Hybrid Electric Power Train and Control Strategies
Automotive Technology Education (GATE) Program

Final Technical GATE Report, 1998-2004
Prepared for United States Department of Energy

Submitted by:

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On behalf of
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DOE Award #: DE-FC02-98CH10959
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Executive Summary

Plug-in hybrid electric vehicles (PHEV) offer societal benefits through their ability to displace the use of petroleum fuels. Petroleum fuels represent a polluting and politically destabilizing energy carrier. PHEV technologies can move transportation away from petroleum fuel sources by enabling domestically generated electricity and liquids bio-fuels to serve as a carrier for transportation energy. Additionally, the All-Electric-Range (AER) offered by PHEVs can significantly reduce demand for expensive and polluting liquid fuels.

The GATE funding received during the 1998 through 2004 funding cycle by the UC Davis Hybrid Electric Vehicle Center (HEVC) was used to advance and train researchers in PHEV technologies. GATE funding was used to construct a rigorous PHEV curriculum, provide financial support for HEVC researchers, and provide material support for research efforts.

A rigorous curriculum was developed through the UC Davis Mechanical and Aeronautical Engineering Department to train HEVC researchers. Students’ research benefited from this course work by advancing the graduate student researchers’ understanding of key PHEV design considerations.

GATE support assisted HEVC researchers in authoring technical articles and producing patents. By supporting HEVC researchers multiple Master’s theses were written as well as journal articles and publications. The topics from these publications include Continuously Variable Transmission control strategies and PHEV cross platform controls software development.

The GATE funding has been well used to advance PHEV systems. The UC Davis Hybrid Electric Vehicle Center is greatly appreciative for the opportunities GATE funding provided.
# GATE Final Report

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Introduction
The Hybrid Electric Vehicle Center (HEVC) received funding for advanced vehicle technology research for the period of October 1998 through September 2004. During this period the HEVC established a hybrid vehicle systems curriculum, supported student research in hybrid technologies, authored multiple technical reports, and developed patents.

The program has helped build two prototype plug-in hybrid electric vehicles (PHEV), Sequoia (Chevrolet Suburban) and Yosemite (Ford Explorer), both vehicles having won numerous awards.

Goals and Objectives
The goals and objectives for the HEVC GATE funding were to nourish engineering research in PHEV technologies. The funding supplied equipment needed to allow researchers to investigate PHEV design sensitivities and to further optimize system components. Over a dozen PHEV researchers benefited from the GATE funding and produced journal articles and intellectual property as a result.

The remainder of this document outlines the productivity resulting from GATE funds. The topics include the following:

- GATE Hybrid Vehicle Systems Related Courses
- Students Supported
- Publications
- Patents

A discussion regarding the HEVC accomplishments with respect to the GATE funding goals is provided in the conclusion.

Project Activities and Products
To accomplish the goals of further optimizing PHEV systems, the HEVC directed student researchers toward a list of Mechanical and Aeronautical Engineering courses to enhance their understanding of PHEV engineering design. The students used the knowledge they gained from this coursework to produce their research deliverables.

GATE Hybrid Vehicle Systems Courses

The following courses were incorporated into the GATE curriculum. The courses were offered during the GATE funding period through the UC Davis Mechanical and Aeronautical Engineering department.
217. Combustion (4)
Lecture—3 hours; discussion—1 hour. Prerequisite: Engineering 103 and 105. Review of chemical thermodynamics and chemical kinetics. Discussions of reacting flows, their governing equations and transport phenomena; detonations; laminar flame structure and turbulent combustion. Offered in alternate years.—II. Shaw

218. Advanced Energy Systems (4)
Lecture—3 hours; discussion—1 hour. Prerequisite: Engineering 103 and 105, or the equivalent. Review of options available for advanced power generation. Detailed study of basic power balances, component efficiencies, and overall powerplant performance for one advanced concept such as a fusion, magnetohydrodynamic, or solar electric powerplant. Offered in alternate years.—(I.) Hoffman

220. Mechanical Vibrations (4)
Lecture—4 hours. Prerequisite: Engineering 122. Multiple degrees of freedom; damping measures; Rayleigh's method; vibration absorbers; eigenvalues and modeshapes; modal coordinates; forced vibrations; random processes and vibrations; autocorrelation; spectral density; first passage and fatigue failure; nonlinear systems; phase plane.—III. (III.) Margolis

222. Advanced Dynamics (4)
Lecture—4 hours. Prerequisite: Engineering 102. Dynamics of particles, rigid bodies and distributed systems with engineering applications; generalized coordinates; Hamilton's principle; Lagrange's equations; Hamilton-Jacobi theory; modal dynamics orthogonality; wave dynamics; dispersion.—I. (I.) Eke

223. Multibody Dynamics (4)
Lecture—4 hours. Prerequisite: Engineering 102. Coupled rigid-body kinematics/dynamics; reference frames; vector differentiation; configuration and motion constraints; holonomicity; generalized speeds; partial velocities; mass; inertia tensor/theorems; angular momentum; generalized forces; comparing Newton/Euler, Lagrange's, Kane's methods; computer-aided equation derivation; orientation; Euler; Rodrigues parameters. (Same course as Biomedical Engineering 223.)—II. (II.) Eke, Hubbard

225. Spatial Kinematics and Robotics (4)
Lecture—3 hours; laboratory—3 hours. Prerequisite: C Language and course 222. Spatial kinematics, screw theory, spatial mechanisms analysis and synthesis, robot kinematics and dynamics, robot workspace, path planning, robot programming, real-time architecture and software implementation. (Same course as Biomedical Engineering 225.) Offered in alternate years.—(II.) Ravani

234. Design and Dynamics of Road Vehicles (4)
Lecture—4 hours. Prerequisite: Mechanical Engineering 134. Analysis and numerical simulation of road vehicles with on design applications. Offered in alternate years.—(III.) Velinsky
237. Analysis and Design of Composite Structures (4)
Lecture—3 hours; discussion—1 hour. Prerequisite: Aeronautical Science and Engineering 137. Modeling and analysis methodology for composite structures including response and failure. Laminated plate bending theory. Introduction to failure processes. Offered in alternate years.—(III.) Rehfield

238. Advanced Aerodynamic Design and Optimization (4)
Lecture—3 hours; discussion—1 hour. Prerequisite: consent of instructor. Application of aerodynamic theory to obtain optimum aerodynamic shapes. Both analytic solutions and solutions obtained with numerical optimization techniques will be examined. Includes introduction to the calculus of variations and numerical optimization techniques. Offered in alternate years.—I. van Dam

250A. Advanced Methods in Mechanical Design (4)
Lecture—4 hours. Prerequisite: Mechanical Engineering 150A and 150B or the equivalents, or consent of instructor. Applications of advanced techniques of solid mechanics to mechanical design problems. Coverage of advanced topics in stress analysis and static failure theories with emphasis in design of machine elements. Design projects emphasizing advanced analysis tools for life cycle evaluation.—I. (I.) Farouki

250B. Advanced Methods in Mechanical Design (4)
Lecture—4 hours. Prerequisite: course 250A. Applications of advanced techniques of solid mechanics to mechanical design problems. Coverage of advanced topics in variational methods of mechanics with emphasis in design of machine elements. Design projects emphasizing advanced analysis tools.—II. (II.) Hill

250C. Mechanical Performance of Materials (4)
Lecture—4 hours. Prerequisite: undergraduate course in stress analysis and mechanical behavior of materials. Occurrence, mechanisms, and prediction of fatigue and fracture phenomenon. Use of stress and strain to predict crack initiation. Use of fracture mechanics to predict failure and crack propagation. Effects of stress concentration, manufacturing, load sequence, irregular loading, and multi-axial loading. Offered in alternate years.—III. (III.) Hill

251. Mechatronics System Design (4)
Lecture—3 hours; discussion—1 hour. Prerequisite: Mechanical Engineering 154 and 172 or Electrical and Computer Engineering 157A, 157B. Motion mechanism design, electric actuator, power electronics motion control, sensor technologies, personal computer-based control systems design, motion control general operating system and real time operating systems, motion control software design, discrete event control software design. Offered in alternate years.—I. Yamazaki
254. Engineering Software Design (4)
Lecture—3 hours; laboratory—3 hours. Prerequisite: C Language, Engineering 180. Principle and design of engineering software. Advanced topics in engineering software design, including object oriented programming, programming in very high-level languages, real-time multi-thread computing and sensor fusion, web-based network computing, graphic user interface and multimedia with applications in engineering. Offered in alternate years.—(III.) Cheng

258. Hybrid Electric Vehicle System Theory and Design (4)
Lecture—3 hours; laboratory—3 hours. Prerequisite: Mechanical Engineering 150B, graduate standing in Mechanical and Aeronautical Engineering. Advanced vehicle design for fuel economy, performance, and low emissions, considering regulations, societal demands and manufacturability. Analysis and verification of computer design and control of vehicle systems in real vehicle tests. Advanced engine concepts. Offered in alternate years.—(III.) Frank

271. Modeling and Simulation of Engineering Systems (4)
Lecture—3 hours; laboratory—3 hours. Prerequisite: Mechanical Engineering 172 or the equivalent. Multiport models of mechanical, electrical, hydraulic, and thermal devices; bond graphs, block diagrams and state space equations; modeling of multiple energy domain systems; 3-dimensional mechanics; digital simulation laboratory.—I. (I.) Karnopp, Margolis

272. Theory and Design of Control Systems (4)
Lecture—4 hours. Prerequisite: Mechanical Engineering 172 or the equivalent. Mathematical representations of linear dynamical systems. Feedback principles; benefits and cost of feedback. Analysis and design of control systems based on classical and modern approaches, with emphasis on applications to mechanical and aeronautical systems.—II. (II.) Eke, Margolis

Lecture—3 hours; discussion—1 hour. Prerequisite: Mechanical Engineering 172. Discrete systems analysis; digital filtering; sample data systems; state space and transform design techniques; quantization effects; multi-input, multi-output systems.—III. (III.) Hess

276. Data Acquisition and Analysis (4)
Lecture—3 hours; discussion—1 hour. Application of computers for data acquisition and control. Topics include computer architecture, characteristics of transducers, hardware for laboratory applications of computers, fundamentals of interfaces between computers and experimental equipment, programming techniques for data acquisition and control, basic data analysis. Offered in alternate years.—I.

**Students Supported**

The following is a list of students supported by the grant by year in ascending order.

00-01: Mark Alexander, David Funston, Brian Huff, Brian Johnston, Laurence Mayer, Brian Morgan, James Vaughn
01-02: Mark Alexander, Charnjiv (Chief) Bangar, Thomas Bradley, Christopher Carde, Brian Huff, Christopher Nitta, Jason Parks, James Vaughn

02-03: Mark Alexander, Charnjiv Bangar, Thomas Bradley, Christopher Carde, Brian Huff, Christopher Nitta

03-04: Charnjiv Bangar, Christopher Carde, Aashish Dalal, Avernethy (Vern) Francisco, Dahlia Garas, Christopher Nitta

04-05: Tashari El-Sheikh, Siddharth Shastri

Publications

The following is a list of publications authored during the GATE funding period.


Huff B. “Design and Simulation of a High Performance Hybrid Electric Vehicle”, University of California: Davis, 2004


Morgan B. “Servo Hydraulic Control of a Continuously Variable Transmission”, University of California: Davis, 2000

Vaughn J. “Emissions Control and Optimization of a Plug-In, Battery Dominant, Charge Depletion Hybrid-Electric Vehicle”, University of California: Davis, 2002

Bangar C. “Integrating Advanced State of Charge Management Techniques and Battery Monitoring System Hardware”, University of California: Davis, 2004

Thomas Bradley T “Simulation of Continuously Variable Transmission Chain Drives with Involute Inter-element Contact Surfaces”, University of California: Davis, 2003


Garas D. “Electric School Bus System Evaluation and Analysis”, University of California: Davis, 2005

Shastri S. “Comparison of energy consumption and power losses of a conventionally controlled CVT with a Servo-Hydraulic Controlled CVT and with a belt and chain as the Torque Transmitting Element”, University of California: Davis, 2004

Automotive patents and applications

The following list of patents and applications that were conceived by the HEVC during the GATE funding period.

US patents and applications

United States Patent  6,116,363  (not University-owned)
Frank  September 12, 2000
Fuel consumption control for charge depletion hybrid electric vehicles
Assignee:  Frank Transportation Technology, LLC (El Macero, CA)

United States Patent  6,847,189
Frank  January 25, 2005
Method for controlling the operating characteristics of a hybrid electric vehicle
Assignee:  The Regents of the University of California (Oakland, CA)

United States Patent  6,809,429
Frank  October 26, 2004
Control method and apparatus for internal combustion engine electric hybrid vehicles
Assignee:  The Regents of the University of California (Oakland, CA)

United States Patent Application 20050050887
Kind Code  A1; Frank, Andrew A. ; et al.  March 10, 2005
Exhaust gas driven generation of electric power and altitude compensation in vehicles including hybrid electric vehicles
Assignee:  The Regents of the University of California (Oakland, CA)
United States Patent Application 20040254047
Kind Code A1; Frank, Andrew A.; et al. December 16, 2004
Method and system for controlling rate of change of ratio in a continuously variable transmission
Assignee: The Regents of the University of California (Oakland, CA)

United States Patent Application 20040060751
Kind Code A1; Frank, Andrew A. April 1, 2004
Method for controlling the operating characteristics of a hybrid electric vehicle

**International (PCT) patents and applications**

(WO 02/058209) METHOD FOR CONTROLLING THE OPERATING CHARACTERISTICS OF A HYBRID ELECTRIC VEHICLE
INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)
WO 02/058209
PCT/US02/00220
03 January 2002 (03.01.2002)
60/259,662 03 January 2001 US
METHOD FOR CONTROLLING THE OPERATING CHARACTERISTICS OF A HYBRID ELECTRIC VEHICLE
THE REGENTS OF THE UNIVERSITY OF CALIFORNIA

(WO 2004/083870) METHOD AND SYSTEM FOR CONTROLLING RATE OF CHANGE OF RATIO IN A CONTINUOUSLY VARIABLE TRANSMISSION
INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)
WO 2004/083870
PCT/US2004/008572
19 March 2004 (19.03.2004)
60/456,226 19 March 2003 US
60/457,453 24 March 2003 US
30 September 2004 (30.09.2004)
G01P
METHOD AND SYSTEM FOR CONTROLLING RATE OF CHANGE OF RATIO IN A CONTINUOUSLY VARIABLE TRANSMISSION
THE REGENTS OF THE UNIVERSITY OF CALIFORNIA
Conclusion

Researchers in the UC Davis HEVC benefited greatly from the financial support of GATE funds. The funds allowed the HEVC to support graduate student research in PHEV technologies and resulted in a variety of technical papers and patents. The research performed related to further optimizing critical PHEV technologies including continuously variable transmission design, power train architecture, and associated control strategies.

The research performed in the HEVC with the assistance of GATE funding also resulting in the construction of two award winning PHEVs: Sequoia (Chevrolet Suburban) and Yosemite (Ford Explorer). Sequoia won first place in the Department of Energy’s 2001 Future Truck Challenge. Yosemite earned first place in the use of advanced power train technologies in the 2003 Future Truck Challenge. The publications supported by GATE funding were directly related to the development of these vehicles.