Structure and Principles



Approach (continued)

Penn State GATE Curriculum 2015

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 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 two of...	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
Or	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	Or	
ME597D Matls Energy Stor & Conv	ME 597F HIL for Auto Development	ME 597F HIL for Auto Development	

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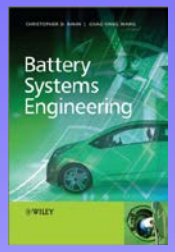
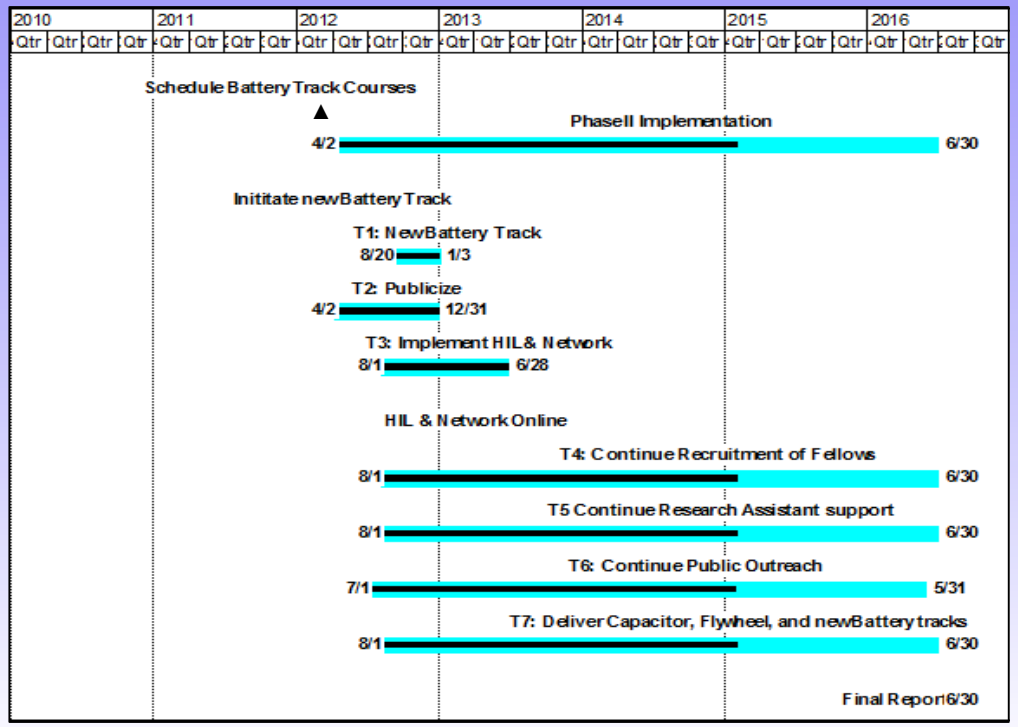
Accomplishments/Progress Phase II Implementation

Phase II Tasks 1-7 (Phase I and full schedule in backup slides)

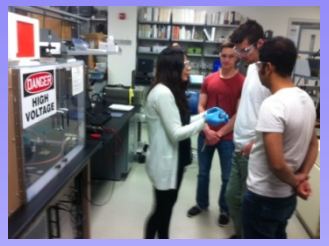
- T1: New Battery Track courses ME 597 B & C initiated 2012
  - C. Rahn and C.Y. Wang published textbook ***Battery Systems Engineering*** for use in ME 597C
- T2-3: Penn State GATE program was publicized, inter-lab HIL network tested
- T4-7: Recruitment, support, outreach, curriculum delivery ongoing





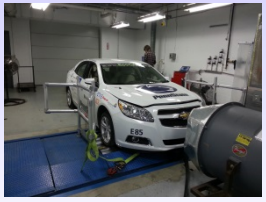
Accomplishments/Progress Required Courses

- 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 and road load models
  - HEV platform and test facility demos
  - Online course version piloted 2013
- ME 442W/443W HEV Laboratory
  - Develop DOE AVTC Competition Vehicles
    - 1999-2004 FutureTruck – Lithium Tech cells
    - 2005-08 Challenge X – Lithium Tech cells
    - 2008-11 EcoCAR – A123 modules and BMS
    - 2012-14 EcoCAR 2 – A123 modules and BMS
    - 2014-15 EcoCAR3 – Architecture proposed accepted
  - Funded faculty support for HIL of EcoCAR 3
  - Senior capstone for ME, EE, Chemical Engineering
  - GATE faculty, fellows and RA's bring energy storage expertise



Dielectric breakdown lab


EcoCAR 2 Competition



Accomplishments/Progress Electives and Initiatives

ME 597F Advanced Vehicle Automotive Hardware-in-the-Loop (HIL) Techniques

- PHEV10 developed as mobile HIL laboratory
  - Two Mode PHEV series (urban) and parallel (highway)
  - Onboard HIL engine dynamometer
  - New 48V Li-ion battery pack with BMS under construction
  - Control strategy optimization
  - On track fuel economy lab

Engine HIL and Chassis dyno testing

HEV topology labs

Li-ion battery and BMS

Battery HIL exercise

- Li-ion and Capacitor modeling & lab
- PI Innovo donated licenses and ECU control hardware implemented in 2014
- ANL donated PSAT/Autonomie licenses
- Scheduled fall semester to support EcoCAR 3 HIL deliverables

Accomplishments/Progress
GATE Students

Current GATE Fellowships

- Stephen Boyle – Systems Track, improved gaseous fuel storage systems (pending)
- Matthew Pryz – Capacitor Track, capacitor materials
- Seth Berbano – Capacitor Track, materials for glass solid electrodes
- Jariullah Safi – Battery Track, battery management and HIL networks
- Daniel Marple – Battery Track, high temp effects on Li-ion batteries

Previous GATE Fellows

- Kamiar Salehi – Battery Track, low temperature abuse effects on Li-ion life
- Maximillian Ripepi – Flywheel Track, hybrid fiber rotor material properties
- Jacob Ross, Ph. D. – Flywheel Track, genetic algorithm rotor optimization
- Julie Sawlsville – Battery Track, battery performance under extreme conditions

Accomplishments/Progress
2014 Sample Publications

Zhang, G., Cao, L., Ge, S., Wang, C.-Y., Shaffer, C., and Rahn, C., "In Situ Measurement of Temperature Distribution in Cylindrical Li-Ion Cells," 2014 ECS and SMEQ Joint International Meeting, Cancun, Mexico, October 5-10, 2014.

Tanim, T., Rahn, C., and Wang, C.-Y., "A Reduced Order Enhanced Single Particle Lithium Ion Cell Model Including Electrolyte Diffusion and Temperature Effect," 2014 American Control Conference, Portland, OR, June 2014.

T. Tanim, C. Rahn, and C.-Y. Wang, "A Temperature Dependent, Single Particle, Lithium Ion Cell Model Including Electrolyte Diffusion," ASME Journal of Dynamic Systems, Measurement, and Control, accepted for publication, 2014.

Y. Li, Z. Shen, A. Ray, and C. Rahn, "Real-time Estimation of Lead-acid Battery Parameters: A Dynamic Data-driven Approach," Journal of Power Sources, accepted for publication, 2014.

T. Tanim, C. Rahn, and C.-Y. Wang, "State of charge estimation of a lithium ion cell based on a temperature dependent, electrolyte enhanced, single particle model," Energy, Vol. 80, pp. 731 – 739, 2014.

G. Zhang, L. Cao, S. Ge, C.-Y. Wang, C. Shaffer, and C. Rahn, "In Situ Measurement of Radial Temperature Distributions in Cylindrical Li-ion Cells," Journal of The Electrochemical Society, Vol. 161, No. 10, pp. A1499-A1507, 2014.

D. Docimo, M. Ghanaatpishe, M. Rothenberger, C. Rahn, and H. Fathy, "The Lithium-Ion Battery Modeling Challenge: A Dynamic Systems and Control Perspective," ASME Magazine, Focus on Dynamic Systems and Control, July 2014.

G. Prasad and C. Rahn, "Reduced Order Impedance Models of Lithium Ion Batteries," ASME Journal of Dynamic Systems, Measurement, and Control, Vol. 136, No. 4, 041012 (8 pgs.), 2014.

Berbano, Seth S., et al. "Chalcogenide-based lithium solid electrolytes processed by the Powder-in-a-tube method." *Materials Letters* 141 (2015): 70-72.

D. Choi, C. Randall and M. Lanagan. "Combined Electronic and Thermal Breakdown Models for Polyethylene and Polymer Laminates." Materials Letters 141: 14-19, 2015.

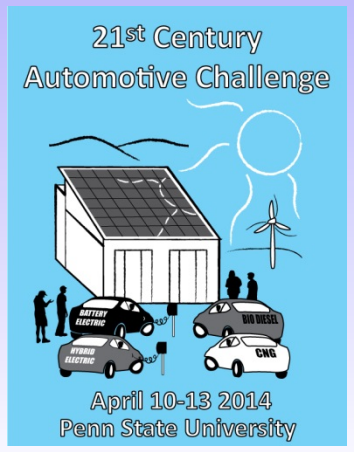
G. Sethi, E. Furman, B. Koch and M. Lanagan, "Influence of Impedance Contrast on Field Distribution and Tree Growth in Laminate Dielectrics," Modelling Simul. Mater. Sci. Eng. 22: (18 pages), 2014.

Accomplishments/Progress
GATE Outreach

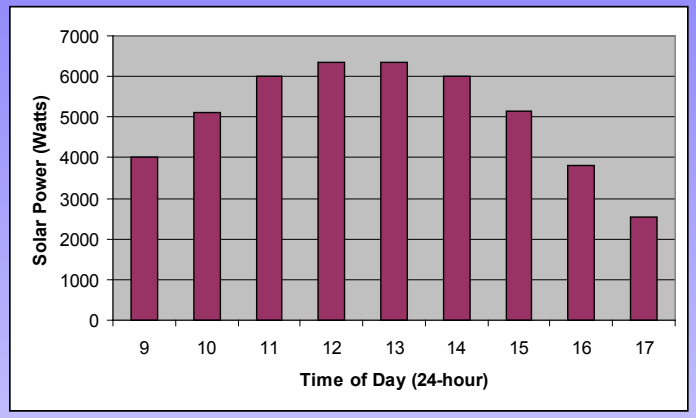
GATE Students and Alumni Help Organize and Host 21st Century Automotive Challenge 2009-2015

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, gasoline
- *2015 EcoCAR team leader from Methacton HS team*
- *2016 planning for Philadelphia Navy Yard event*
- http://www.larson.psu.edu/21st%20CAC



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



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 OpenECU controllers and software
- 21st Century Automotive Challenge Event collaborators
  - Eastern Electric Vehicle Club collaboration
  - Three Rivers Electric Auto Association
  - Penn State Sustainability Institute
  - FTA Bus Test Center
  - Penn State Office of Physical Plant
  - Central Pennsylvania Institute of Technology

Collaboration/Coordination Academic

- Penn State DOE AVTC EcoCAR 3 Team
- Penn State Center for Sustainability and HyRes Solar home
- IQS Barcelona (Spain) Industrial Engineering visiting scholars
- Chalmers, Sweden and Institute National des Sciences Appliquées de Lyon (France) through the Volvo Preferred Academic Partnership
- Clemson University GATE Program
- Pennsylvania College of Technology Advanced Automotive Technology Program
- Central Pennsylvania Institute for Science and Technology Automotive Program

Proposed Future Work

- Continual improvement GATE curriculum and labs
- Continue offering of 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 Berkeley PHEV with new Li-ion pack
  - Range extending series PHEV with Li-Ion pack and active yaw control
  - Neighborhood EV with $LiFePO_4$ pack

No Reviewer Feedback of PSU GATE in 2014

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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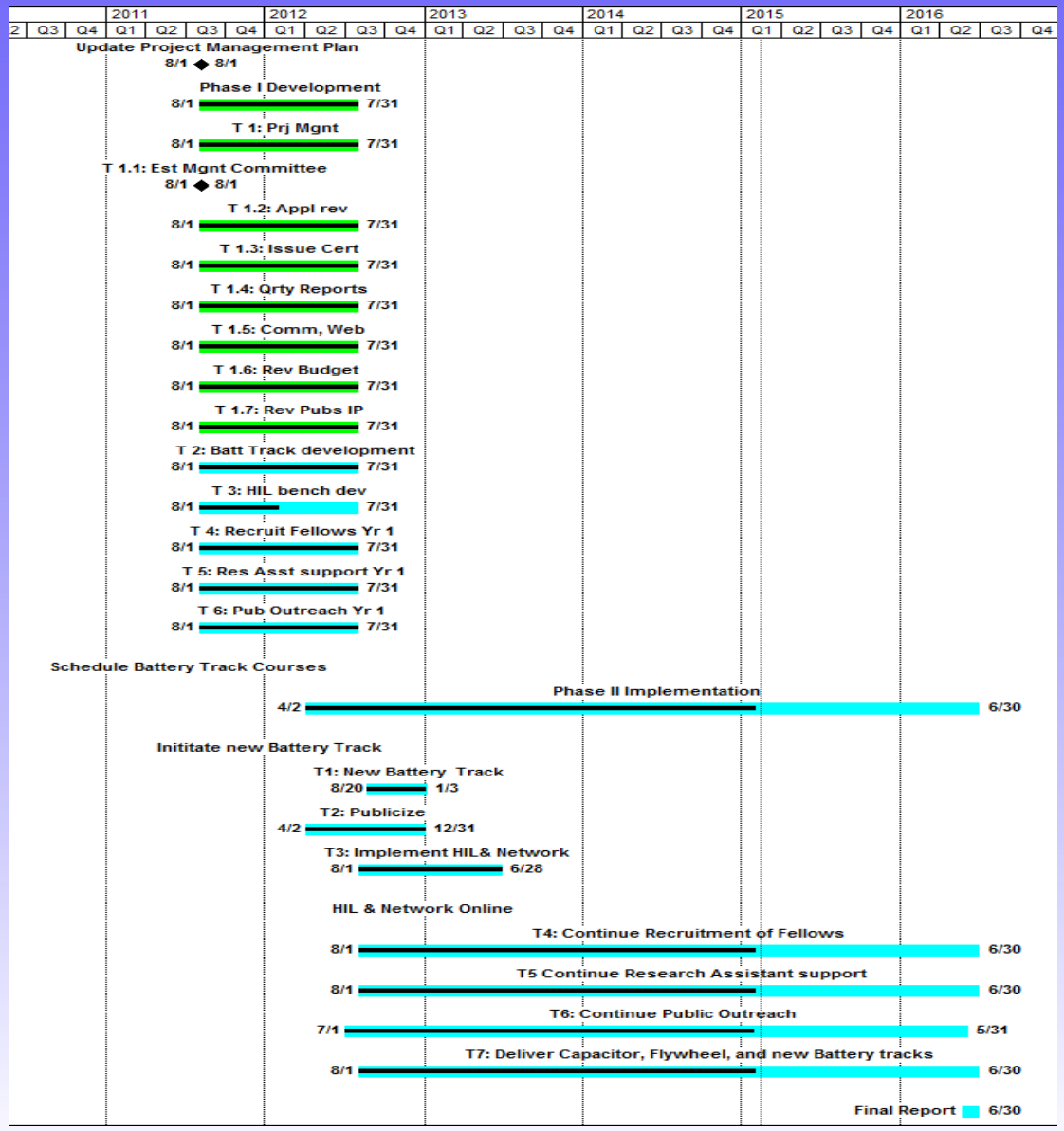
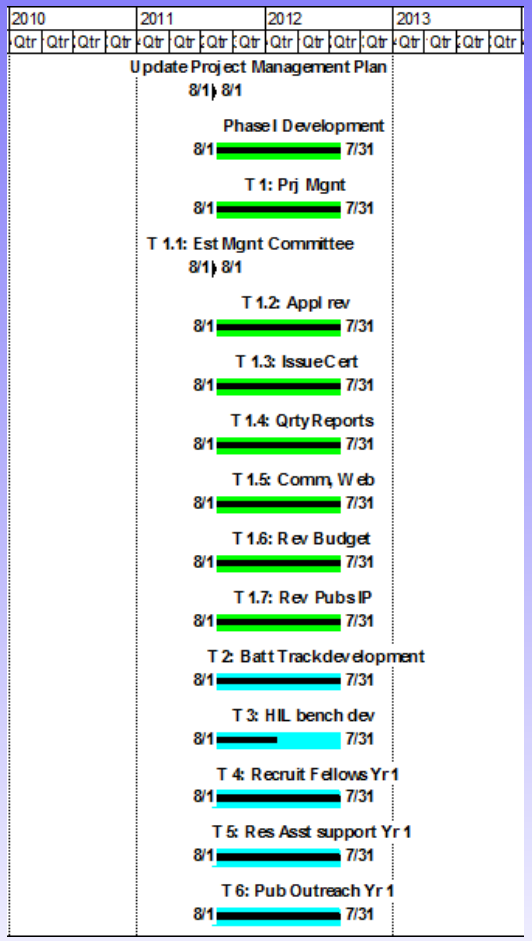
Technical Backup Slides

Progress – Full Gantt



Accomplishments/Progress Phase I Implementation



- Application materials updated
- New GATE Fellow recruited
- New Battery Track development completed
- 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