Graduate Automotive Technology Education (GATE) Program: Center of Automotive Technology Excellence in Advanced Hybrid Vehicle Technology at West Virginia University

Final Report
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SUMMARY

This report summarizes the technical and educational achievements of the Graduate Automotive Technology Education (GATE) Center at West Virginia University (WVU), which was created to emphasize Advanced Hybrid Vehicle Technology. The Center has supported the graduate studies of 17 students in the Department of Mechanical and Aerospace Engineering and the Lane Department of Computer Science and Electrical Engineering. These students have addressed topics such as hybrid modeling, construction of a hybrid sport utility vehicle (in conjunction with the FutureTruck program), a MEMS-based sensor, on-board data acquisition for hybrid design optimization, linear engine design and engine emissions. Courses have been developed in Hybrid Vehicle Design, Mobile Source Powerplants, Advanced Vehicle Propulsion, Power Electronics for Automotive Applications and Sensors for Automotive Applications, and have been responsible for 396 hours of graduate student coursework. The GATE program also enhanced the WVU participation in the U.S. Department of Energy Student Design Competitions, in particular FutureTruck and Challenge X. The GATE support for hybrid vehicle technology enhanced understanding of hybrid vehicle design and testing at WVU and encouraged the development of a research agenda in heavy-duty hybrid vehicles. As a result, WVU has now completed three programs in hybrid transit bus emissions characterization, and WVU faculty are leading the Transportation Research Board effort to define life cycle costs for hybrid transit buses. Research and enrollment records show that approximately 100 graduate students have benefited substantially from the hybrid vehicle GATE program at WVU.

INTRODUCTION

A Graduate Automotive Technology Education (GATE) Center was initiated at West Virginia University, in the College of Engineering and Mineral Resources, in 1998. Dr. Christopher Atkinson, Associate Professor of Mechanical & Aerospace Engineering, served as first Director, with Dr. Parviz Famouri (Computer Science & Electrical Engineering) and Dr. Nigel Clark (Mechanical & Aerospace Engineering) as Co-Directors. Dr. Atkinson left the Department of Mechanical & Aerospace Engineering in 2001, and Dr. Clark assumed responsibility as Director. Additional faculty who have participated in this program are Dr. Gregory Thompson (Mechanical & Aerospace Engineering) and

Dr. Biswajit Das (Computer Science & Electrical Engineering). GATE funding was used to support graduate students who were US citizens, and to support the development of courses relevant to the promotion of hybrid electric vehicle design.

STUDENT ACCOMPLISHMENTS

The GATE program supported students to degree completion, and also supported some students for part of their graduate studies, after which they were funded by other external automotive research grants and contracts. A total of 17 students received GATE support. The following students, who have received GATE funding for all or part of their studies at WVU, have completed graduate degrees:

Jonathan B. Smith
Samuel Taylor
John Jason Conley
Ronald Jarrett
Russel T. King
Thomas Buffamonte
John Gibble
Timothy Hall
Mathew Swartz

In addition, three students who received GATE funds are still completing degrees. They are:

Howard Mearns
Clint Bedick
Derek Johnson

Selected research summaries are presented below:

Samuel Taylor completed a MS degree in Mechanical Engineering. He focused his thesis on the design of high power output hybrid systems. This required examination of various hybrid component arrangements, and simulation of the hybrid powertrain performance using a program HVSIM, which was developed in house at WVU and improved by Samuel Taylor. Samuel Taylor was also engaged with the FutureTruck Program and was responsible for the retrofit of a Chevrolet Suburban with a Detroit Diesel engine, particulate matter trap and Unique Mobility motor.

Jason Conley completed a MS degree in Mechanical Engineering. He contributed in three areas. First, he was engaged with the FutureTruck Program. He presented a control philosophy for managing the FutureTruck hybrid system at the 2000 GATE Symposium. Second, he worked with Csaba Toth-Nagy, a student funded by NAVC, to develop a predictive tool that could model the emissions from heavy-duty trucks, both conventional and hybrid. This model employed the hybrid model ADVISOR, coupled with emissions predictions gained using a neural net model. The neural net was trained on engine emissions data. Data were generated with the model and compared with measured emissions from heavy-duty vehicles. Emissions of Carbon Dioxide were predicted with acceptable accuracy, but emissions of oxides of nitrogen were not well modeled when the engine operated in an “off-cycle” mode. Emissions from hybrid vehicles were strongly dependent on the vehicle control strategy. A Society of Automotive Engineers paper arose from this work. Third, Jason Conley gathered on-road activity data from an instrumented sport utility vehicle, and interpreted the data to represent instantaneous power demand. It was evident that as the size of the energy storage system was reduced (with respect to both energy and power ability), certain regenerative opportunities on a journey were lost, but not in direct proportion to the reduction. A weight tradeoff was needed in sizing the system. The recorded data were used to assess the size of hybrid storage system and motor that could capture a given fraction of the vehicle braking energy and provide a given fraction of its power demand. His work resulted in a novel approach for designing and assessing hybrid drivetrains, and the research resulted both in his thesis and in a paper given at an advanced vehicle technology conference at the University of Suffolk in the United Kingdom.

Eric Corrigan conducted MS research into emissions from diesel engines equipped with aftertreatment. The aftertreatment works within a temperature window, which must be considered in a hybrid control strategy. Mr. Corrigan’s work focused mainly on the effectiveness of both particulate matter catalysts and lean nitrogen oxides catalysts, and their succeptibility to poisoning by fuel sulfur. The research involved developing a novel experimental approach to test two catalysts in parallel. A Society of Automotive Engineers Paper arose from this work.

Ronald Jarrett completed a MS degree by modeling engine emissions for inclusion in hybrid vehicle models (such as ADVISOR or PSAT). He engaged in research to examine the relationship between carbon monoxide emissions and particulate matter emissions, and to relate the emissions found using a conventional filter system to those found using a Tapered Element Oscillating Microbalance (TEOM). Ron Jarrett also examined TEOM data and developed a method for correcting the data to account for transient water loading. His greatest contribution was in the development of neural net emissions models (for diesel engines) that could be incorporated into vehicle models. He recognized the most important variables needed to train the neural net for accurate prediction. Neural Net output can be processed to yield lookup tables to predict emissions in whole vehicle models.

John Gibble, who was funded in part by GATE for his degree, recognized that heavy-duty diesel engine test cycles may not be representative of real-world vehicle emissions. In-use emissions testing would provide engine emissions values under real-world conditions. He examined the accuracy of the West Virginia University Mobile Emissions Measurement System (MEMS) and performed on-road emissions tests with six heavy-duty vehicles. MEMS measured oxides of nitrogen and carbon dioxide, reported on a brake-specific basis. John Gibble used on-road information to create a simulated in-use engine dynamometer cycle, and the on-road and test cell information were compared.

Jonathan Smith conducted his MS research in the area of hybrid vehicle modeling. He modeled Class 2B, Class 6, and Class 8 hybrid vehicles to optimize their design and control over a variety of realistic driving cycles. Both Series and Parallel HEV vehicle configurations were considered. The Series HEV system that he modeled relied on an internal combustion engine to supply energy to the batteries and electric motor for propulsion, while the Parallel HEV system could power the vehicle by either the electrical motor, by the internal combustion engine, or in combination. The model was based on power requirements for vehicle class and addressed concerns such as engine, battery, and driveline efficiencies. Model results showed high increases in fuel economy for Class 6 and Class 8 vehicles on transient cycles while low increases in fuel economy were seen for steady-state cycles.

Russell King worked with a Ford Explorer Sport Utility vehicle that was operated as a diesel-electric hybrid vehicle in the FutureTruck program. He demonstrated a low emissions strategy for the hybrid vehicle. Diesel emissions contain oxides of nitrogen, which are not readily reduced using conventional catalyst systems. Russell King developed a control system and hardware for selective catalytic reduction together with urea injection to achieve the goal of reducing oxides of nitrogen by more than 60 percent. His research involved design of the electronic controller and the development of software based on careful mapping of the engine emissions with the vehicle on a chassis dynamometer and the development of a control strategy to manage the urea injection as a function of catalyst temperature and NOx production. Ultimately the aftertreatment and hybrid control strategies may be combined.

Derek Johnson and Clinton Bedick supported the WVU Challenge X program while funded by GATE. They played a major role in developing an ultracapacitor and diesel engine based hybrid system, and integrating it into a Chevrolet Equinox. The conclusion of the GATE program at WVU ended their support. Their research topics are now still in the automotive area, but their degrees will not be completed with GATE funding. Derek Johnson is currently investigating a retrofit to reduce engine oxides of nitrogen emissions, while Clinton Bedick has been engaged in a Low Temperature Combustion program.

Howard Mearns also played a major role in the Challenge X program, and is engaged in research leading to a thesis on the design, development, implementation and testing of the WVU Challenge X vehicle. His research interest includes the strategy used to maintain state of charge of the ultracapacitor pack. The philosophy used was to deplete the pack so that it could always capture the vehicle kinetic energy associated with braking to a standstill. His approach has built on the work of John Jason Conley. The test data to be collected will compare a stock Equinox with first the diesel only mode and then the full diesel hybrid mode, using the WVU Challenge X vehicle. The tests will be completed on a predetermined public road route.

COURSE DEVELOPMENT

The graduate courses offered under the GATE program were responsible for 132 student registrations for a total of 396 classroom hours. This is estimated to have impacted the education of approximately 100 individual graduate students. In addition, the establishment of the GATE program at WVU encouraged the inclusion of hybrid vehicle information in the MAE 425 Internal Combustion Engines course at WVU, which had total enrollment of 347 students between 1998 and 2006. This MAE 425 course is at the senior undergraduate level, but each semester a number of MS students also enroll in the course and it is estimated that approximately 30 graduate students benefited from this course.

The Lane Department of Computer Science and Electrical Engineering developed two courses for the WVU GATE Program. They were EE 691Q, titled "Power Electronics for Automotive Applications" and 691 S, titled "Sensors and Control for Automotive Applications." The power electronics course was taught by Dr. Parviz Famouri, while the sensors course was taught by Dr. Biswajit Das. The objective of the sensors course was to enable students to design and implement sensor and actuator based electronic systems for automotive applications, including data acquisition, communication, control and display. These courses are essential for the understanding of hybrid vehicle control systems.

The Department of Mechanical and Aerospace Engineering developed four courses under the GATE program. WVU did not have a developed program in any automotive courses prior to GATE, and only an undergraduate elective in internal combustion engines was previously taught. GATE provided the impetus for graduate courses not only in hybrid vehicles, but also in related topics of engines and emissions. One course, addressing Hybrid Electric Vehicle Design and Development, was taught by Dr. Christopher Atkinson, while he was still GATE Director at WVU. Dr. Gregory Thompson taught a course geared towards students conducting research in the transportation sector with specific emphasis on current research and development of advanced engines and their use in the vehicle powertrains. The course was structured to give the student insight into real-world emissions of existing and developmental heavy-duty vehicle system designs using conventional and hybrid-electric propulsion systems. The students developed an understanding of the impact of engine hardware design, engine control strategy, exhaust aftertreatment, fuels, and drivetrain configurations have on the emissions emitted from heavy-duty engines.

Another course, developed and taught by Dr. Nigel Clark, was “Mobile Source Powerplants.” The objective of this course was to provide advanced knowledge of the operation of internal combustion engines for automotive use, with emphasis on compression ignition (diesel) powerplants and their emissions. Topics included review of ideal cycles, real cycles, heat release computation, injection of fuel, sprays, ignition and combustion, formation of pollutants, transient operation control strategies, turbocharging and supercharging, aftertreatment, fuel properties and quality, regulation of emissions, introduction to atmospheric chemistry and environmental issues, and preparation of emissions inventories. Content from this course was merged with hybrid vehicle design material by Dr. Clark to create a new course, entitled “Advanced Vehicle Propulsion,” which covered advanced engine concepts, hybrid powertrains, and the impacts of emissions from transportation. In this course students were introduced to a variety of hybrid architectures and energy storage systems. The hybrid technology objective of the course covered series, parallel and planetary systems, and explained the benefits of hybridization in terms of fuel economy and emissions. Motor and battery technology was presented, and energy management was discussed. The homework tasks for this objective included building a computer model of a hybrid vehicle and using the model to predict performance. The last objective was to make students aware of the interaction of society and technology with respect to the environmental impacts of transportation. Specifically, emissions standards, air quality issues and emerging technologies were addressed.

SYNERGY WITH STUDENT PROGRAMS

The GATE program at WVU was closely associated with the US Department of Energy Student Design Competitions, namely FutureCar, FutureTruck and Challenge X. Graduate students in the GATE program in many cases had been members of the student teams while undergraduates, and continued to work with subsequent undergraduate teams while completing their graduate degrees. As examples, Samuel Taylor and John Jason Conley were involved in the DOE-General Motors FutureTruck competition which involved conversion of a Chevrolet Suburban to a hybrid drive configuration. Russell King was involved with the follow-on competition sponsored by DOE and Ford Motor Company, and was responsible for minimizing emissions from the hybrid drivetrain of a Ford Explorer.

More recently, Howard Mearns has played a leadership role in the Challenge X Chevrolet Equinox program at WVU, and has chosen this platform to provide the data for his thesis. The WVU Challenge X vehicle utilized two PML Flightlink EW 30/30 permanent magnet motors as the primary hybrid powertrain component. These motors were rated at 9.7 continuous output horsepower (hp) each and could be controlled to provide propulsion or regenerative braking. These motors were mounted inside the modified rear subframe of the Equinox and custom driveshafts were used to transmit motor power to the rear wheels. The front wheel drive remained mechanical. The stock Chevrolet Equinox six cylinder 3.4L gasoline engine and five speed automatic transmission were removed, and a four cylinder 1.9L turbocharged General Motors (GM) diesel engine with an AF40 six speed automatic transmission were used for primary propulsion. In order to absorb and discharge energy at high power levels for the hybrid drive system, Maxwell Technologies ultracapacitors were employed. The energy storage system used five strings of 23 capacitors in series. Each string was then connected in parallel for a total of 115 capacitors and a capacitance of 1000 farads at 48V nominal bus voltage. No voltage-to-voltage conversion was used with the ultracapacitor pack.

Of greatest interest was the control strategy designed to manage this hardware. The WVU control strategy was separated into three modes for the Challenge X competition. During normal operation, the hybrid system was controlled by the drive and braking modes. A third mode, for four wheel drive traction, was planned but not fully implemented. In drive mode, the inputs used to calculate the engine power command were based on accelerator pedal position, actual state of charge, vehicle speed, and vehicle weight (for calculation of potential energy). State of charge was calculated reliably using voltage. A target state of charge was determined based on driver request (based on accelerator pedal position), vehicle speed, and vehicle weight. The target state of charge was dynamic, so that at low vehicle speeds, the target state of charge was kept high because the vehicle had a low potential for regenerating energy during braking. The philosophy was that the vehicle energy storage system should be able to absorb the energy associated with a braking event from present speed to a standstill.

SYNERGY WITH WVU RESEARCH

At the time of the GATE award in 1998, WVU had developed broad experience in characterizing the emissions and performance of heavy-duty on-road vehicles, and was engaged in a wide range of programs aimed at measuring emissions from off-road engines, improving atmospheric emissions inventories, and preparing representative emissions test cycles. The GATE program and the FutureCar, FutureTruck and ChallengeX competitions increased awareness of hybrid vehicle technology at WVU, and encouraged WVU research into hybrid heavy-duty vehicles. This research was conducted by the Center for Alternative Fuels, Engines and Emissions. The Center is now led by eight faculty members of the Department of Mechanical and Aerospace Engineering and includes a team of engineers and technicians and over 40 students.

WVU has conducted research on truck and bus emissions for a wide range of sponsors, including DOE, The Department of Transportation, The Environmental Protection Agency, major engine manufacturers, The California Air Resources Board, The National Renewable Energy Laboratory, oil refiners and the States of NY, MA and MD. Much of this research has addressed the effects of fuel formulations and emissions reduction technology (SAE Papers 2001-01-0512, 1999-01-1512, 982526) or the use of alternative fuels (SAE Papers 981393, 982456, 973203, ASME Paper 99-ICE-176). The research has also provided the largest national repository of diesel vehicle field emissions data (SAE Paper 2000-01-2854). WVU has also conducted in-depth chemical speciation studies to characterize levels of toxic air contaminant emissions from gasoline, natural gas and diesel engines (SAE Papers 2002-01-0432, 2002-01-2873) and has conducted fundamental research of fuel formulation and additive effects on combustion and emissions.

In the hybrid vehicle research arena, WVU researchers have advanced the understanding of emissions characterization of hybrid diesel-electric vehicles (SAE Papers 2001-01-3537, 2000-01-2011, Energy and Fuels Vol. 18 No. 1 pp. 257-270). Faculty from WVU played a role in the authorship of SAE J2711 (Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid-Electric and Conventional Heavy-Duty Vehicles) and WVU has conducted emissions, fuel economy and performance characterizations of hybrid electric transit buses for the Orange County (CA) Transit Authority, ISE Research, OmniTrans of San Bernardino CA, The Northeast Advanced Vehicle Consortium and the Defense Advanced Research Projects Agency. WVU researchers are currently engaged in preparing a life-cycle cost hybrid bus model for the Transportation Research Board. Without GATE at WVU, it is likely that the hybrid research thrust at WVU would have been diminished.

SUMMARY TABLE

The following table presents a summary of data for the WVU GATE program. In some cases, where data were not directly available, best estimates were made. For example, it is known how many student registrations occurred for graduate GATE courses, but not how many individual students were represented in the registrations.

Number of new courses developed: 8
Number of course offerings: 13
Number of registrations for graduate GATE courses: 132
Number of student credit hours for graduate GATE courses: 396
Number of students benefiting from GATE courses: 100 (estimated)
Number of students receiving GATE support: 17 (for part of, or whole degree)
Number of graduated students: 9 (with an additional 3 still active, for an estimated total of 12)
Total students impacted by GATE at WVU (estimated, including Student Automotive Project Teams & graduate students in the Internal Combustion Engines course): 275