MTU Final Technical Report

Project Title: Recovery Act – An Interdisciplinary Program for Education and Outreach in Transportation Electrification

Award Number: DE-EE0002493

Recipient: Michigan Technological University
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Report Number: DOE-2013-MTU-01-FINAL

Date of Report: January 30, 2013

Reporting Period: November 1, 2009 – October 31, 2012

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Executive Summary

1) How the project adds to the education of engineering students in the area of vehicle electrification:

This project created and implemented a significant interdisciplinary curriculum in HEV engineering that includes courses focused on the major components (engines, battery cells, e-machines, and power electronics). The new curriculum, rather uniquely, features two new classes and two new labs that emphasize a vehicle level integration of a hybrid electric powertrain that parallels the vehicle development process used by the OEMs - commercial grade software is used to design a hybrid electric vehicle, hardware-in-the-loop testing is performed on each component until the entire powertrain is optimized, the calibration is flashed to a vehicle, ride-and-drives are executed including on board data acquisition. In addition, nine existing courses were modified by adding HEV material to the courses.

2) The educational effectiveness and economic feasibility of the new curriculum:

The new courses are offered at both the undergraduate and graduate levels. They are listed across the college in mechanical, chemical, electrical, and materials science and engineering. They are offered both on campus and to distance learning students. Students across the college of engineering and at all degree levels are integrating these courses into their degree programs.

Over the three year project the course enrollments on-campus has totaled 1,249. The distance learning enrollments has totaled 315. With such robust enrollments we absolutely expect that these courses will be in the curriculum for the long run.

3) How the project is otherwise of benefit to the public:

One outcome of the project is the construction of the Michigan Tech Mobile Lab. Two complete HEV dynamometer test cells, and four work stations are installed in the 16.2 meter Mobile Laboratory and hauled by a class 8 truck. The Mobile Lab is used to teach the university courses. It is also used to deliver short courses to industry, K-12 outreach, and public education. In 2012 the Mobile Lab participated in 22 outreach events, locally, throughout Michigan, and including events in Washington DC, Illinois, and Wisconsin. The Mobile Lab is a hit wherever it goes. In 2013 we will partner with the US Army TARDEC and be featured in their Green Warrior Convoy, a ten city tour starting in Detroit and finishing in Washington DC.

Introduction

The primary objective of this project is the development of an interdisciplinary curriculum that can lead to a professional master's degree that focuses on preparing students to work in industry and train those already in industry. In addition, undergraduate and graduate certificates in Advanced Electric Drive Vehicle Engineering will be developed with the graduate certificate focused on distance learning for engineering in industry.

Development of a mobile laboratory that will include subsystem learning stations, electrified vehicle Software and Hardware In the Loop systems, a portable vehicle chassis dynamometer, and will utilize HEV's provided by GM. This laboratory will serve as a key enhancement to the distance learning laboratories and to established university outreach activities.

The Overarching Objectives of this program were:

1) Develop a master of engineering degree, and graduate and undergraduate certificates in Advanced Electric Drive Vehicles
2) Target enrollment of 120 graduate students in the program with an expected split of 50% on campus and 50% DL in year 3 of the program.
3) Through both the on-campus and the DL programs, address workforce needs and competencies in emerging electric vehicle technologies for US based industries.
4) Promote and raise broad awareness for transportation sustainability through electric propulsion systems with outreach programs for the YES! Expo, GEAR UP, and various local and broad community events utilizing the talents of Michigan Tech's unique Enterprise Program and publicly available interactive software

The program objectives were achieved through the following tasks:

Task 1: Curriculum Development

Task 2: Mobile Laboratory Development and Outreach Development

Task 3: Course Delivery

Task 4: Evaluation

Details regarding the goals and accomplishments of this project are discussed in the next section, organized according to the tasks in the project statement of work. Summaries of the proposed milestones and completion dates are given in the Schedule Status section. Ancillary results including: technology transfer, personnel changes and teaming, publications and inventions, and technologies/techniques are provided in the Ancillary Results section.

Goals and Accomplishments

The tasks that were proposed for the project are listed below. A subsection is devoted to each that briefly describes the goals for this quarter and what was accomplished.

Task 1: Curriculum Development

The automotive industry is in a transformation towards powertrains electrification, development of a wide array of electrified automotive vehicle powertrains has resulted in a significant shift in the automotive and automotive Tier II industries need for professionals such as engineers experienced in multiple disciplines. This shift has resulted in the need for retraining the existing work force along with developing engineers with a broader knowledge base to tackle integration and optimization work in these electrified vehicles. To meet the challenges of both incumbent and transitional workers while simultaneously meeting the needs for the future workforce, Michigan Tech has developed and delivered an education program to meet these needs with funding support of this program from the Department of Energy (DOE). Michigan Tech has partnered with industry, state, and non- profit organizations to develop and deliver a curriculum in Hybrid Electric Drive Vehicles with certificates at the undergraduate and graduate levels and a Master of Engineering Degree. To ensure that distance learning students receive significant hands-on laboratory opportunities a Mobile Laboratory based upon a 53 foot trailer and Class 8 truck has been constructed that will enable laboratory courses to be offered around the country.

The education program delivers courses to on campus and distance learning students for the Advanced Hybrid Electric Vehicle Engineering Certificates. Students are able to continue on for their masters or Ph.D degrees in their respective departments or select an interdisciplinary master's of engineering degree which is focused on preparing students to work in and training those already in industry. The undergraduate and graduate certificates, each requiring 15 credits, contain interdisciplinary courses including (1) Introduction to and (2) Advanced Propulsion Systems for Hybrid Electric Vehicles. Some of the coursework is in existing classes that have modified sections to directly address material related to HEVs. This program leverages and links the automotive systems, engines, and controls expertise in the Mechanical Engineering Department with the electric power, electric machines and power electronics expertise in the Electrical Engineering Department.

The curriculum focuses on preparing students to work in and educating those already in this industry. Distance learning students come from both the transportation and electric power industries. Guidance from these industries ensures that the program meets the needs of their work force, and course content is reviewed by topical industry experts. This education program will provide a supply of engineers to a significant and sustainable U.S. job base.

Goal 1: Development of Two Key Interdisciplinary Courses: Construct and execute developed courses to provide students background knowledge on propulsion systems.

Specific accomplishments: Two new interdisciplinary courses which were dual listed in the Mechanical Engineering-Engineering Mechanics (MEEM) and the Electrical and Computer Engineering (EE) departments were developed and are described below.

EE/MEEM 4295 Introduction to Propulsion Systems for Electric Drive Vehicles

The introductory course in HEV's is EE/MEEM 4295 where the concepts of hybrid and electric drive vehicles are introduced with the main focus on the development of mathematical models of hybrid powertrains. Students are introduced to HEV/EV history, hybrid architecture for series and parallel systems, vehicle characteristics, starting equations of motion, vehicle performance (need for electrification), introduction to model based design in Simulink, electric machines, electric drive systems, regenerative braking, power electronics, battery models as RC circuits, introduction to drive cycles and driver controls, effects of road conditions and energy efficiency over a specified drive cycle.

The assignments were designed to culminate with a complete hybrid vehicle model (HVM) in Simulink with a driver controller (PID), IC engine, electric machine, battery (FreedomCar model), finite ratio transmission and longitudinal vehicle dynamics subsystems linked to a drive cycle. The students developed their own HVM, including diagnostic subsystems using standard Simulink building blocks. Their final HVM included torque blending between the IC Engine and E-Motor, Engine-stop, transmission gear selection based on ICE torque request and fuel usage in each available gear, regeneration during braking and over-all fuel economy for a given drive cycle. The IC Engine model contained the torque, fuel flow rate and engine speed from a current production engine.

EE/MEEM 5295 Advanced Propulsion Systems for Electric Drive Vehicles

The capstone course for the graduate certificate is Advanced Propulsion for Hybrid Vehicles. This course covers advanced vehicle propulsion systems within a hybrid electric vehicle context with a focus on application, integration, testing, and development of vehicle systems. It is a three credit hour course with material developed and presented by faculty from multiple departments and industry experts. There is no textbook, reading and study materials come from technical papers and extracts from other technical sources that are compiled by the instructors. Course topics and learning objectives include the following:

- Vehicle and powertrain systems requirements, regulations, design, implementation, calibration, validation and verification,
- Energy storage, conversion and power systems from the perspective of HEV propulsion systems,
- Model based design, simulation, control, and diagnostics utilizing Matlab/Simulink
- HEV high voltage sub-systems including electrical drive systems, electric machines, and batteries,
- Batteries in application to HEV's including, chemistries, energy densities, costs, rate dependent charge and discharge characteristics and their design, analysis, models, simulation, and control,
- Vehicle dynamics coupled with HEV propulsion systems, simulation, control and calibration.

Applying active learning techniques, material from literature including conference and journal papers are discussed weekly and analysis tools developed in the course are applied to further analyze results and claims. Requirements including regulations for current and future corporate average fuel economy (CAFE) and CO2 regulations are studied and analyzed to underscore the need for rapid advancement of technology integration in the light duty fleets. Student teams a scenario of technology advances for a hypothetical OEM from a baseline of four vehicle types to meet the US CAFE 2016, 2020 CAFE 4%, and 2025 CAFE 4% targets for this fleet. Data from existing literature including the National Academy of Science 2010 study of "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy"[4]. Team portfolios are discussed based on engineering complexity and other factors. This is carried through in a follow-on study to assess back period for technologies to determine customer acceptance.

Throughout the class, content on the primary powertrain subsystems is developed for incorporation and development of a vehicle dynamics model which is used in a model based design study for assessment of technologies, component sizing, control and calibration to assess vehicle performance factors including acceleration and fuel consumption. The course culminates in a group project, which can take one of three forms:

Option 1: Design an HEV including powertrain architecture and components and develop a model for the powertrain and integrate it into a vehicle model. Quantify its performance via drive-cycle simulation and analysis. Compare to HEVs in the market place.

Option 2: Develop a simulation matching an existing HEV. Compile technical data on the vehicle attributes, parameters, and performance characteristics. Tune the model to match the performance characteristics. Quantify its performance via drive-cycle analysis. Compare to data available on the HEV.

Option 3: Develop a high order accurate model of a HEV subsystem and integrate it into a model for vehicle cycle simulation. Verify the subsystem model by developing an independent test procedure and compare to available known solution cases. Validate the subsystem model by testing within the vehicle model.

A vehicle model is provided as a baseline. Throughout the process verification and validation methods are stressed and required. Final projects for the last semester's project included: modeling a 2009 Toyota Prius, hybridize the base Chevy Malibu, model and develop a F1 kinetic energy recovery system (KERS) and validate on a F1 track through vehicle simulation, and development of an enhanced motor drive and electric machine component model.

Goal 2: Development of Associated Laboratories to Interdisciplinary Courses: Develop and provide learning opportunities through hands-on laboratory experiences.

Specific accomplishments: Two new interdisciplinary laboratory courses which were dual listed in the Mechanical Engineering-Engineering Mechanics (MEEM) and the Electrical and Computer Engineering (EE) departments were developed and are described below.

EE/MEEM 4296 Introduction to Propulsion Systems for Electric Drive Vehicles Laboratory

"Introduction to Propulsion Systems for Hybrid Electric Vehicles" focuses on the subsystems within a modern HEV, with emphasis on energy conversions and the thermodynamics based energy balance around the vehicle. In this course the students use the laboratory facilities to characterize specific HEV subsystems, while learning basic operational principals of the systems. Examples include; measurement of engine fuel consumption, determination of motor torque constants and efficiency, development of battery SOC vs capacity relationships, approximation of vehicle drag and rolling resistance including coast down experiments, and measurement of various vehicle parameters including mass and frontal area. Much of this data is collected with the subsystems from a Configurable Hybrid Electric Vehicle (CHEV), also developed as a part of this project. The course also teaches students HEV safety practices and utilizes a defined drive cycle on public roads to demonstrate basic experimental principals. Figure 1 shows a student checking for the presence of high voltage during an HEV safety lab.

Figure 1: Student testing for the presence of high voltage in the Introduction to Propulsion Systems for Hybrid Electric Vehicles" lab course.

EE/MEEM 5296 Advanced Propulsion Systems for Electric Drive Vehicles Laboratory

The first course is a prerequisite for the second course “Advanced Propulsion Systems for Hybrid Electric Vehicles”. In the advanced course, students utilize the subsystems data they collected in the introductory course to calibrate their previously developed vehicle simulation models. In doing so, their models begin to accurately reflect the performance of the CHEV. With their models calibrated, they conduct validation experiments using the powertrain test cells and vehicle. Figure 2 shows students preparing to collect drive cycle data on the CHEV for model validation.

Figure 2: Students preparing for data collection from a CHEV to be used for model validation.

The final project in the course requires students to work in teams to optimize the performance of the CHEV. The students must take many considerations into account including fuel consumption, acceleration, top speed, drivability, charge sustainability, and cost among other factors. Students have a multitude of hardware and software options they can change to affect the vehicle. Examples include mass, frontal area, various gear ratios, and with software can develop improved regenerative braking, torque blending, and engine off algorithms and calibrations. The students use their calibrated models to conduct preliminary sorting analysis to determine performance trends, and develop a promising set of hardware and software changes. Students are given time to test their hardware and software strategies by operating the Powertrain Hardware in the Loop (HIL) test cells over the vehicle drive cycles. This allows the students the opportunity to further refine their models if needed. Students are also given time with the CHEV for testing of their hardware and software solutions. Using the Powertrain HIL test cells and CHEV they can iterate as needed to arrive at a final solution. Final results are presented by the teams of students to a panel of subject matter experts, and course points are awarded based on a multitude of factors including how well the teams’ vehicle performed in each of the target areas. Figure 3 shows the results in the fuel economy category from the Spring 2011 final project.

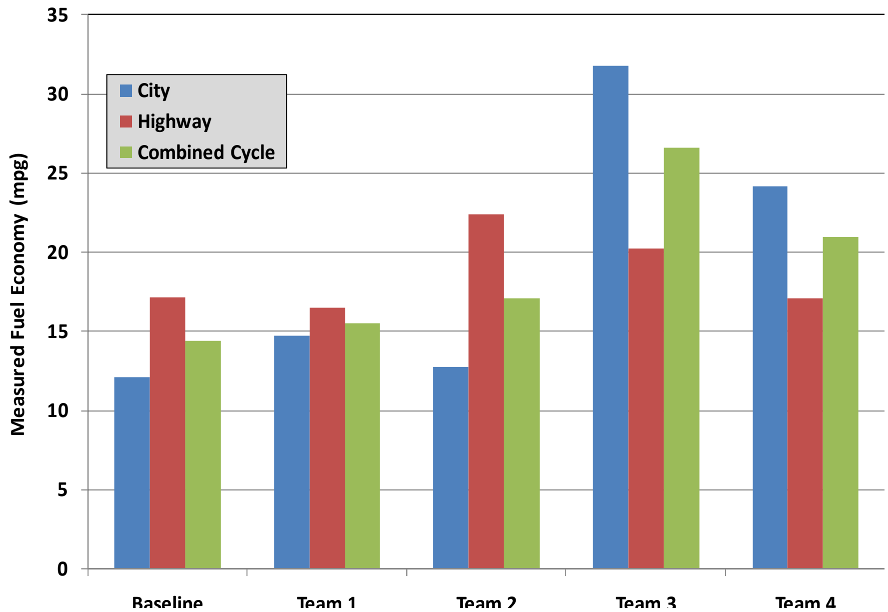


Figure 3: Fuel economy results from the final project in the Advanced Propulsion Systems for Hybrid Electric Vehicles Course.

Goal 3: New Course Development: Develop new courses for the program pertaining to electro-mechanical conservation, battery management, and transmission systems in electric vehicles.

Specific accomplishments: Five new semester courses were developed and offered as on campus and distance learning courses, those courses are described below. In addition, two short courses have been developed to date; these short courses utilize the mobile laboratory to bring HEV education to other intuitions and industries.

<u>EE 5221 "Advanced Electric Machines"</u> - This course centers on the areas of advanced electro-mechanics of rotating and linear machines. Topics included dynamic analysis of machines, reference frame transformations, reduced order models, models of mechanical loads, power electric drives for motors, and digital simulation of machines and electric drive systems. Particular emphasis in the course is placed on advanced control techniques of induction and permanent magnet machines for propulsion systems.

<u>MY/CM 5760 "Vehicle Battery Cells and Systems"</u> – The behavior and application of batteries are examined by introducing concepts from thermodynamics, materials science, transport processes and equivalent circuits. The non-ideal power source behavior of rechargeable batteries in applications will be treated using electrolyte: electrode transport and electrode materials chemistry.

Although there is no laboratory in this course, virtual laboratory activities are carried out in the latter third of the semester using a battery simulation tool. This battery component of this tool is based on a multiple component equivalent circuit with resistances and capacitances dependent upon electrode structure and chemistry (thickness, porosity, conductivity, particle size, cycle history, anode/cathode capacity matching, electrolyte salt concentration…). The equivalent circuit model was developed to correspond to porous electrode behavior. This can be a realistic, low computational cost battery model capable of fitting into the overall MTU certificate program development activities involving HEV/EV system simulations. At present, the battery simulation tool is using the numerical solver/matrix algebra solver in MathCad.

EE/MEEM 4750/5750 "Distributed Embedded Control Systems" – Automotive embedded control systems are introduced in the course "Distributed Embedded Control Systems." The course covers topics such as embedded system architecture, model-based embedded system design, electronic control unit (ECU), sensors and actuators, real-time control, and communication protocols. The course employs industrial standard rapid prototype system, Woodward's MotoTron Control Solutions, for the design and calibration of automotive embedded control systems. Several laboratories related to the lectures have also been developed to allow students to develop vehicle control strategies in MotoHawk/Simulink/Stateflow. The developed model-based controllers can be validated directly in production-level ECMs with real-time calibration software MotoTune. Multiple controllers can communicate with each other using controller area network (CAN) communication protocol.

The final project of the "Distributed Embedded Control Systems" is designed to guide students through the process of developing a control system for the CHEV. The control system consists of eight sub-modules to determine vehicle driving mode, engine/E-motor blend factors, and the sequence of the engine throttle stepper motor coil signals as shown in Figure 4. First, students design control modules based on defined control logics. Then, these control modules are simulated in the MotoHawk/Simulink to test the input and output signals of each module. Once the design of control modules is completed, the application code for programming into the ECM is generated using Matlab Real-Time Workshop, Real-Time Workshop Embedded Coder, and Stateflow Coder. Finally, the entire embedded control system is validated in the hardware-in-the-loop test.

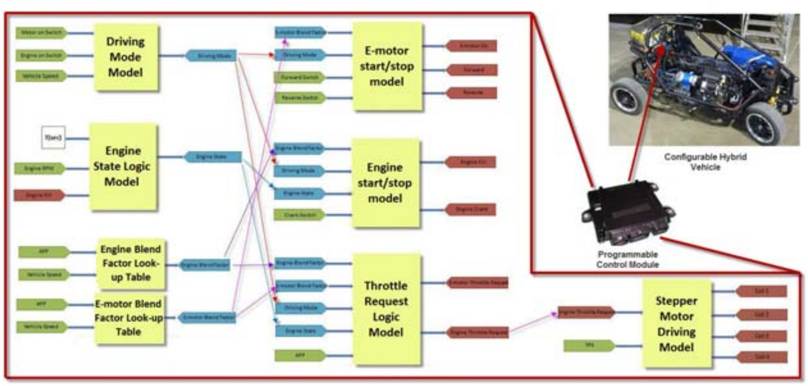


Figure 4: Developing a hybrid vehicle control system in the final project of the "Distributed Embedded Control Systems."

MEEM 4450/5450 "Vehicle Dynamics" – In this course students develop the necessary models to predict performance and handling and compare analytical results to selected measured data from hybrid vehicle test data. Topics covered include: acceleration and braking performance, hybrid electric powertrain architecture, drivetrain performance, vehicle handling, suspension modeling, tire models, steering and steering control, 2DOF dynamics model, and multi-body dynamics. This will culminate in a design project which will require the design of a hybrid vehicle to meet a given vehicle technical specification.

Course content includes:

- An understanding of vehicle dynamics and its important role in the development of any vehicle system.
- Initial design stages and the importance to understand the principles and computational methods which allow prediction of vehicle behavior in the three areas of performance, handling and ride.
- Acceleration and braking performance, and the common practice to talk about the properties of an internal combustion engine as the power plant and the need for a clutch, transmission, torque converter or continuously variable transmission to provide the proper tractive effort under varying conditions.
- How an electric motor or hybrid impacts these choices. In this regard after the traditional material on acceleration performance is presented, the power characteristics of an electric motor is discussed, and students are expected to be able to take an IC engine drive train configuration and replace it with an electric motor and modified drive train so that the acceleration performance is preserved.
- Braking performance, material on regenerative braking, where in a driving cycle regenerative braking should be considered and the power absorption requirements of the electric motor.
- Handling, how the vehicle responds to steering inputs. Simple models which describe steady state cornering and transient driving maneuvers are developed and implemented in Matlab. The important ideas of understeer, oversteer, stability margin, understeer gradient and handling diagrams. The impact of electrification in this area for controlling weight distribution and space requirements for the suspension components. Ride concerns the pitch and bounce of a vehicle as it travels over a non smooth surface. The discussion centers on mode shapes and natural frequencies and the response of the vehicle to road irregularities.
- Students utilize Matlab throughout the course as a computational aid and modeling tool. Models are developed for acceleration performance, braking performance, handling and ride. Towards the end of the course students are asked to rough out a design for a hybrid vehicle that involved sizing the motor and IC engine and determining critical suspension parameters.

MEEM 5255 "Advanced Powertrain Instrumentation and Experimental Methods" - As a result of the development of the courses described above, it was determined that an additional course was necessary to include instrumentation and experimental methods in the curriculum, this course has been newly developed. In this course students are exposed to unique instrumentation used in modern powertrain research and development. Through hands-on experimentation students learn techniques for installation, usage, and calibration. Students are also exposed to data quality checks and techniques to mitigate experimental variation. This course focuses on advanced powertrain instrumentation and experimentation techniques. This new course will be offered in the Spring of 2013, and will heavily utilize the Mobile Lab.

Short Courses

Two short courses have been developed to date for hands-on learning utilizing the mobile laboratory, and ten more are under development based on topical requirements of HEV industry.

A short course titled "Experimental Studies in Hybrid Electric Vehicles" was delivered October 31st – November 1st, 2012 to seventeen instructors within the Wisconsin Technical College System. This was a hands-on course covering the fundamentals of Hybrid Electric Vehicles.

A second short course titled "IC Engine Management" a hands-on course in IC Engines, scheduled to be offered to Engineers at Denso International America during Feb 2013.

We continue to work with our partners on ways in which we can collaboratively develop, deliver, and market short courses.

Goal 4: Enhancing Existing Courses: Improving currently developed courses in electrical and mechanical engineering to provide cross access to the respective departmental students.

Specific accomplishments: Nine existing courses were modified to provide leverages and links with the automotive systems, engines, and controls expertise courses in the Mechanical Engineering Department with the electric power, electric machines, and power electronics in the Electrical Engineering Department.

Goal 5: Undergraduate and Graduate Certificates in Advanced Electric Drive Vehicle Engineering; with the graduate certificate focused on distance learning for engineers working in industry and displaced engineers.

Specific accomplishments: Undergraduate and graduate certificates, each requiring 15 credits, have been established. The certificate course work contains two interdisciplinary courses with the elective course work in existing classes that have modified sections to directly address material related to HEVs.

The Graduate Certificate uses twenty five existing courses in the Chemical, Electrical, Materials and Mechanical Engineering degree programs. Required courses are shown in Table 1, and elective courses are shown in Table 2.

To date there have been 10 undergraduate and 11 graduate certificates awarded. Graduate students may then continue on for a masters or Ph.D. in their respective departments or select an interdisciplinary master's of engineering degree which is focused on preparing students to work in and educating those already in industry.

TABLE 1: REQUIRED COURSES FOR GRADUATE CERTIFICATE IN HEV (9 CREDITS)

Course	**Description**	**Credits**
EE/ME 4295	Introduction to Propulsion Systems for Electric Drive Vehicles	**3**
EE/ME 5295	Advanced Propulsion Systems for Electric Drive Vehicles	**3**
MY/CM 5760	Vehicle Battery Cells and Systems	**3**
EE 4227	Power Electronics OR	**3**
EE 5221	Advanced Electrical Machines OR	**3**
MEEM 5450	Vehicle Dynamics	**3**

TABLE 2: ELECTIVES COURSES FOR GRADUATE CERTIFICATE IN HEV (6 CREDITS)

Course	Description	Credits
EE/ME 4296	Introduction to Propulsion Systems for Electric Drive Vehicles Laboratory	**2**
EE/ME 5296	Advanced Propulsion Systems for Electric Drive Vehicles Laboratory	**2**
EE 5200	Advanced Methods in Power Systems	3
EE 3120	Electric Energy Systems, *ME Only*	**3**
EE 4221	Power System Analysis 1	**3**
EE 4222	Power System Analysis 2	**3**
EE 5223	Power System Protection	**3**
EE 5230	Power System Operations	**3**
EE 5290	Selected Topics in Power Systems	**3**
ME 4220	IC Engines 1	**3**
ME 5220	IC Engines 2	**3**
ME 5680	Optimization	**3**
ME 5700	Dynamic Measurement and Signal Analysis	**3**
ME 5715	Linear Systems	**3**
ME 4260/5220	Fuel Cell Technology	**3**
EE/ME 4750/5750	Distributed Embedded Control Systems	**3**
MY 4165	Corrosion and Environmental Effects	**3**
MY 5100	Thermodynamics and Kinetics I	**3**
MY 5110	Thermodynamics and Kinetics II	**3**
MY 5410	Materials for Energy Applications	**3**
CM/Ent 3974	Fuel Cell Fundamentals	**1**
CM/Ent 3977	Fundamentals of Hydrogen as an Energy Carrier	**1**
CM/Ent 3978	Hydrogen Measurements Laboratory	**1**

EE—Electrical and Computer Engineering, ME—Mechanical Engineering,
MY—Materials Science and Engineering, CM—Chemical Engineering, Ent—Enterprise
Total of 15 credits are required for the certificate. Up to 6 credits of 3000 and 4000 level courses are allowed.

Task 2: Mobile Laboratory Development and Outreach Activities Development and Delivery
Fabrication of a mobile laboratory as a key feature in enhancements to established education and outreach activities. This task is to maximize the educational experience with hands-on learning experiences for all levels of students from primary and secondary school students to Ph.D candidates.

Goal 1: Mobile Laboratory Development: The new HEV curriculum was designed to have a significant distance learning component to accommodate a growing demographic of online students. The majority of these students, primarily incumbent working, or displaced engineers are located in major metropolitan centers hundreds and even thousands of kilometers from Michigan Tech. This geographical separation presented a significant challenge for the program to overcome. Providing lectures, quizzes, exams, and homework to long distance students is a well established process at many, if not most, academic institutions including Michigan Tech where these processes have been in place for decades. However, what was not clear was how to provide these distance learning students with the same level and quality of hands-on, laboratory education as the traditional on-campus students. To address this issue, a Mobile Laboratory has been designed and built which allows educators to bring the same hands-on experiences to distance students that the traditional on-campus students receive. Furthermore, it is an ideal venue for STEM related outreach to pre-college youth, especially those in the many geographically remote areas of the country that tend to be at a disadvantage in this field.

Specific accomplishments: A versatile mobile laboratory has been developed and built that will travel the North American continent serving as a venue for a wide range of educational opportunities including support of curriculum based courses, targeted short courses, community education and outreach. Hands-on discovery based learning activities are an effective means of enabling students to grasp and retain complex topics in engineering and science, and furthermore, engineering students excel when they can relate an individual concept to the overall larger context of product development and societal advancement. With an emphasis on sustainable transportation systems, the mobile lab provides opportunities for hands-on discovery based learning throughout the development process from model based simulation and design to optimization of hardware and controls.

The mobile lab consists of several elements. The primary laboratory structure is a 16.2 m long van trailer that incorporates an expandable center section for a total of 65 m^2 of space. The expandable center section provides for instruction based learning and bench-top activities on four universal and configurable lab benches. The front and rear of the trailer contain test cells that can be operated from the lab benches in a number of modes including a steady state mode to study the operation of specific components and as a dynamic system with real-time Hardware-In-The-Loop functionality. The powertrain in the test cells is a match to the powertrain in a configurable Hybrid Electric Vehicle (CHEV). The CHEV allows students to change many elements of the vehicle including hardware, embedded software and optimized parameter sets. Three production hybrid vehicles are provided to study the operation of production vehicles in real-world driving scenarios. In addition to driving on the road, these production vehicles, as well as the CHEV can be tested on the mobile lab's single role chassis dynamometer enabling the students to emulate specific drive cycles.

The experimental apparatus and activities on the mobile lab are scalable and configurable. This enables educators to tailor the learning experience to many demographics including K-12, college, and the community. Likewise the contact period with the participants can be as short as just a few minutes as in the case of some outreach events, a few days as in the case of some short courses, or a full semester in support of "for credit" curriculum based courses.

The Mobile Lab consists of several elements including an interactive classroom and two testcell facilities, several vehicles, a chassis dynamometer, an interactive micro-grid, and logistics and support vehicles. Figures 5 and 6 show the primary lab, along with the HEV's in the operational state and transport state respectively. With the exception of the primary lab facility and associated infrastructure, all laboratory apparatus has been developed by graduate and undergraduate students, thus making the lab development itself a hands-on learning endeavor.

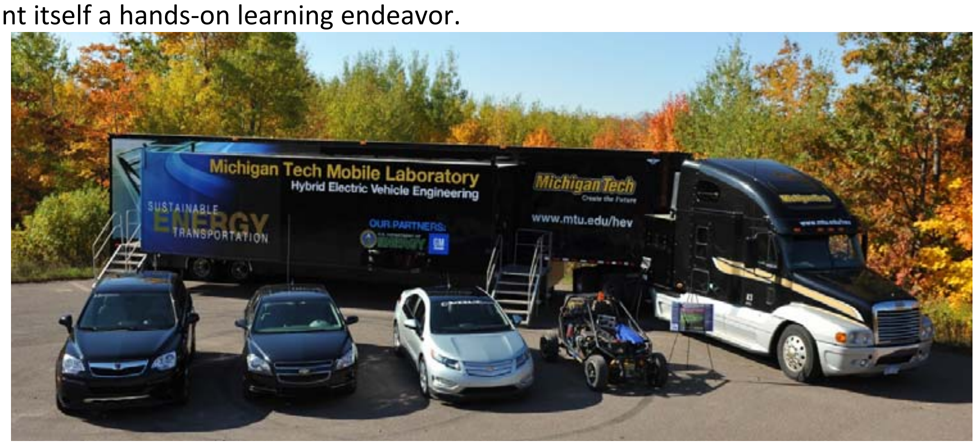


Figure 5: Michigan Tech Mobile Lab's interactive classroom and testcell facility and Hybrid Electric Vehicles.

Figure 6: Michigan Tech Mobile Lab in transportation mode.

Because of an expandable wall, the interactive classroom space is approximately 48.5 m^2. The expanding wall contains two 1.5 m flat panel plasma screens for display of lecture slides or other media from the lab's desktop PC's or any laptop. The expanding wall also has a 2.4 m white board to facilitate traditional lecture methods and open discussions. A small podium on wheels can be positioned in a convenient location for the speaker, shown in Figure 7.

Four lab benches are also on wheels, allowing them to be placed in a multitude of locations and arrangements within the room, to facilitate a wide range of learning situations. The benches are constructed with modular materials to enable future modifications, and feature a T-slot top surface and a flat dry-erase surface as shown in Figure 8. In addition to serving as desks during classroom instruction, they can be used to support benchtop scale experiments as shown in Figure 9. Mounted on the stationary wall are four power panels to support each of the four benches. The power panels supply 5V, 12V, and 48V DC power, 110V single phase, 208 V 3-phase power, and compressed air, all of which can be used to support various benchtop activities. Furthermore, the lab benches serve as control consoles for the two dynamometer testcells. The two forward benches control Testcell #1, and likewise the two rearward benches control Testcell #2. Between the two benches for a given Testcell, control is integrated via a software switch.

The entire facility is insulated and has dual electric heating, cooling, and ventilation systems. This allows the lab to be utilized year round in any climate.

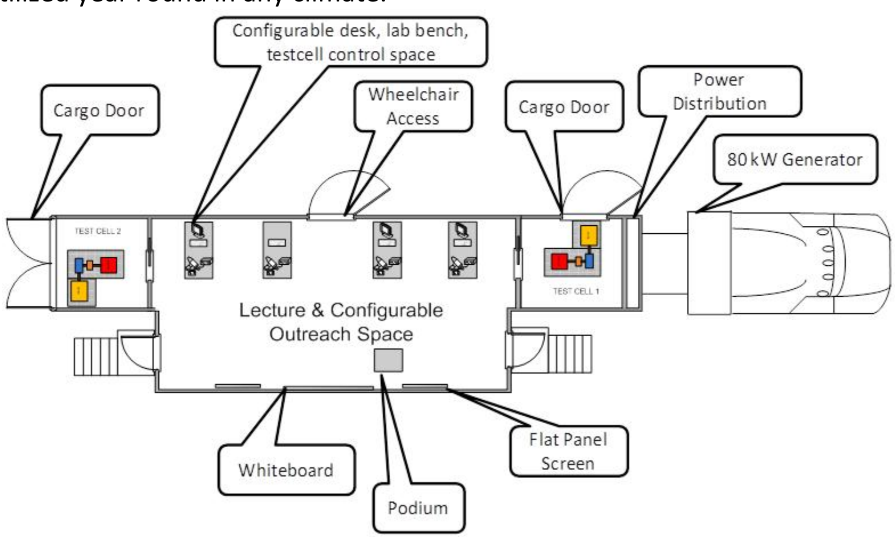


Figure 7: Layout of interactive classroom and testcell facility.

Figure 8: The universal lab benches are on wheels and employ T-Slots and removable dry erase hard surfaces

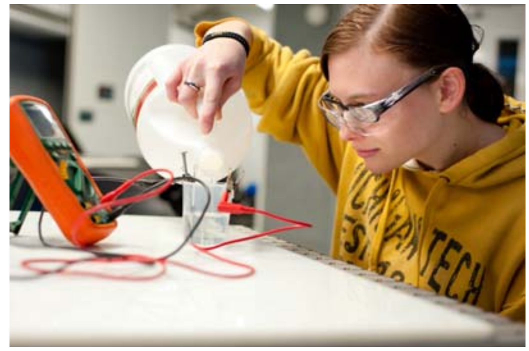


Figure 9: The universal lab benches support a wide variety of STEM related hands-on activities. Here a student builds a battery and learns the fundamental principals governing battery operation and performance.

The lab contains two testcells (refer again to Figure 7). Both cells are currently configured to facilitate testing of an HEV powertrain. The powertrain, which includes the engine, propulsion motor, battery pack, control system, and drivetrain (upstream of the drive axle, which is not included) is a duplicate of the powertrain in the lab's Configurable Hybrid Electric Vehicle (CHEV) (which will be discussed in a subsequent section). The testcells use a 100 kW Baldor 480V 3-phase permanent magnet electric machine as the dynamometer. The four-quadrant ABB drive enables the dyno to operate in either an absorbing or motoring condition with either clockwise or counterclockwise rotation. This enables both steady state testing as well as dynamic tests to emulate a recorded vehicle drive cycle. Currently dynamometer absorbed power is dissipated through a liquid cooled load bank, this system has also been integrated into the labs micro-grid (discussed in a subsequent section) to further demonstrate energy storage and usage.

All data acquisition is handled with National Instruments PXI hardware and Wineman Technologies INERTIA software. The same National Instruments / Wineman system also controls the overall testcell facility, such as dynamometer speed and torque commands, test cell ventilation, fuel pumps, and initiates appropriate remedial action sequencing if key measured and calculated parameters are out of limit, including signals from the three CO and HC sensors.

The testcell fuel tanks are located in the bellybox area under the trailer floor. Currently two fuel tanks supply both test cells. The dual tanks allow for learning activities and demonstrations comparing alternative fuels such as E85 vs. gasoline or Biodiesel vs. petroleum diesel. The design and construction of the testcells has been carried out by graduate and undergraduate students funded through this DOE curriculum development grant.

A team of Undergraduate Capstone Senior Design students have designed and built a portable vehicle chassis dynamometer. A Land & Sea 300 kW single role eddy current dynamometer has been mounted on an 8 m long flatbed trailer. A highly mechanized ramp and platform system was created to position the vehicle atop the roll. A National Instruments Compact DAQ system is has been developed for data acquisition and control. The dynamometer is towed with the Mobile Lab's logistics and support vehicle, which can also supply compressed air and electrical power to operate the dyno, if it is used far from the primary classroom and testcell facility.

The dynamometer allows students to experience a wide range of concepts in the automotive and transportation fields, which has far reaching implications in the larger STEM area. Tests can be conducted on any of the Mobile Lab's test vehicles including the Configurable Hybrid Electric Vehicle (CHEV). The 300 kW capacity allows the testing of most production vehicles. An image of the Chassis Dynamometer is shown in Figure 10.

Figure 10: The Mobile Lab's vehicle chassis dynamometer.

The Mobile Lab consists of three road-legal vehicles which are used for hands-on learning activities by the students in the HEV Engineering curriculum, and can also be used for a wide range of outreach and community education opportunities. The vehicles, a Chevy Volt Extended Range Electric Vehicle (EREV), a Chevy Malibu Belted Alternator Starter (BAS), and a Saturn Vue Mulit-Mode HEV represent a majority of the technology currently available in Hybrid and electric automobiles today. Data acquisition is done with ETAS hardware running INCA software. The data acquisition system interfaces with the vehicles CAN bus through the OBD-II connector. A National Instruments CAN module running in a Compact DAQ chassis can be utilized as an alternative to the ETAS system. All three vehicles can be seen in Figure 1, and Figure 2 while Figure 11 shows a student preparing to collect data during a coastdown experiment.

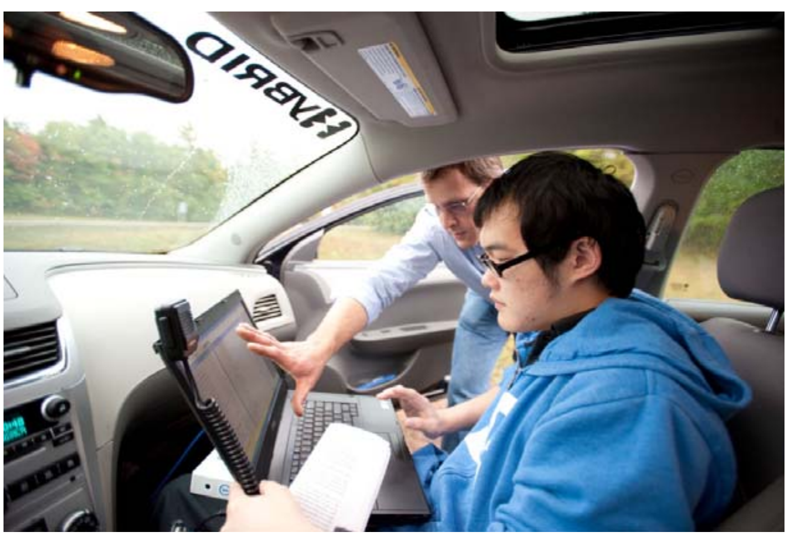


Figure 11: A student preparing for coastdown testing with one of the Mobile Lab's three road-legal vehicles.

A smartgrid, renewable energy sources as well as a plug in vehicle charging infrastructure are critical topics for electric power education. The mobile lab is a standalone electric power grid and thus enables a unique opportunity for participants to study electrical energy interactions of various electrical sources and loads on a micro-grid. The labs electrical system is fully instrumented with current and voltage sensors on all electrical circuits. To further enhance the educational experience, a 600 W photovoltaic solar array and a 300 W wind turbine have been added as part of a Capstone Senior Design Project. A graphical interface allows students to see, in realtime, the flow of power among various sources and loads. Sources include the 80 kW diesel fueled generator, the test cell dynamometers (when in absorbing mode, and once connected to the micro-grid), and the solar or wind generation systems. Loads include the HVAC system, test cell support systems, computers, lights, dynamometers (when in motoring mode), an electric vehicle supply equipment (EVSE) charging station for plug-in HEV's and EV's including the lab's Chevy Volt and CHEV. A controllable 5 kW loadbank has been installed to provide participants with additional degrees of freedom in creating perturbations and injected harmonics into the microgrid. A National Instruments PXI system (separate from the systems used to control the testcells) is used to monitor the sensors, and control the loadbank.

Through this system, the micro-grid allows lab participants to view the flow of energy, and understand how real-time control decisions are made. The micro-grid component of the mobile lab is used as an educational tool to highlight the balance of energy generation and needs in domestic and public buildings, and how the increasingly electrified transportation and renewable energy sectors interact with these buildings.

Goal 2: Secondary School Visits: Execute an outreach program where engineering students will develop the audio and visual material to be used in the visits to GEAR UP secondary schools.

Specific outcomes included: Several undergraduate and graduate students developed various components of the educational outreach materials, demonstrations, and experiments which range from very large and complex vehicle development to very simple experiments.

Configurable Hybrid Electric Vehicle - Four Senior Capstone Design teams developed and built a Configurable Hybrid Electric Vehicle (CHEV) which is a component of the Mobile Lab. Road-legal vehicles are an invaluable teaching too, they allow students to make real-world measurements, and see the end result when a vehicle manufacturer produces a product. This includes being able to see how the various subsystems operate together. However, one limitation is that it is impractical for students to be able to make changes to the vehicle, either hardware or software, and assess the impact of those changes, unfortunately limiting the overall pedagogy being targeted with the mobile lab.

To address this shortcoming, a unique HEV was designed and built by an interdisciplinary team of undergraduate Senior Capstone Design Students at Michigan Tech. The objective was to create an educational tool that employed an open architecture throughout, thus permitting a high degree of configurability in all aspects of the vehicle. Figure 12 shows an image of the CHEV.

Figure 12: The Mobile Lab's Configurable Hybrid Electric Vehicle (CHEV) allows students to change virtually all aspects of the vehicle, and assess those changes on vehicle performance.

The CHEV is a rear wheel drive platform with a longitudinal powerflow. An IC engine and electric motor operate in parallel on a common shaft. The engine is currently an 18.6 kW fuel injected Kohler 2 cylinder, 4 stroke, spark ignited engine, and the propulsion motor is currently a 9.7 kW 48V DC motor. Both power sources are mounted on a universal mounting mechanism, allowing alternative configurations. The gearing between the engine and mainshaft and motor and mainshaft is also easily configurable, as is the gearing in the Halibrand rear axle. The battery pack is currently comprised of four, 12V lead acid modules, although, like the motor and engine, was designed to be easily reconfigured. Mass can be added or removed to the vehicle in 9 kg increments up to 100 kg through ballast plates. Aerodynamics can be changed with an adjustable airfoil. Rolling resistance can be changed by either altering tire pressure, or changing tires, as the vehicle utilizes typical automotive tires and wheels.

The CHEV utilizes a MotoTron 112 pin controller as the supervisory controller, which communicates via a CAN bus to the motor controller. Currently engine control is performed through the production Kohler controller, with plans in place to integrate the engine controls into the MotorTron controller. The MotoTron controller supports rapid prototyping, allowing students to quickly evaluate the impact of changes they make on both the algorithms and the calibrations.

Additional configuration options are being continually added. Forthcoming configurations that are being developed include an AC motor, a Compression Ignition engine, and a Lithium-Ion battery pack.

Portable Vehicle Chassis Dynamometer - As described above, Capstone Senior Design students designed and built a portable vehicle chassis dynamometer.

Capstone Senior Design students also developed and built a 600 W *Photovoltaic Solar Array* and a 300 W *Wind Turbine* for integration into the Micro-grid of the Mobile Lab, as described above.

Human Electric Hybrid Bicycle - A Stationary Human – Electric hybrid bicycle is used to demonstrate the basic operating and energy conversion principals governing HEV's was designed and built by Capstone Senior Design students.

Additional outreach content for various ages was developed by graduate and undergraduate students through coursework in ED5510 "Communicating Science," where coursework projects were to develop and demonstrate outreach content for the Mobile Lab. The projects included building electric motors, creating batteries with simple household items, and exercises in aerodynamic. These activities are utilized during age appropriate outreach events.

A final outreach and teaching experiment developed and built by undergraduate students was a "*Road Ranger Fuel Optimization Driving Simulator."* Utilizing an Eaton 18 speed, Road Ranger Transmission, a shift platform was built to allow visitors to shift a truck transmission under load and "feel" the shift quality.

Figure 13: A sample of Mobile Lab Outreach Activities. Clockwise from Top Left; evaluating the effects of axle gearing on vehicle acceleration, learning the operating principals of engines, identifying key components in Hybrid Vehicles, learning the operating principals and energy conversions in Hybrid Vehicles.

Goal 3: Interactive Electric Drive Vehicles Software for Education and Outreach: Develop an interactive software and game package to serve as an educational tool for electric vehicle technology and operation.

Specific accomplishments: An undergraduate student enterprise team was given the objective to create a stand-alone interactive software and game package to serve as an educational tool for electric vehicle technology and operation. A 3-D first person driving game was developed where players can design and test HEV's where users receive feedback to create better and safer driving habits. The software program designed specifically to target 8th – 12th grade students, general public, community college, and non-degree seeking undergraduates to raise awareness for hybrid vehicles, and to be used in tandem with a full presentation about hybrid vehicles. The game software program was created with an alpha release and later a beta release with improved graphics, game play experience and driver feedback. The game includes a driving simulation, gas pedal, choice of vehicles, and modes of driving styles/speeds. This interactive software is utilized as a hands-on activity in the mobile lab. Figure 14 shows a screen shot of the game in demo mode and feedback to the player with educational messages about the benefits of hybrid vehicle technology.

Figure 14: Screen shots of beta release of HEV educational game. Left- demo mode, right –results feedback.

Goal 5: Summer Youth Programs: Coordinate an outreach program to supplement scholarships to ensure a diverse group of students.

Specific accomplishments:
The mobile lab was utilized for Michigan Tech "Summer Youth Programs" during years 2 and 3, with 40 students participating in each year. The mobile lab was also utilized for Michigan Tech's "Women in Engineering" program during years 2 and 3.

Nine students were recruited for the National Science Foundation (NSF) Research Experiences for Undergraduates (REU) project of "Research in Advanced Propulsion and Fuel Technology for Sustainable Transportation in year 2, and eleven students were recruited in year 3. The goal of the NSF REU Site program is to excite and equip students for further success in undergraduate and graduate programs that provide tomorrow's scientists and engineers with higher level skills, resources, and room for imagination to substantially transform our energy and transportation systems, this was a 10 week summer program.

Three high school teachers were funded by the National Science Foundation in year 2 for (NSF) Research Experience for Teachers (RET) program and two high school teachers participated in year 3. The goal of the NSF RET Site program is for high school teachers in STEM to observe and conduct research over a six week summer program, and from this develops unit plans for incorporation of their research experiences into the classroom. Teachers worked in various engine and combustion research laboratories at Michigan Tech.

Goal 6: *YES!* Expo: Mobile laboratory exhibit at the *YES*! Expo in Detroit, Michigan starting in 2010.

Specific accomplishments: This was goal was not accomplished as the *YES!*Expo program was discontinued before this program had an opportunity to participate.

The outreach activities of the Mobile Laboratory January through October, 2012 are summarized below in Table 3.

Table 3: Outreach Events of the Mobile Laboratory January – October 2012

Event	Date	Approximate Number of Attendees
Support of ED5540 Communicating Science**	Spring 2012	500
Support of SS3800 Energy Technology and Policy**	March 2012	35
Overview of Mobile Lab to Senator Carl Levin, KI Sawyer International Airport	March 2012	3
Western UP Math & Science Fair, Houghton, MI	April 2012	100
Demonstration of the Mobile Lab on Capitol Hill, Washington, DC	April 2012	50
USA Science & Engineering Festival, Washington, DC	April 2012	1000
High School Enterprise Showcase, Detroit, MI	May 2012	75
Overview of Mobile Lab at Chrysler, Auburn Hills, MI	May 2012	60
Overview of Mobile Lab at TARDEC, Warren, MI	May 2012	60
Overview of Mobile Lab at University Transportation Center Conference, Houghton, MI	June 2012	40
School Food Bicycle Tour and STEM Day at CLK Schools**	June 2012	200
2012 Michigan Tech Summer Youth	July 2012	40
Civil Air Patrol Summer Encampment, Alpena, MI	August 2012	160
Overview of Mobile Lab at Detroit Diesel, Detroit, MI	August 2012	100
Overview of Mobile Lab at Mahle, Ann Arbor, MI	August 2012	50
2012 Heroes Alliance Parental Boot Camp, Detroit, MI	August 2012	300
Houghton County Fair, Houghton, MI	August 2012	200
2012 Michigan Tech Alumni Reunion	August 2012	100
Overview of Mobile Lab at CNH & Cat w/ Outreach to Monmouth College, Peoria & Monmouth, IL	September 2012	300
2012 Michigan Tech Presidential Council of Alumni	September 2012	20
Overview of Mobile Lab at 2012 Michigan Tech Career Fair	October 2012	50
Overview of Mobile Lab at 2012 MEEM Open House**	October 2012	100

*** Partial Setup*

Task 3. Course Delivery

Goal 1: Effective teaching and delivery methods for current or developing courses established. Distance learning courses are delivered with the same material and quality of instruction as traditional classroom based courses. The distance learning courses are provided by the faculty in collaboration with the Universities Educational Technology Services and Online Learning department and staff.

Specific accomplishments:
All courses have been offered multiple times over the course of this project. Course content and delivery methods were reviewed for the new and modified courses by the project team during development and as course and teacher evaluations were performed. A summary of the courses is shown in Table 4 below, the courses are summarized by the course type, year offered, semester, and mode of delivery, enrollment numbers for each semester are also included. Course and teacher evaluations are discussed later in this report.

- Eight new courses developed for this curriculum have been offered; of those five have been offered via distance learning.
- Nine courses were modified to incorporate HEV content into the foundation of the course, of those six have been offered via distance learning.
- Seventeen existing engineering courses which are elective courses to the HEV curriculum have been offered; of those eleven have been offered via distance learning.

Table 4: Summarizes the total course offering, by year, semester, and by mode of delivery, with number of students enrolled for each offering.

New Courses				2010 Spring		2010 Fall		2011 Spring		2011 Fall		2012 Spring		2012 Fall		2013 Spring		Total No. Semesters Offered	
Name	Dept.	Number	Credits	DL	C	DL	C	DL	C	DL	C	DL	C	DL	C	DL	C	DL	C
Intro. To Prop. Systems for HEV	EE/ME	4295	3			9	42			11	37			4	44			3	3
Adv. Prop. Systems for HEV	EE/ME	5295	3	64				6	20			1	32			2	34	4	3
Intro. To Prop. Systems for HEV Laboratory	EE/ME	4296	1			X	13			X	15			X	13			0	3
Adv. Prop. Systems for HEVLaboratory	EE/ME	5296	1					X	4			X	10			X	10	0	3
Advanced Electric Machines	EE	5221	3			15	30			9	18							2	2
Vehicle Battery Cells and Systems	MY/CM	5760	3			5	7			19	4			4	11			3	3
Vehicle Dynamics	ME	4450/5450	3									6	34			5	41	2	2
Distributed Embedded Control Systems	EE/ME	4750/5750	3	X	22			X	27			X	37			X	20	0	4

Modified Courses				2010 Spring		2010 Fall		2011 Spring		2011 Fall		2012 Spring		2012 Fall		2013 Spring		Total No. Semesters Offered	
Name	Dept.	Number	Credits	DL	C	DL	C	DL	C	DL	C	DL	C	DL	C	DL	C	DL	C
Intro. to Motor Drives	EE	3221/4219	4	X	65			X	56			X	45			36	39	1	4
Power Electronics	EE	4227	3			15	26			29	40			22	48			3	3
Power Electronics Lab	EE	4228	1			X	14			X	27			X	12			0	3
Power System Operations	EE	5230	3							X	7			X	26			0	2
Power System Protection	EE	4223/5223	3					29	26							40	40	2	2
Power System Protection Lab	EE	4224/5224	1					X	16							X	40	0	2
Distribution Engineering	EE	4225/5250	3	27	32			X	11			27	31					2	3
Intro to IC Engines	ME	4220	3					9	87			8	40			3	43	3	3
Internal Combustion Engines II	ME	5250	3	X	17					1	35			0	37			2	3

Existing Courses				2010 Spring		2010 Fall		2011 Spring		2011 Fall		2012 Spring		2012 Fall		2013 Spring		Total No. Semesters Offered	
Name	Dept.	Number	Credits	DL	C	DL	C	DL	C	DL	C	DL	C	DL	C	DL	C	DL	C
Electric Energy Systems (EE/Non EE)	EE	3120	3	11	27	X	60	33	40	X	34	16	39	X	39	29	39	4	7
Power System Analysis 1	EE	4221	3			22	37			34	41			23	36			3	3
Power System Analysis 2	EE	4222	3	28	38			15	30			24	40			15	29	4	4
Advanced Methods in Power Systems	EE	5200	3			13	9			18	14			14	25			3	3
Classical Control Systems	EE	4261	3			X	27			X	32			X	32			0	3
Thermodynamics/Fluid Mechanics (Non ME)	ENG	3200	4	X	112	X	77	X	106	X	76	X	117	X	63	X	89	0	7
Principles of Energy Conversion	ME	4200/5290	3	X	39	25	33			21	46			10	38			3	4
Dynamic Systems and Controls	ME	4700	3(DL)/	2	108	X	126	X	103	X	109	X	119	X	118	X	114	1	7
Advanced Thermoddynamics	ME	5200	3			4	51			5	68			9	45	1	X	4	3
Experimental Design in Engineering	ME	5670	3			X	12			X	23			X	12			0	3
Optimization	ME	5680	3					7	22					X	17			1	2
Dynamic Systems and Signal Analysis	ME	5700	4			2	25			X	26			1	31			2	3
Linear Systems	ME	5715	3	X	24			4	16									1	2
Fuel Cell Technologies	ME	4260/5220	3			7	25			6	35			5	22			3	3
Senior Capston Design (4 Projects, Avail DL)	EE/ME	4901/4911	2 & 2	X	20	X	20	X	5	X	5	X	5					0	5
Fuel Cell Fundamentals	CM/ENT	3974	1			X	23			X	23			X	18			0	3
Fundamentals of Hydrogen as an Energy Carrie	CM/ENT	3977	1			X	15											0	1

Task 4. Evaluation
Develop both qualitative and quantitative methods to be used to assess program objectives. Formative and summative evaluation efforts are planned for each goal.

Goal 1: Evaluation of Course Reviews: reviewing syllabi for course material, developing effective evaluation tools, and assessing data collected throughout the execution of each course.

Specific accomplishments: Evaluations included both formative and summative efforts. Both quantitative and qualitative methods were used to evaluate the project's success at meeting its designed objectives. For the core courses of the project, permission was granted by the University Institutional Review Board for a survey to the students on both technical content and teaching methods of these courses. The survey consists of three categories of questions: general questions (4 questions), course-based questions (6 questions), and program-based questions (6 questions). The course survey was conducted using Survey Monkey. To accurately evaluate course content in a blended learning environment, additional survey questions were designed for the distance learning students to assess the impact that delivery mechanism may have on learning. Online students complete these additional questions to assist in determining the effectiveness of online learning tools.

In addition to the internal project evaluation, Michigan Tech's Center for Teaching, Learning, and Faculty Development conducts independent, external evaluations of all courses related to the project. This formative and independent feedback assisted the project team in determining which elements of the new courses were meeting objectives and which required further improvement to better meet student and workforce needs.

Course evaluation results - The course survey using Survey Monkey was conducted four semesters; Fall 2010, Spring 2011, Fall 2011, and Spring 2012 respectively. The results of the general questions showed an improvement of student's knowledge of hybrid vehicles after taking these courses. Most students had some knowledge of hybrid vehicle systems before the semester, and improved to full knowledge or working knowledge at the end of the semester. Students also improved the understanding of how to apply course materials to the design of hybrid vehicles. Most students had some knowledge of this application and improved to working knowledge or full knowledge at the end of the semester.

For the course-based questions, most students agreed or strongly agreed that the course sessions and exams contributed to the learning of the course materials. These students strongly agreed or agreed that the teaching methods and homework assignments contributed to the learning of the course materials. For those students who participated in laboratories agreed that the experiments contributed to their learning of the course materials.

For the program-based questions, the survey result shows that our program is attracting more and more engineering students to the graduate or undergraduate certificate in hybrid electric drive vehicle engineering and perhaps a career in related areas. After completing these courses, 83% of students are interested in the (graduate or undergraduate) certificate in hybrid electric drive vehicle engineering and 67% of students are interested in the Masters of Engineering with emphasis in hybrid electric drive vehicle engineering.

Teaching Evaluations - Michigan Tech's Center for Teaching, Learning, and Faculty Development Teacher Evaluations came back highly positive for the majority of courses. In the multiple choice section, students could rate the instructor and course in several areas on a 1 – 5 scale. The average scores for the questions related to teaching quality and available resources are listed below in Table 5.

Table 5: Instructor and course ratings by students.

Question	Average Score (1 - 5 scale)
The organization of the course helped me to learn.	4.28
The instructor explained the importance of what we were learning.	4.36
The instructor communicated the course materials clearly.	4.22
The classroom and equipment (if applicable) were adequate to support effective learning	4.17
I am more interested in the subject now than I was before I took this class.	4.04

Laboratory Courses - The final assessments for the Laboratory courses MEEM/EE 4296 and MEEM/EE 5296 were positive. Students continue to enjoy the experiential learning and the opportunity to conduct experiments with the Hybrid Vehicles that they get when they take these hands-on courses.

Evaluation results of the outreach activities - Michigan Tech's Department of Educational Opportunity organizes Summer Youth Program annually for students in grade 6-12. The program provides a variety of week-long intensive programs aimed at investigating and discovering careers in the areas of engineering, science & technology, business, computing, outdoors & environmental studies, and humanities & social sciences. "Motor Sports" is one of such programs with a focus on hybrid and electrical vehicles. A survey instrument was developed and distributed at the end of the Motor Sports" program, participation in the survey was voluntary. The questions on the survey and survey results, which were very positive, are summarized in Table 6.

TABLE 6: SURVEY QUESTIONS AND RESULTS OF THE MOTOR SPORTS PROGRAM.

Q: What was your reasoning behind choosing your exploration?				
70.27% - I was really interested in the subject	10.81% - My friends were in this class	8.11% - My parents made me take this class	2.70% - My guidance counselor	8.11% - Other
Q: How would you rate the hands-on activities during your exploration?				
45.71% - Excellent	34.29% - Good	5.71% - Average	14.29% - Fair	
Q: How inspired are you to learn more about your exploration after attending the Summer Youth Program as a result of your experience here?				
29.41% - Extremely	44.12% - Very	26.47% - Moderately		
Q: If you received a scholarship, would you have attended the program if you had not received one?				
24.24% - Yes	18.18% - No	57.58% - N/A		
Q: Would you recommend your exploration to others?				
94% - Yes				

Goal 2: Monitor Student Enrollment: Track enrollment of both on campus and distance learning students as the new courses are delivered.

Specific accomplishments: Enrollments for each course offering has been monitored each semester and for each mode of course delivery, as shown in Table 4 above. The enrollments have been steadily increasing, and are higher than anticipated. Figure 15 shows the enrollments for the new and modified courses in the HEV curriculum. Enrollment targets have exceeded expectations, and continue to grow both with the distance learning students and the traditional students on campus.

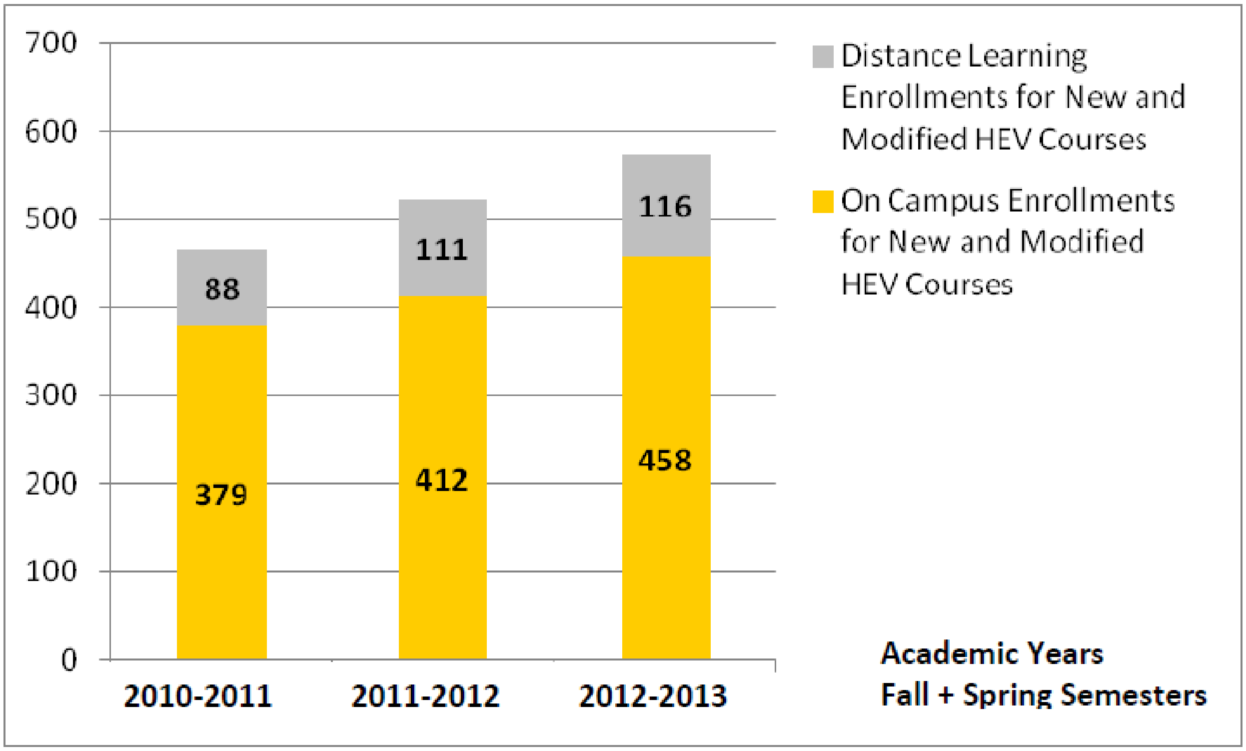


Figure 15: Number of student enrollments for new and modified courses in the HEV curriculum developed through this program.

Conclusions

A curriculum in HEV Engineering, which includes certificates at the graduate and undergraduate level has been developed at Michigan Tech. Maintaining a high level of hands-on education and catering to the needs of long distance students were driving factors in much of the curriculum development. Together these factors led to the development of a unique Mobile Laboratory. The mobile lab is themed around Sustainable Transportation and specifically Hybrid Vehicle engineering, but due to its highly configurable nature, can be used for a variety of STEM related activities. The Mobile Lab is well suited to three educational modes; support of curriculum courses, delivery of short courses, and outreach to pre-college youth and the community. Collectively, the Mobile Lab will be a valuable tool allowing Michigan Tech to deliver exciting and engaging hands-on educational experiences to a diverse, and geographically far reaching demographic for years to come.

Schedule Status

Following is a description of the major milestones proposed with this project. All milestones have been completed for this project; many were completed ahead of schedule and exceed the anticipated results proposed. The accomplishments were:

Milestone Log:

A summary of the milestone proposed on this contract and the completion dates are shown below.

Budget Year 1:

1. First Round of Course Teaching Complete. Completion December, 2010.
2. Mobile Laboratory Complete. Trailer built and first test cell completion August, 2011. Mobile Laboratory utilized in years 2 and 3 for teaching and outreach events. Mobile Lab 100% complete October 2012.
3. Modifications complete for the on-campus Introduction to Propulsion Systems for Electric Drive Vehicles Laboratory course. Completion August, 2010. The course utilized the mobile laboratory in years 2 and 3.
4. Development and Modifications Complete for three new courses and three existing courses. Completion August, 2010. Development and Modifications complete for one new course and seven remaining existing courses in year 2. Completion August 2011. Development of final new course in year 3. Completion December 2011.

Budget Year 2

1. Enterprise teams deliver 2nd stage simulators and content for Mobile Lab. Completion December, 2010
2. Senior Design Team One completes HEDV project “Configurable Hybrid Electric Vehicle (CHEV).” This was a four team effort and was completed December, 2010
3. Outreach for first year of YES! Expo, GEAR UP, and SYP. The Yes! Expo was discontinued before this project was able to participate. The first Summer Youth Program Participation Completion July, 2011
4. Senior Design Team Two completes HEDV project “Configurable Hybrid Electric Vehicle (CHEV).” Completion December, 2010
5. All course development complete. Completion December, 2011.

Budget Year 3

1. Senior Design Team Three completes HEDV project “Configurable Hybrid Electric Learning Modules (CHEV).” Completion December, 2010
2. Senior Design Team Four completes HEDV project “Configurable Hybrid Electric Learning Modules (CHEV).” Completion December, 2010. Three additional Senior Design Teams designed and developed the “*Human Electric Hybrid Bicycle*” completion May 2011, The “*Portable Vehicle Chassis Dynamometer*,” completion May 2011, and “*Photovoltaic Solar Array* and *Wind Turbine”* for integration into the Micro-grid of the Mobile Lab, Completion May 2012.
3. Enterprise teams integrate final stage simulators to Mobile Laboratory. Completion April, 2012
4. Final outreach during funding period complete. Completion September, 2012.
5. Program running in a sustainable mode. All course modifications including DL portions and courses and repeating outreach, senior design, and enterprise activities have been taught at least once. Completion August, 2012.

Ancillary Results

This section summarizes publications, web site development, additional collaborations fostered by the project, and inventions.

Publications and Presentations

- Weaver, W., Worm, J., Beard, J., Anderson, C., Naber, J., Bohmann, L., Chen, B., and Keith, J., "An Interdisciplinary Program for Education in Hybrid & Electric Drive Vehicle Engineering", *Presentation* 2012 ASEE Annual Conference in San Antonio TX.
- Worm, J., Beard, J., Weaver, W., Anderson, C., and Naber, J., "A Mobile Laboratory as a Venue for Education and Outreach Emphasizing Sustainable Transportation," *Presentation* 2012 ASEE Annual Conference in San Antonio TX.
- Cai, Z., Worm, J., and Brennan, D., "Experimental Studies in Ground Vehicle Coastdown Testing", *Presentation* 2012 ASEE Annual Conference in San Antonio TX.
- Lei Feng, Wenjia Liu, and Bo Chen, "Driving Pattern Recognition for Adaptive Hybrid Vehicle Control," SAE 2012 World Congress, Intelligent Vehicle Initiative (IVI) Technology, Advanced Controls and Navigation Systems, SAE Paper No. 2012-01-0742, April 24-26, 2012.
- Weaver, W., Anderson, C., Naber, J., Keith, J., Worm, J., Beard,J., Chen, B. and Hackney, S., "An Interdisciplinary Program for Education and Outreach in Hybrid and Electric Drive Vehicle Engineering at Michigan Technological University", 2011 IEEE Vehicle Power and Propulsion Conference. *Presentation September, 2011, in press*.
- Worm, J.J. et al. "HEVs – Exploring Advanced Vehicle Technologies," Outreach event coupled with SAE Clean Snowmobile Competition", *Presentation* First Mobile Lab Public Event - March 2011. Houghton, MI
- Worm, J.J., Anderson, C.L., and Naber, J.D., "Mobile Laboratory as an Outreach and Education Platform," *Presentation* to SAE, March, 2011.
- Naber, J.D., and Anderson, C.L., "Michigan Tech's Hybrid Vehicle Engineering Graduate Certificate, *MAGMA Webinar*, February 2011, Hosted by SAE.
- Anderson, C.L., and Naber, J.D., "HEV Curriculum Overview and Distance Learning Opportunities," February 2011, *Presentation* GM, Warren, Michigan.
- Anderson, C.L. and Naber, J.D., "An Interdisciplinary Program for Hybrid Electric Vehicle Engineering Education," *Presentation* TARDEC, January, 2011, Warren, Michigan
- Naber, J.D., Worm, J.J., Allen, J.S., Anderson, C.L., Beard, J.E., Burl, J.B., Keith, J.M., Hackney, S., Weaver, W., Woychowski, T., and Smith, R., "Curriculum and Delivery in Engineering for Hybrid Electric Drive Vehicles, Meeting the Needs of the Automotive Industry for New Engineering Talent and Retraining," *Presentation* SAE Convergence 2010, October 2010, Detroit, Michigan.
- Anderson, C.L., "MAGMA Advisory Council Meeting – Marketing Plans," *Presentation* Engineering Society of Detroit, Nov 2010. Southfield Michigan.
- Naber, J.D., Anderson, C.L., and Weaver, W., "Overview to GM Directors – Michigan Tech's and GM Teamed in Advanced Propulsion Education and Research," *Presentation* July, 2010, Warren, Michigan
- Naber, J.D., Beard, J.B., Weaver,W.W., Hackney, S.A., and Worm, J.J., "A Set of HEV Short Courses – HEV Overview, Vehicle Dynamics, IC Engines, E-Machines, Batteries and Controls," *Presentation* June 2010, Southfield, Michigan.

Publications in Progress

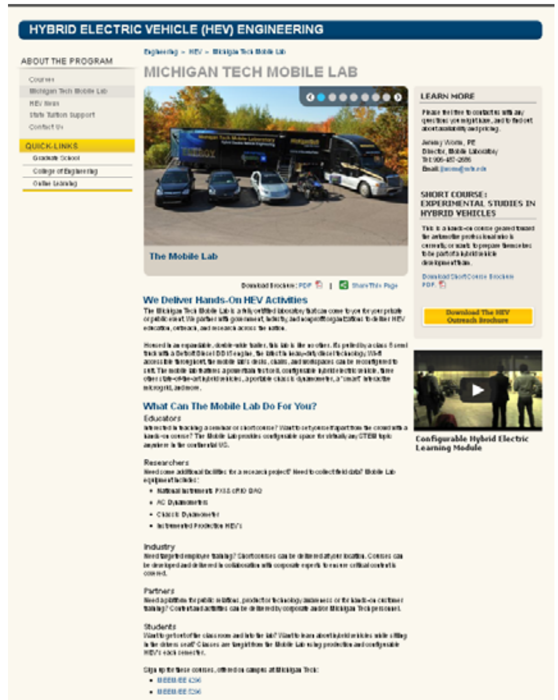
- "Determination of Vehicle Frontal Area Using Image Processing", Brennan. D, Worm, J., Morgan, C., SAE 2013.

Web Site Development

The College of Engineering has developed a website to promote this program to potential students and employers. The site overviews of the variety of available HEV educational programs of study, course requirements for each program, course availability by semester and distance learning course offerings.

http://www.doe.mtu.edu/hybrid_vehicle_engineering/index.htm

Web pages have also been developed and deployed specifically for the mobile lab, and the various manners of utilization. http://www.mtu.edu/mobile-lab



Additional Collaborations

Additional industry collaborators have been identified who will partner with this program to provide additional support; 3M, AVL, Argonne National Laboratory, Carter Brothers, Detroit Diesel, Halibrand, Eaton, EMP Engineered Machine Products, Engineering Society of Detroit, GM, Horiba, Kohler, Mathworks, Michigan Green Jobs, National Instruments, Pace, Phoenix International, Schweitzer Engineering Laboratories, Wineman Technologies, Woodward.

Inventions

None

Video Products

Three videos were professionally prepared for the purpose of promoting short courses, and outreach. A short approx. 45 second video which is a general information video on what the mobile lab is and how it can be utilized. The other two are longer videos approx. 3-4 minutes the first is focused on outreach and STEM activities, and the other is focused on twelve short course offerings and research capabilities targeted for industry needs.

DELIVERING HANDS-ON HEV ACTIVITIES THROUGHOUT THE NATION

The Michigan Tech Mobile Lab partners with government, industry, and nonprofit organizations to deliver HEV education, outreach, and research across the nation. We can bring the Mobile Lab to you for your private or public event.

USES

- Hands-on education: courses, short courses, seminars
- Outreach: schools, exhibits, conferences, community events
- Research partnerships
- Product and research demonstrations

AUDIENCE

- College and pre-college students
- Distance learning engineers
- Corporate decision makers
- Governmental policy makers
- Defense personnel

As an alternative, individuals and groups are welcome to come experience the Mobile Lab right here at our home base—the Michigan Tech campus—located near the shores of Lake Superior in Michigan's Upper Peninsula.

Find Out More

There is no substitute for seeing firsthand what the Michigan Tech Mobile Lab has to offer. We invite you to come take a tour.

CONTACT

Please feel free to contact us with any questions you might have, and to find out about availability and pricing.

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Michigan Tech

Michigan Tech

Hybrid Vehicle Engineering

The Michigan Tech Mobile Lab:

A unique venue for education, research and outreach

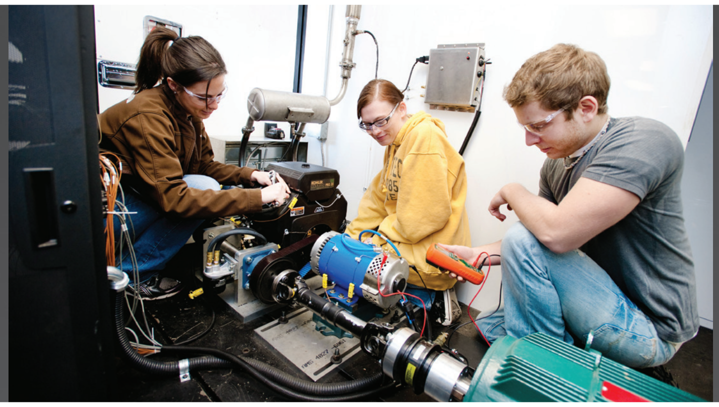
Michigan Tech Mobile Lab

Michigan Tech's pioneering program in hybrid electric vehicle engineering, one of the first of its kind in the nation, was started by a $3 million US Department of Energy grant and $750,000 of in-kind contributions from industry sponsors and partners. Graduate and undergraduate courses are offered on campus, online, and—thanks to the showpiece of the program—on the road.

That showpiece is a huge, handsome mobile lab and classroom that enables Michigan Tech to take hands-on hybrid electric vehicle education right to working and displaced engineers, company employees, students, and communities, wherever they may be.

The Michigan Tech Mobile Lab is housed in an expandable, double-wide trailer. It's pulled by a class 8 semi truck with a Detroit Diesel DD15 engine, the latest in heavy-duty diesel technology. Wi-fi accessible throughout, the mobile lab's desks, chairs, and workspaces can be reconfigured to suit. The mobile lab features a powertrain test cell, configurable hybrid electric vehicle, three other state-of-the-art hybrid vehicles, a portable chassis dynamometer, a "smart" interactive microgrid, and more.

Features Of the Mobile Lab



POWERTRAIN TEST CELLS

The Mobile Lab's powertrain "hardware-in-the-loop" test cells are cutting-edge developmental tools that show how hybrid electric vehicle (HEV) components work—batteries, engines, electric machines, embedded controls, and power electronics.

Use the test cells to analyze energy management through the system. Operate the powertrain in a steady state, or while emulating a drive cycle. Investigate torque blending between the engine and motor, regenerative braking characteristics, and more.

CONFIGURABLE HYBRID VEHICLE

The Mobile Lab's configurable hybrid electric vehicle is one of a kind. Everything on it—rear axle, engine controls, motor, and battery—can be changed and changed quickly. For instance, it's possible to switch out gears in three minutes, something that would take three days on a regular vehicle in a shop.

Use the configurable hybrid electric vehicle to evaluate up to 14,000 possible combinations through testing or simulation, then prepare the vehicle for final validation testing.

INTERACTIVE SMART MICROGRID

A portion of the research now taking place aboard Michigan Tech's Mobile Lab is aimed at providing US military installations with safe, reliable power generation for operating bases and humanitarian missions.

We offer education, demonstrations, and research in this area utilizing an on-board, state-of-the-art, interactive, "smart" microgrid.

Smart microgrid features:

- PHEV & 5kW controllable load
- 80kW generator
- PV array & wind turbine
- Wireless communication
- Interactive GUI & data acquisition

HYBRID VEHICLES

Experience the state-of-the-art HEV technology in a Chevy Malibu hybrid, Saturn Vue hybrid, and Chevy Volt. Compare the effects of various parameters on fuel economy and driveability.

Science, Technology, Engineering & Math (STEM) Outreach

WHY USE THE MOBILE LAB FOR YOUR STEM OUTREACH?

We offer hands-on, short duration, high impact experiences in sustainable transportation, sustainability, and energy surety. New activities are continually being developed and can be customized to fit your specific audience and age group. Options include:

- Try your hand at HEV gaming: a virtual garage and drive route
- "Feel" the energy flow with a hybrid electric bicycle
- Conduct hardware-in-the-loop (HIL) testing with a real powertrain
- Improvise with a "seat of the pants" configurable HEV
- Discover how hybrid electric vehicles are produced in the "real world"
- Learn how batteries, engines, and electric machines work

WHAT CAN THE MOBILE LAB DO FOR YOU?

EDUCATORS

Interested in teaching a seminar or short course? Want to set yourself apart from the crowd with a hands-on course? The Mobile Lab provides configurable space for virtually any STEM topic anywhere in the continental US.

RESEARCHERS

Need some additional facilities for a research project? Need to collect field data?

Mobile Lab equipment includes:

- National Instruments PXI & cRIO DAQ
- AC Dynamometers
- Chassis Dynamometer
- Instrumented Production HEVs

INDUSTRY

Need targeted employee training? Short courses can be delivered at your location. Courses can be developed and delivered in collaboration with corporate experts to ensure critical content is covered.

PARTNERS

Need a platform for public relations, product or technology awareness or for hands-on customer training? Content and activities can be delivered by corporate and/or Michigan Tech personnel.

STUDENTS

Want to get out of the classroom and into the lab? Want to learn about hybrid vehicles while sitting in the drivers seat? Classes are taught from the Mobile Lab using production and configurable HEVs each semester.

Sign up for these courses, offered on campus at Michigan Tech:

- MEEM/EE 4296
- MEEM/EE 5296
- MEEM 5250

LEARN MORE AT

WWW.MTU.EDU/HEV

TOPICS

- HEV safety & architecture
- Drive cycles & experimental techniques
- Fuel economy & emissions regulations
- Aerodynamics & rolling resistance
- Batteries
- Engines
- Electric machines & power electronics
- Embedded controls
- Systems integration
- Vehicle modeling

HANDS-ON EXPERIMENTS

Use cutting-edge tools from National Instruments, Wineman Technology, and others to conduct hands-on experiments:

- Disable a high-voltage electrical system
- Identify and become familiar with components
- Determine in situ fuel economy
- Determine the effects of aerodynamics & rolling resistance through vehicle coast-down testing
- Characterize the performance of a battery pack
- Characterize the efficiency & output of an engine
- Characterize the efficiency & output of an electric machine
- Send & receive messages on a CAN bus
- Vehicle simulation
- Optimize a configurable hybrid vehicle

INSTRUCTOR

Jeremy Worm, PE

As Director of the Michigan Tech Mobile Lab, Worm teaches curriculum courses in the area of hybrid vehicles, engines, and powertrain instrumentation. His research interests include hybrid vehicle energy management, and IC engines including efficiency improvements and alternative fuels.

Prior to joining Michigan Tech, Worm held various positions at GM Powertrain where he gained experience in many areas of vehicle development including an engine for a new hybrid vehicle. Worm has multiple US patents, and has authored or coauthored numerous journal articles, conference papers, and book chapters.

LEARN MORE AT
WWW.MTU.EDU/HEV

Michigan Tech Short Course:

Experimental Studies in Hybrid Vehicles

Experimental Studies in Hybrid Vehicles is a hands-on short course geared toward the automotive professional who is currently, or wants to prepare themselves to be part of a hybrid vehicle development team.

Michigan Tech

Michigan Tech Short Course:

Experimental Studies in Hybrid Vehicles

COURSE DESCRIPTION

Vehicle powertrain hybridization is a critical step on the pathway to sustainable transportation. Hybrid powertrain systems are able to realize improvements in efficiency through strategic energy management principals. Although effective, these systems bring a significant degree of complexity to the vehicle development process, and engineers must be familiar with the operation of systems outside their core area of expertise.

This introductory short course treats the vehicle as a series of energy conversion processes. The course will rely on a mix of lecture, hands-on experimentation using production and one-half scale configurable Hybrid Vehicles and a complete powertrain test cell. Participants will learn the basic operating principals governing all major hybrid vehicle subsystems before using commercial vehicle modeling software and operational hardware to optimize the performance of a configurable hybrid electric vehicle.

LEARNING OBJECTIVES

1. Understand the energy conversion processes and energy flow through a hybrid electric vehicle
2. Understand the basic operating principals of Hybrid Electric Vehicles and their subcomponents, especially their impact on the energy conversion process
3. Be able to interface with engineers across various disciplines on a hybrid vehicle development team
4. Understand typical experimental techniques and apparatus used in vehicle development
5. Become familiar with vehicle simulation and correlation to experimental data

AUDIENCE

This short course is intended for engineers new to the hybrid vehicle field, those wishing to enter the hybrid vehicle field, or experienced hybrid vehicle engineers wishing to learn more about other areas of the hybrid vehicle outside their area of expertise. The course is also appropriate for managers and technicians wishing to expand their knowledge of hybrid vehicles.

PREREQUISITES

An engineering degree, or a working knowledge of thermodynamics, a basic understanding of electronic data acquisition, and the ability to solve closed-form equations.