Modeling, Simulation Design and Control of Hybrid-Electric Vehicle Drives

a DOE GATE Center at The Ohio State University

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DISCLAIMER

1. Introduction

The Ohio State University GATE Center was founded in October 1998 with a grant from the US Department of Energy (DOE). This final report documents the activities of the Center between Oct. 1, 1998, and Sep. 30, 2005. The original investment made by DOE has been multiplied many fold thanks to the support of many partners, external and internal. The foresight demonstrated by the OSU College of Engineering in matching DOE funds from the original grant has been rewarded by numerous commitments to the program made by industry and government sponsors. The following executive summary is extracted from the original proposal submitted to DoE in 1998, and outlines the goals and objectives of the program.

2. Executive Summary

OSU is uniquely poised to establish such a center, with interdisciplinary emphasis on modeling, simulation, design and control of hybrid-electric drives for a number of reasons, listed below.

I. The OSU Center for Automotive Research (CAR) already provides an infrastructure for interdisciplinary automotive research and graduate education; the facilities available at OSU-CAR in the area of vehicle and powertrain research are among the best in the country. CAR facilities include 31,000 sq. feet of space, multiple chassis and engine dynamometers, an anechoic chamber, and a high bay area.

II. OSU has in excess of 10 graduate level courses related to automotive systems. A graduate level sequence has already been initiated with GM. In addition, an Automotive Systems Engineering (ASE) program co-sponsored by the mechanical and electrical engineering programs, had been formulated earlier at OSU, independent of the GATE program proposal. The main objective of the ASE is to provide multidisciplinary graduate education and training in the field of automotive systems to Masters level students. This graduate program can be easily adapted to fulfill the spirit of the GATE Center of Excellence.

III. A program in *Mechatronic Systems Engineering* has been in place at OSU since 1994; this program has a strong emphasis on automotive system integration issues, and has emphasized hybrid-electric vehicles as one of its application areas.

IV. OSU researchers affiliated with CAR have been directly involved in the development and study of: HEV modeling and simulation; electric drives; transmission design and control; combustion engines; and energy storage systems. These activities have been conducted in collaboration with government and automotive industry sponsors; further, the same researchers have been actively involved in continuing education programs in these areas with the automotive industry.

The proposed effort will include:

- The development of a laboratory facility that will include: electric drive and IC engine test benches; a test vehicle designed for rapid installation of prototype drives; benches for the measurement and study of HEV energy storage components (batteries, ultra-capacitors, flywheels); hardware-in-the-loop control system development tools.
- The creation of new courses and upgrades of existing courses on subjects related to: HEV modeling and simulation; supervisory control of HEV drivetrains; engine, transmission, and electric drive modeling and control. Specifically, two new courses (one entitled HEV Component Analysis: and the other entitled HEV System Integration and Control) will be developed. Two new labs, that will be taught with the courses (one entitled HEV Components Lab and one entitled HEV Systems and Control lab) will also be developed.
- The consolidation of already existing ties among faculty in electrical and mechanical engineering departments.
- The participation of industrial partners through: joint laboratory development; internship programs; continuing education programs; research project funding.

The proposed effort will succeed because of the already exceptional level of involvement in HEV research and in graduate education in automotive engineering at OSU, and because the PIs have a proven record of interdisciplinary collaboration as evidenced by joint proposals, joint papers, and co-advising of graduate students. OSU has been expanding its emphasis in Automotive Systems for quite some time. This has led to numerous successes such as the establishment of the Center of Automotive Research, a graduate level course sequence with GM, and numerous grants and contracts on automotive research. The GATE Center of Excellence is a natural extension of what educators at OSU already do well.

3. Outcomes

3.1 Faculty participation

The principal faculty involved in the GATE Center program and their areas of specialty (fundamental/applied) are:

Giorgio Rizzoni, Professor, ME and ECE, *Fellow of IEEE and SAE*
(electromechanics and system dynamics/engine dynamics and control, energy storage system and hybrid drivetrain design, dynamics and control)

Yann Guezennec, Professor, ME
(fluid and thermal sciences/combustion engines, fuel cells, energy storage systems and hybrid drivetrain analysis and modeling)

Stephen Yurkovich, Professor, ECE, *Fellow of IEEE*
(control systems/engine and powertrain control, fuel cell control)

Gregory Washington, Professor, ME
(control systems and system dynamics, smart materials/sensor and actuator design and control, hybrid vehicle control)

Ahmed Soliman, Research Scientist, CAR, Lecturer, ME
(Fluid and Thermal Sciences/engine diagnostics, engine sensors)

Vadim Utkin, Professor, ECE and ME, *Fellow of IEEE*
(Control Systems/engine control, electric machine control, hybrid drivetrain control)

The GATE program at OSU has built upon especially strong faculty collaborations. In 2002, the GATE program faculty (Rizzoni, Guezennec, Yurkovich, Soliman, Washington and Utkin) received the first *Lumley Interdisciplinary Research Award* awarded by the OSU College of Engineering in recognition of interdisciplinary research and graduate education. The above named faculty were recognized for their achievements as part of the GATE program between 1998 and 2002 including: 35 co-authored publications; 18 program graduates (4 Ph.D.); 6 distinct graduate courses co-taught in two departments; $2.7M in externally funded research grants with two or more of these faculty as co-PIs. These accomplishments were further strengthened between 2002 and 2004.. The GATE program was also the recipient of research funding in the amount of over $6M between '99 and '04 (see PI bios for details).

3.2 Grants and Contracts

Research program funding for the GATE program has come from: DaimlerChrysler, GM, Ford, Honda, Bosch, Delphi, Dana, Oshkosh Truck, Eaton, NREL, U.S. Army TARDEC, NSF, U.S. D.o.T.. The topic areas of the research funded through these programs are: *advanced combustion engines*, *advanced energy storage systems*, *fuel cell systems*, *smart materials for automotive sensing and actuation* and *advanced hybrid propulsion and control systems*. Ford, General Motors, DaimlerChrysler, Honeywell, Luk, Cummins and Honda provided matching funds for the GATE Fellowship program in the amount of $300,000, nearly matching the DOE Fellowship contributions dollar for dollar. Further, OSU matched the 22 Graduate-Student-years supported by DOE with tuition and fee waivers in the amount of $176,000.

The participating faculty have outstanding research records in the five sub-areas listed below. Total current funding (in current active contracts at CAR) for this research exceeds $5M.

1. *Advanced engine combustion, sensing, actuation and control*: Guezennec, Rizzoni, Serrani, Soliman, Utkin, Washington, Yurkovich.
2. *Advanced electrochemical energy storage systems modeling and system integration*: Guezennec, Rizzoni.
3. *Fuel cell system modeling, design and control*: Guezennec, Mazumder Rizzoni, Yurkovich.
4. *Research in smart materials with application to sensing and actuation in automotive systems*: Dapino, Washington
5. *Modeling, design, system integration and control of light- and heavy-duty hybrid-electric vehicles*: Guezennec, Rizzoni, Srinivasan, Utkin, Washington, Weide, Westervelt, Yurkovich.

3.3 Graduates

The OSU GATE Center accomplished the intended results, leveraging the curriculum development funds ($200,000) and the Fellowship funds ($350,000) received from DOE. In particular, DOE GATE funding supported 22 Graduate-Student-years; additional funding at OSU-CAR during the GATE period of performance permitted supporting an additional 96 Graduate-Student-years. Between 1999 and 2004, GATE graduated 29 M.S. and 9 Ph.D. students. 33 of these 38 professionals are now employed in the automotive sector. The details are given in Table 1.

Table 1 - OSU GATE program graduate summary

Year	M.S.	Ph.D.
1999	3	1
2000	2	0
2001	7	4
2002	8	1
2003	3	0
2004	6	3
TOTAL	**29**	**9**
2005*	7	5

* scheduled graduations

Company	Hires
DaimlerChrysler	1
Ford	4
General Motors	4
Hyundai	2
Caterpillar	6
Cummins	3
Oshkosh Truck	1
DDC	2
Bosch	1
Delphi	2
Ballard	1
OSU CAR	2
Battelle (fuel cells)	1
Army (USMA)	1
Other automotive	2
TOTAL	**33**

3.4 Curriculum development

The year-long HEV course sequence developed at OSU as part of the first GATE program was incorporated in the OSU continuing education program, and was offered to GM to its technical education program. The HEV course sequence was offered in academic years 1999, 2000, 2002, and 2004. Over 60 OSU students and 35 GM employees have taken these courses. Further, during the span of the GATE program, a Graduate Specialization in Automotive Systems Engineering, described in the next subsection, was approved by the Graduate School, and is currently active.

Automotive Systems Engineering Specialization (ASES)

The Automotive Systems Engineering Specialization (ASES) program at The Ohio State University has been formulated to provide an interdisciplinary graduate level education in the engineering discipline of primary interest to the student, while focusing on the application area of automotive systems. Students who complete the program requirements may elect to have the graduate specialization in the area of automotive systems appear on their permanent record along with the formal name of the graduate degree program. The ASES is administered by the student's home department in cooperation with CAR.

The ME and ECE Departments are participants in the interdisciplinary ASES[1]. Since the ASES is not a degree program, students wishing to participate are required to gain admission to the graduate program of one of the participating ("home") departments. The ASES program has been formulated based on the typical MS program, under the assumption that departmental doctoral degree programs encompass requirements of the MS degree. The program is open to both M.S. and Ph.D. students. The requirements are:

[1] It is envisioned that other departments in the College of Engineering may participate in the future.

- Thesis option students are required to take one core sequence. It is expected that the thesis be on a topic related to automotive systems.
- Non-thesis option students (MS only) are required to take two core sequences.
- In addition to the core sequence(s), students fill out the coursework portion of their degree requirements with expertise area courses, some of which should be drawn from the core focus area courses. A partial list of suggested expertise area courses is attached to this document (due to the extensive array of math courses possible, these are not listed).
- All students are required to regularly attend seminars on topics in automotive systems.

The requirements on the number of core course/sequences and expertise areas serve to increase the breadth of skills that the graduate engineers can apply to complex automotive problems. At the same time, the student will better understand the perspectives, capabilities, and approaches of other engineering disciplines as well as their relevance to automotive systems.

The ASES requirements are flexible enough to provide adequate depth within engineering disciplines of primary interest to the student. It is expected that participating students will choose elective courses so that the programs of study have an appropriate focus on an automotive-related discipline in addition to the breadth of scope resulting from the core area courses and expertise area requirements. Table 1 summarizes the requirements of the ASES Program.

TABLE 1. ASES PROGRAM REQUIREMENTS

Program Option	Courses	Credit Hours
Thesis	One Core Course Sequence	9
	Expertise area courses*	21-27
	MS Thesis	9-15
	Seminar on automotive topics	n/a
Non-Thesis	Two Core Course Sequences	18
	Expertise area courses*	27
	Seminar on automotive topics	n/a

Core Course Sequence Requirement

Core sequences consist of basic courses of critical importance to automotive systems in areas matching the research focus areas of the OSU Center for Automotive Research (CAR). A student completes a core sequence by selecting three courses from one of the core focus areas listed below.

Core Focus Area 1: Internal Combustion Engines

ME 630	**Energy Conversion in IC Engines (Selamet)**
ME 726	**Introduction to Combustion (Various)**
ME 730	**IC Engine Modeling (Guezennec)**
ME 632	**Powertrain Instructional Laboratory (Soliman)**

Core Focus Area 2: Powertrain Dynamics and Control

ME 781 Powertrain Dynamics (Rizzoni and Srinivasan)

The course introduces the essential aspects of modeling and control of automotive powertrains. Focus on the integration of the dynamics of mechanical, fluid, and thermodynamic systems; sensor and actuator technology; driveability and emissions. Primary emphasis is placed on fuel-injected, spark-ignited, internal combustion engines, and on stepped automatic transmission. More recent technologies, such as direct injection, variable valve actuation, and continuously variable transmissions have recently been included in the course. A computer simulation of the overall powertrain system is used throughout the course. A special modeling and simulation project is developed for each offering of the course.

ECE 753.01 Powertrain Control (Yurkovich and Rizzoni)

This course focuses on implementation issues relevant to automotive control systems. A review of sampled data systems, particularly relevant to the implementation constraints common to production powertrain systems and subsystems, lays the foundation for subsequent control design discussions. Controller synthesis techniques focus on subsystems of the overall system, such as the air-to-fuel ratio control loop and idle speed dynamics. Techniques discussed for application to the representative subsystem range from simple linear lead-lag compensator designs, to state variable design techniques, including linear quadratic regulator designs. The course is complemented by a design project similar to the modeling/simulation project conducted in ME781.

ME 632 Powertrain Instructional Laboratory (Soliman)

The instructional powertrain laboratory is intended to provide an experimental components of the current course offerings in automotive powertrains, resulting in an effective experimentally-oriented curriculum in the area.

Core Focus Area 3: Advanced Propulsion Systems

ME784 Energy Analysis of Hybrid Vehicles (Guezennec and Rizzoni)

This course is focused on the overall energy conversion, storage, utilization and optimization of complete road vehicle systems, for conventional and hybrid electric vehicles (HEVs). Objectives include: (1) Analyze and quantitatively evaluate energy consumption in road vehicles; relate energy usage in road vehicles to fuel economy and exhaust emissions. (2) Understand the concept and potential benefits of drivetrain hybridization strategies; develop and use mathematical models of energy storage and conversion subsystems used in hybrid vehicles. (3) Develop a methodology for constructing general models of energy storage and power flow processes in hybrid vehicles, and implement using Matlab/Simulink. (4) Learn principles of optimal energy management. (5) HEV design and optimization of fuel economy using simulation environment in Matlab/Simulink.

ME 785 Modeling, Simulation and Control of Hybrid Vehicles (Yurkovich, Washington, Rizzoni)

The material in this course is focused on the optimization and control of advanced propulsion systems in hybrid-electric vehicles. Course objectives include: (1) Introduce design optimization concepts, and apply them to the design of hybrid electric vehicle drivetrain architectures. (2) Review principles of optimization, and develop capabilities for numerically solving constrained optimization problems in the context of HEV design. (3) Formulate and solve (numerically) energy optimization problems in hybrid electric vehicles. (4) Review control design methods to be used for drivetrain control. (5) Apply control methodologies to the problem of improving driveability in hybrid electric vehicles. A special modeling and simulation project is developed for each offering of the course.

ME787 Fuel Cell Systems for Automotive Applications (Guezennec) (proposed)

This course is focused on fuel cells in automotive systems, providing a description of basic principles as well as an in-depth technology overview of fuel cells stacks, fuel cell systems and fuels for such systems. The course also covers the analysis and modeling of such fuel cell systems, including their control. Special emphasis will be given to the energetics of the entire process, including upstream fuel processing (i.e., "well-to-wheel" analysis). Much attention is devoted to the numerous challenges faced by fuel cell systems towards their integration for use in automotive applications, ranging from fuel storage, fuel processing, packaging, control, performance and cost targets. Course assignments focus on modeling of various facets of fuel cell systems (stack, air delivery sub-system, fuel delivery sub-system, reformer, complete fuel cell system, energy management, etc.), culminating in a project centered on modeling an entire fuel cell vehicle.

3.5 Facilities

Finally, the research laboratories pertinent to the program (described below) are all located at CAR, in a single 35,000 ft² facility entirely dedicated to automotive systems research, which also hosts the graduate students enrolled in the GATE program. During the course of the first GATE program, OSU-CAR developed new research laboratories, raising $1.5M in state funding through the Ohio Board of Regents and receiving numerous equipment and cash donations (from Ford, GM, DaimlerChrysler, Eaton, Denso). More recently, OSU-CAR has received additional equipment funding ($200,000) through the State of Ohio "Wright Centers of Innovation" program to enhance its fuel cell laboratory capability.

Advanced Combustion Engine Laboratory

The laboratory includes 200 hp DC electric and 300 hp AC electric dynamometers. The lab also has a dual set of Horiba MEXA 7500 analytical benches for Diesel engine exhaust gas analysis. In addition, the laboratory offers all major engine measurement and data acquisition capabilities as well as rapid control prototyping capabilities (dSpace and ETAS). Various modern Diesel engines are available (Fiat, VM motori), as well as exhaust after-treatment catalysts and components.

These facilities were recently been upgraded in part through a $800,000 grant from the Ohio Board of Regents.

Recent projects:

"CAR Industrial Research Consortium – Model-based control and emissions aftertreatment in advanced CIDI Engines forlight- medium- and heavy-duty applications"

Ford Motor Company – "Control of Diesel NOx Emissions using a Lean NOx Trap (LNT)"

"CAR Industrial Research Consortium: Diesel HCCI with external mixture formation and mixed mode HCCI/DI, Year I"

Recent Graduates:

1. Devesh Upadhyay, Ph.D., ME, "Modeling and control of advanced CIDI engines", Spring 2001. Current position: Ford Scientific Research Laboratory, Dearborn, MI.
2. Michael B. Hopka, M.S., ME, "Mean Value Modeling and Validation for Control of a Modern Light Duty Diesel Engine", June 2002, currently employed at Ford Motor Company.
3. Manik Narula, M.S., ME "Development and Validation of a Quasi-Steady IMEP Model for an Advanced CIDI Engine" August 2003. Employed at Cummins.
4. Larry Slone, M.S., ME, "Investigation of urea-SCR injection delivery systems for NOX reduction in Diesel engines". August 2004. Employed at Caterpillar.

Fuel Cell Systems Laboratory

The fuel cell systems lacboratory comprises both computational and experimental facilities. Computational work ranges from three-dimensional and one dimensional models of FC stacks, to control oriented models of fuel cell systems. Emphasis is on both PEFC and SOFC.

The experimental facilities include a 2.5kW PEM Fuel Cell Stack (shown in the figure); a Software-in-the-Loop system for analyzing the air dynamics of PEM Fuel Cell; two 1-kW FC Power Systems (Relion Independence 1000). A fuel-cell hybrid Golf Cart (under development) and a H_2 refueling station (summer 2005)

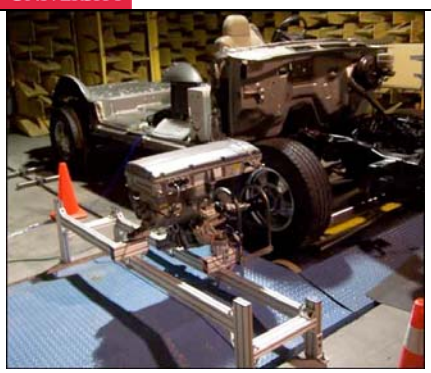
Recent Graduates

Dr. Daisie Boettner, "Modeling of PEM Fuel Cell Systems Including Controls and Reforming Effects for Hybrid Automotive Applications", August 2001. Professor and Head, Mechanical Division, USMA Department of Civil and Mechanical Engineering.

Diwakar Bansal, Topic: multi-variable control of PEM fuel cell systems, co-advised with S. Yurkovich, expected graduation: March 2005.

Sai v. Rajagopalan, " Dynamic characterization and modeling of a pressurized PEM fuel cell system", June 2005. Continuing Ph.D. student

Chad Allison, " Experimental characterization of a PEM fuel cell stack", June 2005. Accepted employment at Ford.



Hybrid Vehicle System Integration Laboratory

The OSU-CAR hybrid vehicle program currently receives funding from the CAR Industrial Consortium, the U.S. Army TARDEC, and NREL to research various aspects of light-and heavy-duty hybrid vehicle propulsion systems.

The facilities available to the laboratory include a light-duty chassis dynamometer, the fully operational FutureTruck 2004 hybrid Ford Explorer, and a vehicle build area.

In addition, the laboratory offers multiple control rapid prototyping hardware and software platforms, and all of the relevant modeling and simulation software tools.

Recent Graduates:

Avra Brahma, M.S. ME, "Optimal control of hybrid electric vehicles", September 1999. Currently employed at Ford (Scientific Research Laboratory).

Alan Holmes, M.S. ME, "Modeling and analysis of electrically variable transmissions", August 2000. Currently employed at GM (Hybrid Powertrain).

Makoto Tateno, "Emissions Modeling For Enhanced Hybrid Electric Powertrain Control", M.S. ME, August 2001. Employed at Stanley Electric.

Qi Ma, "Mode-based SI engine idle speed control with integrated starter/alternator", M.S. ME, Spring 2002, currently pursuing a Ph.D. at OSU.

Xi Wei, "Modeling and Control of a Hybrid Electric Drivetrain for Optimum Fuel Economy, Performance and Driveability" Ph.D. ME, September, 2004, Employed at Cummins.

Advanced Energy Storage System Laboratory

The advanced energy storage systems laboratory focuses on modeling and experiments related to the electro-thermal behavior of electrochemical capacitors and advanced batteries, and to the modeling of life cycle, damage and reliability of cells and systems. Further, the laboratory provides experimental support for various vehicle projects, including the ChallengeX, Buckeye Bullet and Hybrid Fuel Cell golf cart.

The facilities include:

- Environmental chamber (-20 to _ 60 degC)
- Programmable dynamic supply load (± 2.5 kW)
- Programmable dynamic load (-50 kW)

Recent Graduates:

Kevin Do, DYNAMIC ELECTRO-THERMAL MODEL OF DOUBLE LAYER "SUPERCAPACITORS" FOR HEV POWERTRAIN APPLICATIONS, M.S. ME, June 2004. Employed at Caterpillar.

Ryan Somogye, AN AGING MODEL OF NI-MH BATTERIES FOR USE IN HYBRID-ELECTRIC VEHICLES, M.S. ECE, August 2004. Employed at Caterpillar.

Hansung Kim, "Dynamic Battery Modeling in Hybrid Electric Vehicles", M.S. ME, June 2002, currently pursuing a Ph.D. at OSU.

3.6 Industry participation

Industry participation in the program

Industry involvement in the OSU GATE Center include the following elements.

1 Internship programs.
2 Participation through funded research programs (grants, contracts and consortium programs).
3 Industry matching funds for DOE Fellowships.
4 Participation in Industrial Advisory Board.
5 Participation in CAR Industry Seminar Series

Technology transfer

Technology transfer through industry from the GATE program is another distinctive feature of the OSU program. The following items describe how such transfer has taken place.

1. CAR Industrial Research Consortium: CAR has been operating a membership fee-based industrial research consortium (since 1999) that includes the participation of OEMs (Caterpillar, DaimlerChrysler, Ford, General Motors, Honda, Oshkosh Truck Corporation), as well as Tier-1 suppliers (ArvinMeritor, Bosch Dana, Delphi, Eaton, TRW). The consortium raises approximately $0.5M annually in support of exploratory research. All of the above mentioned companies have signed a consortium agreement that governs IP, publications and other important contractual matters. Each year 8-10 projects are selected by the members; the results of these projects are made available to the members through a web-based knowledge repository, by direct communications, and through two annual reviews conducted at CAR and in Detroit. To illustrate the relevance of this program, we list the following among recently funded Consortium Projects:
   Aging, Reliability and Life Cycle Models of Electrochemical Energy Storage Devices
   Control and Diagnostics of NOx After-treatment systems
   Control and Diagnostics of Automotive Fuel Cell Systems
   Diesel HCCI with external mixture formation and mixed mode HCCI/DI
   Smart Power Flow Concept in HDV Series Hybrids
2. OSU and CAR have formulated a *Certificate Program*, which began in Autumn 2003. In this program, off-campus students from industrial partners can receive a Certificate of Completion by taking courses (primarily for graduate credit, with some additional self-paced courses for continuing education credits) through a focused, strategically-aligned curriculum. The program is available via distance education, with no on-campus requirements, and are issued through OSU's Center for Automotive Research and Office of Continuing Education. The Certificates are earned as stand-alone achievements for students who wish to acquire a body of knowledge to successfully perform their short and long term work assignments. Although the Certificates are aimed at students who have no immediate interest in earning a graduate degree, the graduate credit hours earned in the Program could be transferred to other degree granting institutions. Each Certificate consists of graduate-level courses and/or a preparatory seminar, with lectures delivered asynchronously (typically within a few days), as taught to on-campus students. Certificates currently available are: *Certificate in Advanced Propulsion Systems*; *Certificate in Powertrain Modeling and Control.* Other certificates may be established in future.
3. Periodic program review are held in conjunction with the semiannual meetings of the Board.
4. Finally, and most important, the most effective means for technology transfer is the hiring of GATE program graduates. All of the companies that have participated in the GATE program have strong recruitment programs at OSU. The track record illustrated in Table 1 speaks for itself.

4. Conclusion

This report outlines the development of a unique graduate education program. The OSU GATE program enjoys the unconditional support of the OSU College of Engineering, Graduate School, Center for Automotive Research and Departments of Mechanical Engineering, Electrical and Computer Engineering, and Computer Science and Engineering..

GATE has proven to be an invaluable catalyst in attracting research funding in advanced automotive technology research to Ohio State, and has created a pipeline of young professionals joning the ranks of the automotive industry. We strongly believe that the OSU GATE program has met and exceeded the intent of the original GATE solicitation, and we are pleased to be a participating school in this exciting program.