Final Report

Graduate Automotive Technology Education (GATE) Center

for

Hybrid Electric Drivetrains and Control Strategies

DOE Project Number
DE-FC02-98CH10955

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September 2008

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EXECUTIVE SUMMARY

Beginning the fall semester of 1999, The University of Maryland, Departments of Mechanical and Electrical Engineering and the Institute for Systems Research served as a U.S. Department of Energy (USDOE) Graduate Automotive Technology Education (GATE) Center for Hybrid Electric Drivetrains and Control Strategies. A key goal was to produce a graduate level education program that educated and prepared students to address the technical challenges of designing and developing hybrid electric vehicles, as they progressed into the workforce. A second goal was to produce research that fostered the advancement of hybrid electric vehicles, their controls, and other related automotive technologies. Participation ended at the University of Maryland after the 2004 fall semester.

Four graduate courses were developed and taught during the course of this time, two of which evolved into annually-taught undergraduate courses, namely Vehicle Dynamics and Control Systems Laboratory. Five faculty members from Mechanical Engineering, Electrical Engineering, and the Institute for Systems Research participated. Four Ph.D. degrees (two directly supported and two indirectly supported) and seven Master's degrees in Mechanical Engineering resulted from the research conducted. Research topics included thermoelectric waste heat recovery, fuel cell modeling, pre- and post-transmission hybrid powertrain control and integration, hybrid transmission design, H_2-doped combustion, and vehicle dynamics. Many of the participating students accepted positions in the automotive industry or government laboratories involved in automotive technology work after graduation.

This report discusses the participating faculty, the courses developed and taught, research conducted, the students directly and indirectly supported, and the publication list. Based on this collection of information, the University of Maryland firmly believes that the key goal of the program was met and that the majority of the participating students are now contributing to the advancement of automotive technology in this country.

PROJECT SUMMARY

Background

In August 1998, the University of Maryland, Departments of Mechanical and Electrical Engineering and the Institute for Systems Research were selected to be a U.S. Department of Energy (USDOE) Graduate Automotive Technology Education (GATE) Center for Hybrid Electric Drivetrains and Control Strategies. The goal was to produce a graduate level education program that educated and prepared students to address the technical challenges related to the design and development of hybrid electric vehicles. The GATE program provided the resources necessary to develop new curricula related to hybrid electric drivetrains and control strategies and to offer fellowships to student engineers interested in pursuing research and careers in this branch of automotive technology.

Maryland organized a multi-disciplinary team of faculty from the Departments of Mechanical and Electrical Engineering, as well as the Institute of Systems Research (ISR), under the leadership of Professor David Holloway. The faculty team consisted of:

Dr. David Holloway	Mechanical Engineering
Dr. William Levine	Electrical Engineering and ISR
Dr. Gregory Walsh	Mechanical Engineering and ISR
Dr. Greg Jackson	Mechanical Engineering
Dr. Lung-Wen Tsai	Mechanical Engineering

Their combined experience included hybrid powertrain systems engineering and design integration, advanced control theory and applications, powerplant technology, internal combustion engine theory and design, combustion modeling, fuel cell theory, design and modeling, hybrid transmission design, and vehicle dynamics. Dr. David Holloway had formerly served as the 1997 President of SAE International, bringing a wealth of automotive industry knowledge to the program. Dr. Lung-Wen Tsai had previously worked as a research engineer at General Motors specializing in novel transmission and engine mechanism design and held numerous patents in these fields.

Courses were developed around this expertise, focusing on hybrid electric vehicle drivetrain and control issues, including vehicle dynamics, powerplant technology (analysis of internal combustion engines and fuel cells), automotive control systems, and hybrid electric vehicle drivetrain system integration. The courses were offered from the fall of 1999 through the fall of 2001, and were available to graduate students and the GATE fellows. Two of the courses evolved into undergraduate courses, which continue to be offered at Maryland.

Graduate research covered topics such as thermoelectric waste energy recovery, combustion with H_2 doping, hybrid transmission design, fuel cell starvation modeling, pre- and post-transmission parallel hybrid electric vehicle control and integration, potential gains in conventional powertrain efficiency, vehicle stability using bifurcation analysis, and handling testing optimization. Two Ph.D. dissertations and seven Master's Theses were directly produced through the GATE Center, and two additional Ph.D. Dissertations were produced indirectly. A

detailed description of the courses offered, research supported, fellowship recipients and other students affected, resulting journal and conference publications, and other supporting information are provided below.

Courses Offered

Four courses were developed and taught by the faculty members listed above. Table 1 provides a summary of the course offerings, and a description of each course is provided in the following paragraphs. Dr. Jackson was solely responsible for teaching Powerplant Technology (Analysis of Internal Combustion Engines and Fuel Cells), and Dr. Holloway was primarily responsible for teaching Vehicle Dynamics and Hybrid Electric Vehicles, but also had teaching support from Dr. Tsai. Dr.'s Walsh and Levine shared duties equally teaching Automotive Control Systems.

TABLE 1. MARYLAND'S GATE CENTER CURRICULA

Course Number	**Course Title**	**Instructor**	**Semester Taught (Number of Students)**					
			Fall 99	**Spr 00**	**Fall 00**	**Spr 01**	**Fall 01**	**Spr 02**
ENME 808O	Powerplant Technology *(Analysis of Internal Combustion Engines and Fuel Cells)*	Jackson	11		8		6	
ENME 808Q	Automotive Engineering Vehicle Dynamics	Holloway	17		17		# not verified	
ENME 808D	Automotive Control Systems	Levine and Walsh		9		3		
ENME 808I	Hybrid Electric Vehicles	Holloway		5		9		

ENME 808O- POWERPLANT TECHNOLOGIES (ANALYSIS OF INTERNAL COMBUSTION ENGINES AND FUEL CELLS). This course focused on teaching the principles of power plant/energy conversion for hybrid electric vehicles, spark ignition internal combustion engines, advanced compression ignition engines, and automotive fuel cells, particularly the proton exchange membrane fuel cell. Topics covered in the class included a review of energy conversion and thermodynamic analysis for automotive power plants, thermodynamics of combustion and SI engine cycles – impact of design parameters, intake systems and mixture control in SI engines, engine heat transfer, combustion chemistry and exhaust emissions for SI engines, models and control of SI engine processes, analysis of advances in SI engines – gasoline direct injection and lean burn engines, thermodynamics of diesel engine cycles - how parameters impact performance, fuel injection in CIDI engines,

combustion chemistry and exhaust emissions for DI engines, modeling and control of DI engine processes, recent advances in CI engines - direct injection and homogeneous charge, fuel cell introduction and thermodynamics, heat and mass transport in fuel cells and design models for fuel cell material issues and integration of fuel cell power plants for automotive applications, modeling and control of fuel cells, and recent advances in fuel cells: direct methanol fuel cells and solid oxide fuel cells.

ENME 808Q- AUTOMOTIVE ENGINEERING AND VEHICLE DYNAMICS. This course taught the fundamentals of vehicle dynamics with added emphasis on the dynamic effects caused from the integration of heavy hybrid electric vehicle powertrain components, such as battery packs. Students gained a thorough understanding of road loads affecting fuel economy, including aerodynamic, rolling resistance, grade and powertrain parasitic loads. In doing so, they studied the fundamental aspects of engine and transmission control, as related to operating along gradients of minimum brake specific fuel consumption, as well as power and traction limited acceleration. Emphasis was also placed on understanding handling, stability and directional response of vehicles. Specific topics included steady-state cornering and steering gradients, yaw and lateral acceleration response, roll and bump steer, suspension compliances, suspension and steering design, roll-over, tire properties and behavior, and ride quality. Additional topics also included the dynamic rotational imbalances and vibrations in different engine formats (e.g. straight fours, V6s, etc), reciprocating forces within an engine, manual and automatic transmission design, and differential kinematics and design.

ENME 808D- AUTOMOTIVE CONTROL SYSTEMS. This course included classroom and experimental laboratory components. Focus was placed on teaching the fundamentals of feedback control systems, and familiarized the students with the characteristics and limitations of real control devices. Classroom topics included basics of linear time-invariant systems, feedback and open-loop control, stability, design of linear feedback controllers, introduction to embedded controllers, introduction to electric motors and generators, basics of DC motor behavior and characteristics, control of the DC motor, basics of induction motors, control of the induction motor, introduction to energy management, batteries, regenerative braking, and transmission and their controls. The laboratory component had the students build and test proportional (P), proportional and integral (PI) or lag compensator, and proportional, integral, and differential (PID) control systems using an automotive heater experiment, a dc-servomotor experiment with position and velocity control, and a custom project of the students choice.

ENME 808I- HYBRID ELECTRIC VEHICLES. This course taught the common powertrain and power electronics architectures used for serial and parallel hybrid electric vehicles. Emphasis was placed on studying the Toyota Prius and Honda Insight powertrains, including the control schemes used to regulate engine, generator, traction motor, and battery packs. Guest lectures were provided by Honda and Ford hybrid vehicle design engineers and hybrid transmission researchers.. Additional topics included battery state of charge, driving cycles, means to estimate battery state of charge, low-rolling resistance tires, recent engine improvements for efficiency, classification of hybrid powertrains, recent aerodynamic improvements, and component sizing. Students were also introduced to the use of DOE's ADVISOR model for driving and fuel economy research and simulation.

ENME 454 (VEHICLE DYNAMICS) and ENEE 461 (CONTROL SYSTEMS LABORATORY)- The Vehicle Dynamics course, ENME 808Q, evolved into an undergraduate course taught each year starting the fall semester of 2002. ENME 454 Fundamentals of Vehicle Dynamics is currently taught by Dr. Gregory Schultz, and has approximately 60 undergraduate students each fall semester. The course still includes content related to hybrid electric vehicle design, architectures, and reasons why hybrid electric vehicles offer improvement in fuel economy. Likewise, ENME 808D evolved into an undergraduate course taught each spring by Dr. Levine as ENEE461 (and ENME 489N), based primarily on the experimental laboratory component of the ENME 808D class.

Research and Students Directly Supported

Eleven research fellowships were granted through Maryland's GATE Center, directly supporting two Ph.D. students and eight Master's students. The titles of the research topics, the students and faculty conducting the research, and the degrees sought are shown in Table 2. The placement after graduation of each student (if known) is summarized in Table 3. Abstracts for the research dissertations and theses are provided in the appendix. A small number of undergraduate students were also directly supported through the GATE program on a limited basis as research assistants for the graduate students and faculty members. Their names are provided in Table 4. The majority of these students were concurrently participating in the DOE-sponsored FutureCar and FutureTruck programs. This provided synergy, since Rightmyer's research required extensive use of the GM Suburban participating in the FutureTruck competition. The undergraduates also assisted in preparing laboratory spaces, supported experiments, and audited some of the courses.

Students Indirectly Supported

Kevin Kefauver- During Mr. Kefauver's research, his faculty advisor, Dr. Greg Walsh, left the university to pursue a career in the private sector. Consequently, Mr. Kefauver was forced to change research topics and his advisor. Dr. Levine became Mr. Kefauver's new dissertation advisor, and his research was adapted to the development of hybrid control system theory. In this case, hybrid does not refer to hybrid electric vehicles, but instead systems that switch back and forth between states. Mr. Kefauver has completed his new research while working full-time, and will graduate with his Ph.D. during the fall of 2008. An abstract of Mr. Kefauver's dissertation is provided in the appendix.

Gregory Schultz- Though not formally part of the GATE program, Greg Schultz was conducting his Ph.D. research with Dr. Lung-Wen Tsai when the GATE Center program was initiated. His research was in the area of hybrid electric vehicle transmission design, and he attended ENME808 O, Q, and D. An abstract of Dr. Schultz's dissertation is provided in the appendix.

TABLE 2. SUMMARY OF RESEARCH AND GRADUATE STUDENTS SUPPORTED.

Research Topic	Student	Faculty Advisor	Degree Achieved	Year Degree Awarded
Optimizing thermoelectric waste heat recovery from an automotive cooling system	Douglas Crane	Jackson	Ph.D.	2003
Response of premixed hydrocarbon flames with and without hydrogen addition to steady and oscillatory strain rates	Joseph Plaia	Jackson	Ph.D.	2005
Fuel Use Optimization Using Environment Observation	Kevin Kefauver	Walsh	Ph.D.	2008
Development and validation of a dynamic model for a methanol fuel cell system	Stefan Pototschnik	Jackson	Masters	2001
Control of the Maryland Proteus: A Gasoline-electric Post Transmission Parallel Hybrid SUV	Joli Rightmyer	Holloway	Masters	2003
Development of a hybrid electric powertrain for an autonomous vehicle	Kristin Dahlgren	Holloway	Masters	2002
Control systems and component testing for a diesel electric CVT hybrid vehicle powertrain	Jason Marcinkoski	Holloway	Masters	2002
Modeling the Influences of Powertrain Variables on Vehicle Fuel Economy and Performance	Ivan Tong	Holloway	Masters	2002
	Matthew Sterns	Holloway	Masters	Dropped out
Vehicle Handling, Stability, and Bifurcation Analysis for Non-Linear Vehicle	Vincent Nguyen	Schultz	Masters	2004
Vehicle Path of Emergency Lane Change for Vehicle Simulation	Steven O'hara	Schultz	Masters	2004

TABLE 3. GRADUATE STUDENT PLACEMENT

Student	Post Research Placement	Position
Douglas Crane	BSST (subsidiary of Amerigon Inc.)	Thermoelectric researcher
Joseph Plaia	unknown	unknown
Kevin Kefauver	U.S. Army Aberdeen Test Center, Automotive Directorate	Automotive Test Engineer and Researcher
Gregory Schultz	U.S. Army Aberdeen Test Center, Automotive Directorate and University of Maryland	Automotive Test Engineer and Researcher, and Adjunct Associate Professor
Stefan Pototschnik	Form Motor Company	Engineer, Hybrid Vehicle Strategy & Planning
Joli Rightmyer	AnthroTronix	Mechanical Design Engineer
Kristin Dahlgren	U.S. Naval Academy	Controls Instructor
Jason Marcinkoski	U.S. Department of Energy	Technology Development Manager
Ivan Tong	U.S. Army Aberdeen Test Center, Automotive Directorate	Automotive Test Engineer and Researcher
Matthew Sterns	Unknown	Unknown
Vincent Nguyen	University of Maryland	Ph.D. student and Navy Fellow
Steven O'hara	unknown	unknown

TABLE 4. UNDERGRADUATE RESEARCH ASSISTANTS

Undergraduate Research Assistants	Placement (after graduation)
Kevin Denton	Ford Motor Company
Blaine Woehr	Lockheed Martin
Joshua Goldman	-ISE Corp. (ThunderVolt® Hybrid Drive Systems), Manager of Engine Development for hybrid applications, Manager of Technical Training and Manager of Heavy Duty Certifications -Aug 2007 joined Mobile Energy Solutions as Director of Business
Luke Wilhelm	ECD Ovonics

Publication List

Dissertations

Crane, Douglas, 2003, *Optimizing thermoelectric waste heat recovery from an automotive cooling system,* Ph.D. Dissertation, Department of Mechanical Engineering, University of Maryland, College Park, MD.

Plaia, Joseph, 2005, *Response of premixed hydrocarbon flames with and without hydrogen addition to steady and oscillatory strain rates*, Ph.D. Dissertation, Department of Mechanical Engineering, University of Maryland, College Park, MD.

Schultz, G. A., 2002, *A Parallel Hybrid Transmission*, Ph.D. Dissertation, Department of Mechanical Engineering, University of Maryland, College Park, MD.

Kefauver, Kevin, 2008, *Optimal feedback control for hybrid systems, with application to the automobile,* Ph.D. Dissertation, Department of Mechanical Engineering, University of Maryland, College Park, MD.

Master's Theses

Pototschnik, Stefan, 2001, *Development and validation of a dynamic model for a methanol fuel cell system,* Master's Thesis, Department of Mechanical Engineering, University of Maryland, College Park, MD.

Rightmyer, Joli, 2003, *Control of the Maryland Proteus: A Gasoline-electric Post Transmission Parallel Hybrid SUV*, Master's Thesis, Department of Mechanical Engineering, University of Maryland, College Park, MD.

Dahlgren, Kristin, 2002, *Development of a hybrid electric powertrain for an autonomous vehicle,* Master's Thesis, Department of Mechanical Engineering, University of Maryland, College Park, MD.

Marcinkoski, Jason, 2003, *Control systems and component testing for a diesel electric CVT hybrid vehicle powertrain*, Master's Thesis, Department of Mechanical Engineering, University of Maryland, College Park, MD.

Tong, Ivan, 2002, *Modeling the Influences of Powertrain Variables on Vehicle Fuel Economy and Performance*, Master's Thesis, Department of Mechanical Engineering, University of Maryland, College Park, MD.

Nguyen, Vincent, 2004, Vehicle *Handling, Stability, and Bifurcation Analysis for Non-Linear Vehicle*, Master's Thesis, Department of Mechanical Engineering, University of Maryland, College Park, MD.

O'Hara, Steven, 2004, *Vehicle Path of Emergency Lane Change for Vehicle Simulation*, Master's Thesis, Department of Mechanical Engineering, University of Maryland, College Park, MD.

Archival Journals

Crane, D.T. and Jackson, G.S. (2004), "Optimization of Cross Flow Heat Exchangers for Thermoelectric Waste Heat Recovery", Energy Conversion and Management, 45(9-10), 1565-1582.

Tsai and Schultz, "A Motor-Integrated Parallel Hybrid Transmission", ASME Journal of Mechanical Design, March 2004.

Tsai, Schultz, Higuchi, "A Novel Parallel Hybrid Transmission", ASME Journal of Mechanical Design, June 2001.

Schultz, Tsai, Higuchi, Tong, "Development of a Novel Parallel Hybrid Transmission", 2001 SAE Transactions, SAE Paper 2001-01-0875.

Jackson, Gregory S., Sai, Roxanne, Plaia, Joseph M., Boggs, Christopher M., Kiger, Kenneth T., "Influence of H_2 on the response of lean premixed CH_4 flames to high strained flows," *Combustion and Flame*, v 132, n 3, Feb 1, 2003, p 503-511.

Reviewed Conference Papers

Crane, D.T., Jackson, G.S., and Holloway, D., "Towards Optimization of Automotive Waste Heat Recovery Using Thermoelectrics", SAE Paper No. 2001-01-1021, published in SAE Publication SP-1613 Thermal Systems Management and Heat Exchangers, 2001.

Crane, D.T. and Jackson, G.S., "Systems-Level Optimization of Low-Temperature Thermoelectric Waste Heat Recovery", Proceedings of International Energy Conversion Engineering Conference, Washington, DC, July 2002.

Tsai, L. W. and Schultz, G. A., 2002, "A Motor Integrated Parallel Hybrid Transmission," *ASME International Design Engineering Technical Conferences*, DETC2002/MECH-34363, Sept. 29-Oct. 2, 2002, Montreal, Canada.

Schultz, G. A., Tsai, L. W., Higuchi, N., and Tong, I. C., 2001, "Development of a Novel Parallel Hybrid Transmission," *Proceedings of the 2001 SAE International Congress and Exposition*, March, Detroit, MI, paper No. 2001-01-0875.

Tsai, L. W., Schultz, G., and Higuchi, N., 2000, "A Novel Parallel Hybrid Transmission," *CD-ROM Proceedings of the 2000 ASME International Design Engineering Technical Conferences*, September, Baltimore, MD, paper No. DETC2000/MECH-14173.

Other Conference Presentations

Crane, D.T. and Jackson, G.S., "The Potential of Thermoelectric Waste Heat Recovery for Automotive Electrical Systems", MIT/Industry Consortium on Advanced Automotive Electrical/Electronic Components and Systems, Marina Del Rey, CA, January 2002.

Appendix- Abstracts

A. Dissertations

Crane, Douglas

The potential for thermoelectric (TE) power generation (via automotive waste heat recovery) to displace alternators and/or provide additional charging to hybrid electric vehicles has increased with recent advances in thermoelectric materials. While previous studies have focused on exhaust-based waste heat recovery, this study optimizes thermoelectric waste heat recovery from an engine cooling system with the goal of providing insight into the feasibility and potential of increasing automotive fuel efficiency.

The study creates MATLAB-based steady-state numerical model for a cross-flow heat exchanger, where industry-provided operation data validate the heat transfer and pressure drop correlations. Using distinct attributes of an automotive cooling system, the model simulates the cross-flow heat exchanger as an automotive radiator. The study integrates the thermoelectrics into the radiator model and then incorporates this model into an optimization scheme to maximize the average net power output of the TE radiator on a system level for a range of coolant flows and temperatures. Simple experiments validate the thermoelectric governing equations. The optimization scheme developed for the task is a hybrid algorithm combining the local search speed of gradient-based methods with the global search superiority of genetic algorithms. Feasibility robustness is also incorporated to study the impact of variation and uncertainty in design variables and parameters.

The study transforms the steady-state model into a dynamic model to evaluate the transient response of the optimal TE waste heat recovery system over three different driving cycles. The transient model provides a more complete picture of the potential of an optimized thermoelectric waste heat recovery system and its benefits relating to automotive fuel efficiency. Transient results show that radiator configurations with advanced TE devices used during aggressive driving cycles can recover over 2 kW in net power with 150 seconds of sustained recovery of over 1 kW. Replacing the alternator with the TE radiator for standard drive cycles can achieve fuel efficiency gains up to 3.3%. Using the multi-parameter optimization and transient evaluation techniques developed, the study concludes that with future research, TE waste heat recovery from the automotive cooling system can become a practical means of improving automotive fuel efficiency.

Plaia, Joseph

The response to steady-state and oscillatory strain rates of lean, premixed hydrocarbon-air flames with and without H_2 doping has been investigated analytically, numerically and experimentally. The analytical analysis provides a theoretical framework for assessing steady-state flame temperature (T_{flame}) response to strain rate as a function of reactant composition, through Lewis numbers (Le_k), and of non-dimensional stretch defined by the Karlovitz number (Ka). An integral analysis with discrete reaction zones for each fuel has been developed, capturing the linear response of T_{flame} to Ka (<0.2) for steady-state CH_4-H_2 and C_3H_8-H_2 lean

flames as predicted by numerical models using full chemistry (GRI-Mech V3.0). This method improves predictions from single-flame zone integral analyses.

Detailed transient numerical simulations using GRI-Mech V3.0 determined the effects of H_2 addition on CH_4 premixed flame responses to strain oscillations. Symmetric velocity (pressure) oscillations in an opposed jet counterflow configuration were simulated for frequencies, f, ranging from 100 to 1000Hz, focusing on behavior at large Ka, near extinction. The oscillations cause flame characteristics (e.g. species mass fractions and T_{flame}) to vary significantly from steady-state responses. While flame responses to 100Hz oscillations closely follow quasi-steady behavior, responses for f>200Hz deviate, with phase lags and different amplitudes, from quasi-steady predictions. At f=1000Hz, the flame acts as a low pass filter, reducing amplitudes in property oscillations compared to quasi-steady analysis. For the higher frequencies, predictions
indicate premixed flames can persist momentarily beyond steady-state extinction strain rate limits during oscillations.

Strain rate oscillation amplitudes required to extinguish flames, A_{ext}, are determined numerically with the computational model and compared with experimental measurements. Simulations show that A_{ext} increases with f due to attenuated flame response for f>200Hz. Increasing flame equivalence ratio, ϕ, and/or percentage of O_2 consumed by H_2, α, increases reaction rates, decreasing the deviation from quasi-steady behavior and reducing the relative A_{ext}. Counterflow premixed flame experiments with upstream speaker-imposed oscillations are also used to evaluate A_{ext}. Phase-locked velocity measurements (with laser Doppler anemometry) assist in understanding how
upstream pressure oscillations translate into velocity field (strain rate) oscillations.
Measured A_{ext} values validated trends in the computational results.

Schultz, Gregory

A parallel hybrid transmission is developed and explored. This transmission incorporates the design features of conventional automatic transmissions with the ability to sum power from two sources, an internal combustion engine and an electric motor. It can operate either as a multi-speed, fully automatic (1-DOF) transmission with motor power assist, or as a continuously variable transmission (2-DOF) that permits the engine speed to be regulated throughout the vehicle speed range, or as a combination of both. Launching is accomplished using the electric motor, eliminating the need for a master clutch. The transmission uses a single motor/generator unit, and since no torque converter is used, the transmission is more efficient than conventional automatic transmissions. Another advantage is the relative absence of torque holes during shifting operations, since the design is based on a "powershift" automatic transmission.

Kinematic, static torque, and power flow relationships are developed, along with a notional shift and control strategy. A prototype transmission was designed, fabricated, and tested as a proof-of-principle and to assist with efficiency predictions. Gear mesh power loss equations were developed for each of the transmission's operating modes, along with two supporting theorems for the rolling (or latent) power of planetary gear sets. Transmission efficiency characteristics were developed for the prototype, based on the test results, gear mesh power loss equations, and

other literature findings. These predicted results were used for efficiency comparison of the operating modes. An ADVISOR Version 3.2 driving simulation model was created to verify drivability using the notional transmission shift and control strategy, assist with development of a powertrain controller, and predict potential fuel economy of a vehicle equipped with the transmission.

Kefauver- Dissertation not yet published (expected Fall 08)

B. Master's Theses

Tong

Much research has been done on modeling vehicle's performance and fuel economy. The focus of recent work has been primarily on hybrid-electric vehicle (HEV) operation, with some work on modeling existing, mass-production conventional vehicles as a baseline for comparisons with HEVs. An important implication of this approach is that the research on conventional vehicle operation has failed to capture all of the design options that conventional-vehicle engineers have had available and instead has focused on the specific design choices that were actually made. This work attempts to explore those design options that were not selected- in essence, constructing vehicles that were never built. The design variables that have been explored are engine size, number of transmission ratios (or more accurately, the overall range of transmission ratios), final drive ratio, electronic throttle control (assuming electronic transmission control is already implemented), shift schedule, engine technology, and the implementation of integrated starter alternators (ISAs).

This exercise reveals insights on the design choices that vehicle engineers made. Perhaps the main conclusion is that even with virtually no additional cost or technology, conventional vehicles can achieve significantly better performance and fuel economy. For example, modifying the shift schedule so that the engine speed is reduced under normal operating conditions can yield up to a 15% improvement in fuel economy. However, these improvements typically come at the cost of drivability. When the shift schedule is modified for lower engine operating speeds, the transmission exhibits an objectionably large number of shifts.

Rightmyer

Gasoline/electric hybrid technology provides a practical means for improving the gas mileage and emissions of the present day automobile. With the recent and unflagging popularity of Sport Utility Vehicles (SUVs) and the increasing awareness of the need to curb the United Stated dependence on foreign oil and to protect the global environment, a hybrid "future truck" may indeed be a practical bridge between today's gas guzzlers and tomorrow's hydrogen powered fuel cell vehicles. This thesis describes the implementation of a powertrain control strategy that attempts to minimize the fuel consumption of the Maryland Proteus, a parallel post-transmission hybrid SUV. The transitions between the five possible modes of operation of the vehicle (electric motor only, engine only, engine with electric motor assist, battery charge, and regenerative braking mode) are determined by examining the efficiencies of the various electrical and mechanical components. The coding of the control algorithm in Matlab Simulink and XPC

Target are presented, along with descriptions of simple electrical circuits that enable the control computer to send and receive signals out to and in from the powertrain components. The tractive loads demanded of the Proteus during a city drive cycle are estimated and may suggest that the Proteus' fuel efficiency improvements from the hybrid system may be limited due to sizing of powertrain components. A method for sizing the powertrain components based upon the targeted driving cycle is then proposed.

Marcinkoski

This thesis describes the development of the control system hardware, and the control algorithms used for controlling the components of a pre-transmission hybrid electric vehicle powertrain. The powertrain and control system were rapidly designed and fabricated in six months for use in an unmanned military vehicle. The main components that needed to be controlled were a diesel engine, a brushless DC motor, a continuously variable transmission (CVT), and an electromagnetic clutch.

The powertrain requirements and configuration are reviewed. The major components are specified and described. An overview of the controller processor and driver circuits is given followed by a description of the 14 actuators, 12 sensors and associated circuits for integration of the high voltage, CVT, electromagnetic clutch, electric motor and engine systems.

A complete fuel consumption mapping was performed as a basis for an optimized supervisory control. The engine speed governor gains were tuned for adequate response characteristics. Experimental data was taken for correlating the fuel rack actuator power to the engine torque so that the CVT belt clamping pressure could be set for high efficiency. The low-level actuator control algorithms were developed using The Mathwork's Matlab, Simulink, Realtime Workshop, and XPC. The powertrain and controller are a work in progress. All of the hardware has been demonstrated to be fully functional and performed as designed. The low-level control has been implemented with success, and the engine efficiency has been determined for future development.

Dahlgren

General Dynamics Robotic Systems (GDRS) contracted the University of Maryland Center for Automotive Research (UMCAR) to assemble a hybrid electric powertrain and develop a controller to be integrated into an autonomous vehicle that GDRS designed. GDRS chose the main powertrain components of a Kubota compression-ignition internal combustion engine, a UQM DC brushless electric motor, a Nissan Primera continuously variable transmission, and Hawker lead-acid batteries. UMCAR was responsible for integrating the powertrain components and designing and implementing a control strategy.

The thesis describes the development of the powertrain design and controller. The main focus of the thesis is the powertrain controller design, which incorporates research done in hybrid electric powertrain control, knowledge of individual component control requirements, design requirements set forth by GDRS, and finite-state machine theory. Individual component control is designed according to component operation requirements. Overall powertrain control is composed of four operational modes as determined by the GDRS vehicle master controller: internal combustion engine only, electric motor only, hybrid, and stationary charge. Four states

are associated with the operational modes: off, idle. Drive, and reverse. Control algorithms for each state are presented. Conclusions and suggestions for future work are made.

Pototschnik

In 1999 the University of Maryland took delivery of a fuel cell powered transit bus utilizing an onboard reformer. Methanol is converted to a hydrogen rich stream in the reformer and fed into the fuel cell anode. The anode exhaust gases are burned to generate heat for the endothermic reformation reaction. Rapid fuel cell transients can cause hydrogen starvation in the system. In this thesis a model is developed to help better understand this mechanism of failure and predict system-operating characteristics.

An onboard data acquisition system was developed using LabView. Steady state and transient operational data was gathered. Next, computer models of system components were developed. The reformer model was developed as a dynamic system since it is the slowest responding component. The reformer was modeled as three continuously stirred tank reactors in series. The fuel cell model was developed from first principles electro-chemical equations. Since the fuel cell responds more quickly than the reformer, quasi-steady operation was assumed. An adiabatic flame temperature model was used for the reformer burner. Fits for fuel and air flows within the system were developed from the experimental data and documentation provided with the vehicle.

The individual component models produced results consistent with experimental data. The entire system was able to predict some general system trends in current, voltage, and catalyst temperatures. The model confirms that a drop in reformer temperature below 240°C reduces methanol conversion resulting in hydrogen starvation at the fuel cell anode and thus a drop in fuel cell power.

O'Hara

Driver-based handling tests, such as the Double Lane Change (DLC) maneuver are subjective in nature and depend largely on driver skill and road conditions. They also suffer from poor repeatability. Implementation of these tests on hardware-in-the-loop simulators can also produce subjective results if the steer profiles are not systematically generated. This research produced a vehicle path optimization algorithm that generated optimal paths for handling tests based on minimizing the maximum curvature during the maneuver. This approach lessened the dynamics of the vehicle and increased the chances of successful test results at given speeds. Excel's Solver was used for the optimization. The model results were compared to field test and hardware-in-the-loop test results, showing potential for reductions in lateral acceleration and vehicle side-slip.

Nguyen

Vehicle handling, stability, and bifurcation of equilibrium conditions were studied using a state vector approach. The research provided a framework for an improved method of vehicle handling assessment that included non-linear regions of performance and transient behavior. Vehicle models under pure lateral slip, constant velocity, and constant front steer were developed. Four-wheel, two-axle vehicle models were evolved from simpler models and were

extended to include vehicle roll dynamics and lateral load transfer effects. Nonlinearities stem from tire force characteristics that include tire force saturation. Bifurcations were studied by quasi-static variations of vehicle speed and front steer angle. System models were expanded, assessing overall stability, including vehicle behavior outside normal operating ranges. Nonlinear models of understeering, oversteering, and neutral steering vehicles were created and analyzed. Domains of attraction for stable equilibrium were discussed along with physical interpretations of results from the system analysis.