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, May 15, 2013

“This presentation does not contain any proprietary or confidential information”
Overview of PSU GATE Program

- **Timeline**
  - Start Oct 2011
  - End Oct 2016

- **Budget**
  - Awarded: $944,753
  - PSU Match: $374,672
  - Obligated: $287,412
  - Expended: $137,378
  - Expended match: $27,567

- **Barriers**
  - Energy storage cost and durability
  - Public Acceptance of electric drive (cost)

- **Partners**
  - US DOE and GM via EcoCAR 2
  - Clemson University
### Schedule

**On Schedule through Q1 2013**

<table>
<thead>
<tr>
<th>Task</th>
<th>Quarter</th>
<th>Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Update Project Management Plan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase 1 Development</td>
<td>8/1</td>
<td>7/31</td>
</tr>
<tr>
<td>T 1.1: Pj Mgmt</td>
<td>8/1</td>
<td>7/31</td>
</tr>
<tr>
<td>T 1.1: Est Mgmt Committee</td>
<td>8/1</td>
<td></td>
</tr>
<tr>
<td>T 1.2: AppRev</td>
<td>8/1</td>
<td>7/31</td>
</tr>
<tr>
<td>T 1.3: Issue Cert</td>
<td>8/1</td>
<td>7/31</td>
</tr>
<tr>
<td>T 1.4: Org Reports</td>
<td>8/1</td>
<td>7/31</td>
</tr>
<tr>
<td>T 1.5: Comm, Web</td>
<td>8/1</td>
<td>7/31</td>
</tr>
<tr>
<td>T 1.6: Rev Budget</td>
<td>8/1</td>
<td>7/31</td>
</tr>
<tr>
<td>T 1.7: Rev Pubs IP</td>
<td>8/1</td>
<td>7/31</td>
</tr>
<tr>
<td>T 2: Batt Track dev</td>
<td>8/1</td>
<td>7/31</td>
</tr>
<tr>
<td>T 3: HIL bunch dev</td>
<td>8/1</td>
<td>7/31</td>
</tr>
<tr>
<td>T 4: Need Flows Yr 1</td>
<td>8/1</td>
<td>7/31</td>
</tr>
<tr>
<td>T 5: Rev Asst spt Yr</td>
<td>8/1</td>
<td>7/31</td>
</tr>
<tr>
<td>T 6: Pub Outreach Yr 1</td>
<td>8/1</td>
<td>7/31</td>
</tr>
<tr>
<td>Schedule Battery Track Courses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase II Implementaion</td>
<td>42</td>
<td>6/30</td>
</tr>
<tr>
<td>Initiate new Battery Track</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>T 1: Unit new Batt Track</td>
<td>8/20</td>
<td></td>
</tr>
<tr>
<td>T 2: Publicize</td>
<td>12/31</td>
<td></td>
</tr>
<tr>
<td>T 3: Imp, HIL &amp; Ref</td>
<td>8/1</td>
<td>6/28</td>
</tr>
<tr>
<td>HIL &amp; Network Online</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T 4: Cont Rect Flws</td>
<td>8/1</td>
<td>6/30</td>
</tr>
<tr>
<td>T 5: Cont Res Asst support</td>
<td>8/1</td>
<td>6/30</td>
</tr>
<tr>
<td>T 6: Cont Public Outreach</td>
<td>8/1</td>
<td>6/30</td>
</tr>
<tr>
<td>T 7: Deliver Cap, Flywheel, and new Battery Tracks</td>
<td>8/1</td>
<td>6/30</td>
</tr>
<tr>
<td>Final Report</td>
<td></td>
<td>6/30</td>
</tr>
</tbody>
</table>
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 batteries, capacitors, flywheels and their combinations.

• Integrate system topics into energy storage curriculum including vehicle configurations, advanced combustion, fuel cells, power electronics, controls, alternative fuels and vehicle fuel efficiency to prepare students for careers.

• Develop relationships between GATE students, faculty, industry/research partners, and employers.
Penn State GATE Program Approach

Larson Transportation Institute HHVRL provides grant coordination and industry/outreach initiatives.

Students & Technology to Industry from Centers

Students & Technology to Industry from Centers
Penn State GATE Program Approach

• 1999 PSU GATE Program Faculty
  – Director/Systems - Donald Streit (ME) followed by Joel Anstrom (PA Transportation Institute, Systems)
  – Battery storage – Chao-Yang Wang (ME, ECEC)
  – Ultra-capacitors – Michael Lanagan (ES&M, CDS)
  – Flywheels – Charles Bakis (ES&M, CMTC)

• 2005 Expanded System Theme and Added GATE Faculty
  – Adv. Combustion – Andre Boehman (EMS, DCEL)
  – Power Electronics – Jeff Mayer and Heath Hofmann in 2009 (EE, PEL)
  – Controls – Sean Brennan (ME, Controls)
  – HEV Lab Instructor, Challenge X Advisor – Daniel Haworth (ME, Advanced Combustion)

• 2011 Created Four Separate Curriculum Tracks and Added GATE Faculty
  – Christopher Rahn – Battery Engineering and Controls
  – Hosam Fathy – Battery Management and Controls
  – Gary Neal – EcoCAR 2 Advisor
  – Timothy Cleary – Hardware in the Loop Support
Penn State GATE Program Approach

- Team planning and teaching of GATE courses
- Research in five Centers, HHVRL coordinates GATE industry outreach
- GATE Fellows follow curriculum and pursue energy storage thesis topic
- Any student in GATE curriculum 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
- GATE graduates advance energy storage targets
Penn State GATE Faculty Organization 2013

GATE Program Administration
- Dr. Joel Anstrom, Director
- Robin Talon, Administration
- Timothy Cleary, Laboratories
- Debra Weaver, Staff Assistant

Core Energy Storage Courses
- Dr. Chao Yang Wang
- Dr. Christopher Rahn, Batteries
- Dr. Charle Bakis, Composite Flywheels
- Dr. Michael Lanagan, Dielectrics

Advance Vehicle Laboratories and System Engineering Courses
- Gary Neal, Dr. Daniel Haworth, Dr. Hosam Fathy, Dr. Jeffery Mayer, HEV Lab - EcoCAR 2
- Dr. Joel Anstrom, Dr. Sean Brennan, Timothy Cleary, Hardware in the Loop Laboratory
- (Engage Future Hire) Advanced Combustion
- Dr. Jeffery Mayer, Power Electronics
- Dr. Hosam Fathy, Battery Management
- Dr. Beshah Ayalew, Clemson, Hydraulic Hybrids
Penn State GATE Curriculum for 2013

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 Courses - Three Credits

- **Battery Track** C. Rahn
  - ME 597C (S13)*
  - Battery Sys Eng

- **Capacitor Track** M. Lanagan
  - ME 597K (S13)
  - Energy Storage

- **Flywheel Track** C. Bakis
  - ME 597K (S13)
  - Energy Storage

- **System Track** J. Anstrom
  - ME 597K (S13)
  - Energy Storage

Group III Elective Courses - Six Credits

- **New Track**
  - ME 597D (S13)
    - Materials for Energy Conversion & Storage
  - ME 597B (F13)
    - Optimal Control of Energy Systems
  - ME 59XX
    - Battery Mfg (Future)

  - Or
  - ME 442W (F12), 443W (S13)
    - Adv. Veh. Design

  - Or
  - ME 597F (F14)
    - HIL for Auto Development

  - Or
  - ESci 597A/MatSc 597D
    - MicroWave Proc. of Materials

  - And
  - ME 597F (F14)
    - HIL for Auto Development

  - And
  - EMech 471 (F13)
    - Engr. Composite Materials

* Current or next semester course offering
GATE Core Courses

• ME 597K/Esc 597C High Power In-Vehicle Energy Storage
  – Fundamental science of energy storage
    – Batteries: NiMH, Lithium Chemistries, battery management principles
    – Capacitors: double layer
    – Flywheels: composite rotor design and motors
  – Introduction to Energy Storage Models
  – Vehicle road loads, demos, and laboratories
  – **Online pilot S13** taught by five GATE faculty

• ME 442W/443W HEV Laboratory
  – Develop **DOE AVTC** Competition Vehicles
    • 1999-2004 FutureTruck – Lithium Tech cells
    • 2005-2008 Challenge X – Lithium Tech cells
    • 2008-2011 EcoCAR – A123 commercial pack
    • 2012-2013 ECOcar II – A123 commercial pack
  – GATE Students bring energy storage expertise
  – Senior capstone for ME, EE, Chem Eng
  – Available engineering elective or as volunteer
  – Three GATE faculty advise team recruit students
Hardware in the Loop Benches for GATE Labs

- Developed automotive Hardware-in-the-Loop lab/course for GATE
  - 2-mode PHEV developed as HIL test bench
  - Mathworks™ donated licenses and hardware
  - ANL donated PSAT/Autonomie licenses
  - Energy storage HIL
    - Battery model & lab
    - Capacitor model & lab
  - System HIL labs
    - Engine model & lab
    - Electric motor & lab
    - Control strategy optimization
    - On track fuel economy

- Extend HIL capability to other GATE Centers/Labs
  - Piloting HIL button cell voltemetry in Materials Research Lab
  - Demonstrate HIL benefits at small scale
  - Extend HIL to other labs where beneficial
  - Leverage as GATE course laboratory exercises
Current GATE Fellows

- Jacob Ross
  - PhD Eng Science advisor Charles Bakis
  - Flywheel Rotor Design Optimization with Evolutionary Algorithms

- Julie Sawlsville
  - Masters Mechanical Engineering advisor C.Y. Wang
  - Battery and fuel cell research

- Max Ripepi
  - Masters Engineering Mechanics advisor Charles Bakis
  - Self levitating flywheel design
Accomplishments 1999-2013

- Current and previous GATE Programs (1999-2013) accomplishments:
  - 4 GATE fellows funded under current GATE program
  - 18 funded as GATE Fellows with previous DOE funding
  - ~50-70 funded as GATE Students with other funding
  - 5 PhD students graduated
  - ~500 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, NREL, INL, Oakridge NL, Mack Volvo, Aberdeen Proving Grounds
Select 2013 GATE Publications


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+

Carbon footprint score includes solar power fraction from PSU Solar Decathlon home introducing consumer choices of travel and charge time into overall lifestyle efficiency
Current Government and Industry Relationships

- Volvo and GE research and educational partnerships
- ARPA-E Modular BMS project
- ANL online course development for battery development
- Mathworks license arrangement with Penn State
- ANL Autonomie license arrangement for GATE HIL class
- Pi Innovo providing five M211F OpenECU controllers and OpenECU Developer Platform Sim32 software at significant discount
- GM annual gift to GATE - $5K
- Eastern Electric Vehicle Club collaboration for 21st Century Automotive Challenge Event
PSU GATE Academic Collaborations

• Penn State DOE AVTC EcoCAR 2 Team
• Pennsylvania College of Technology Advanced Automotive Technology Program
• Penn State Center for Sustainability and 2007 DOE Solar Decathlon home
• Penn State Applied Research Lab
• Clemson University GATE Program
  – GATE Seminar at Greenville SC February 2012
  – ASME IDETC AVT 5
Future Work

• Continue offering GATE core and elective courses
• Continue HEV lab participating in DOE EcoCAR 2
• Continual improvement GATE curriculum and labs
• Expand industry involvement, sponsorship, and projects
  – Continue recruitment of GATE partners
  – Annual vehicle competitions outreach to public, new students
• Expand online courses towards offering distance GATE certificate
• Continue focus vehicle use for GATE student thesis
  – EV1 based fuel cell vehicle
  – Two-mode PHEV LiFePO₄ pack
  – PHEV series hybrid with front wheel motors
Penn State GATE Summary

- GATE funding has been highly leveraged to support many students with other funding sources
- Good progress in energy storage centered curriculum development with system background
- Good progress in obtaining projects and collaborations with industry
- Strong outreach component
Contact Information

Joel R. Anstrom
Director of Penn State GATE Center
201 Transportation Research Building
University Park, PA 16802

(814) 863-8904
jra2@psu.edu