Final Report

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DISCLAIMER

Executive Summary

This collaborative educational project between the University of Michigan—Ann Arbor, University of Michigan—Dearborn and the Kettering University successfully executed almost all the elements we proposed to do. In the original proposal, we proposed to develop four graduate courses, six undergraduate courses, four professional short courses, a K-12 electric vehicle education kit, a Saturday morning seminar series, and a set of consumer education material to support the advancement of transportation electrification. The first four deliverables were all successfully developed and offered. When we held the kick-off meeting in NETL in Morgantown back in early 2010 with all the ten ARRA education teams, however, it quickly became clear that among the ten ARRA education grantee teams, our proposed "consume education" activities are not better or with the potential to create bigger impact than some of activities proposed in other teams. For example, the Odyssey 2010 event held by the West Virginia University team had planned and successfully reached to more than 230,000 attendees, which is way more than what our proposed 100k event could ever reach. It was under the suggestion of Joseph Quaranta, the ARRA education Program Director at that time, that we should coordinate and eliminate redundancy. The resources should then be focused on activities that have less overlap. Therefore, the originally proposed activities: Saturday morning seminar series, and a set of consumer education material were dropped from our scope. We expanded the scope of our "education kit" activity to include some educational materials, mainly in the form of videos. The target audience also changed from general public to K-12 students.

The majority of the project cost (~70%) goes toward the establishment of three undergraduate laboratories, which provides critically needed hands-on learning experience for next-generation green mobility engineers. We are very proud that the ARRA money, which was distributed as part of the economy stimulus package back in 2009, was used to invest in laboratories which are already impacting the learning experience of our undergraduate and graduate students, and will continue to do so in the coming decades.

The offering and enrollments of the ten undergraduate and graduate courses developed under the support of this educational grant is summarized in the table below. The grant was finalized in September 2009, and four new courses were developed and offered soon after in Winter 2010. The other six courses were developed thereafter. The total number of students who took these new courses over the duration of this grant is just over 1,000. In the first 2 years, under the DOE funding, the courses are offered more regularly. After that, the courses were considered together with other existing courses in the planning of teaching schedule and may not be offered each year. Almost all of the 10 courses have healthy enrollments and we do expect them to be offered continuously in the future. The graduate courses perhaps will be offered every 2-3 years, and the undergraduate courses most likely on a yearly basis.

Semester	W10	F10	W11	F11	W12	F12	W13
401 I-HES Lab							65
402 Power elec. Lab		24		41		47	
403 FC and H2	47			30		19	
404 Elec. Mach. and Drive	47		25		25		
405 Veh. Power and loads		19		35			
406 Green Mobility Lab		10		20	32	18	
501 Electrified Vehicles	93		78		101		65
502 Batteries	59		41		52		
503 Green Manufacturing			20				
504 Plug-in Infrastructure		20				26	
Total	246	73	164	126	210	84	155

The course content developed for these ten courses were also used to develop several short courses that cover state of the art development in the field such as hybrid vehicles, battery systems, and innovative manufacturing. These short courses have been offered both in face-to-face and distance learning settings. More than 300 students attended these short courses.

We offered a green transportation summer camp to high school students in 2010-2011. A total of 30 students joined the camp. They not only learned from a broad range of energy related lectures, they also got a chance to visit sites in their own neighborhood to witness the cutting edge development of clean energy and clean vehicles, they also participated in model electric vehicle competitions. Attracting high school students to get engaged in these activities and make them excited about STEM as a career choice is important to ensure we will continue to have the best engineers to develop and produce future clean vehicles.

The K-12 outreach activities also include the development of some educational materials, mainly conducted at Penn State University. The three main deliverables are a toy kit, a set of educational videos and an educational videogames. The details of the development and findings are summarized in two undergraduate theses and a master thesis.

Budget and Cost Share

The financial details can be found in the financial report. Regarding the required cost share, the University of Michigan has committed far more than the 20% originally required for this education grant. Just for the renovation of the laboratory for the hybrid-in-loop system laboratory, the construction cost is close to 1 Million dollars, far more than the 500k required for this 2.5M project. This demonstrated the full and enthusiastic support from the University of Michigan.

In summary, all ten courses and three laboratories we contemplated to develop were successfully developed and commissioned. These courses significantly strengthened the curriculum of UM Ann Arbor, UM Dearborn and Kettering university in the field of electrified transportation.

Final Report

The overall objective of this DOE sponsored grant is to develop and provide a comprehensive set of education programs and services to accelerate the migration toward transportation electrification. We originally aimed to develop four graduate courses, six undergraduate courses, four professional short courses, a K-12 electric vehicle education kit, a Saturday morning seminar series, and a set of consumer education material to support the advancement of transportation electrification. However, at the suggestion of the program manager to coordinate and reduce repetition, the last two planned activities were significantly scaled back. We only offered two summer camps to regional high school students. The majority of the project cost (~70%) goes toward the establishment of three undergraduate laboratories, which will provide critically needed hands-on learning experience for new green mobility engineers.

All ten graduate and undergraduate courses to be developed by this project have been developed and offered at least once. The overall enrollments in all the ten courses are summarized in Table 1 below. We are glad to report that over the past 7 semesters, a total of **1059** students enrolled in the courses developed for this DOE grant. These students were exposed to the state-of-the-art education in the field of electrified vehicles. Some of them are graduating and will have a chance to use the knowledge they earned in the courses developed under this DOE grant to impact the development of future electrified vehicles. We also would like to note that most of the courses have very healthy enrollments and these courses likely will continue to be offered even after this DOE grant ended.

Table 1 Summary of the enrollments in the ten courses developed under this DOE grant.

Semester	W10	F10	W11	F11	W12	F12	W13
401 I-HES Lab							65
402 Power elec. Lab		24		41		47	
403 FC and H2	47			30		19	
404 Elec. Mach. and Drive	47		25		25		
405 Veh. Power and loads		19		35			
406 Green Mobility Lab		10		20	32	18	
501 Electrified Vehicles	93		78		101		65
502 Batteries	59		41		52		
503 Green Manufacturing			20				
504 Plug-in Infrastructure		20				26	
Total	246	73	164	126	210	84	155

Summary of Project Activities

Graduate courses:

Overall, four graduate courses were planned over the span of the project, covering key sub-systems (Battery Systems and Control), vehicle integration (Modeling, Analysis and Control of Hybrid Electric Vehicles), vehicle-grid integration (Plug-in Vehicle Infrastructure) and manufacturing processes (Green Energy Manufacturing). Two of these courses were developed and offered for the first time in the Winter term of 2010 (Jan-April 2010). The third course was developed and first offered in Fall 2010, and the last of the four courses was developed and offered for the first time in Winter 2011. Details of the activities over the last quarter are provided below.

501 Modeling, Analysis and Control of Hybrid Electric Vehicles: This course was first developed and taught in the Winter term of 2010 with an enrollment of 33. This course was videotaped and subsequently offered again during the Spring/Summer term of 2010. 60 students, all of them from General Motors, took this course in the Spring/Summer term of 2010 through distance learning. Because of the large class size, significantly more office hours were offered. And one additional lecture on hybrid vehicle testing and evaluation was added.

This course was offered for the third time in Winter 2011. There were 23 students taking the course in the classroom. In addition, 55 students (most of them from General Motors) took this course through distance learning. The course content was continuously improved over these offerings to reflect the new development in the field. For example, focused discussion and homework problem was added to introduce the output power split hybrid vehicles, which was used in the high speed driving of Chevy Volt.

In Winter 2012 (Jan-April of 2012), this course was offered for the fourth time with a record number of enrollments: a total of 101 students enrolled in this course (35 through distance learning). This is the first time the course is taught solely by Prof. Huei Peng, because of the departure of Prof Zoran Filipi, who moved to the Clemson University as a chaired professor. The course is revised significantly to reduce its content in the area of international combustion engines, and significant amount of additional content on the topic of modeling ad control were added.

In April 2012, as the Winter 2012 semester draws to an ends, the 101 students worked on 27 projects and the final report counts for almost half of their final course grade. An oral presentation was also required for on-campus student teams. The project titles are shown in Table 2. Many of the final project topics are forward looking—to study concepts have not been available on the market yet. This is precisely what our DOE project aims to achieve—educating students who can design future clean vehicles.

Table 2 Titles of the final projects of course 501 (ME 566 in the official book) in Winter 2012

Design and Control of High Performance hybrids	Ultra-Capacitor ICE Hybrid Bus	FC of a small engine power split
flywheel hybrid system in race-car	CNG hybrid bus	2PG+Atkinson Cycle + Battery
Hydraulic hybrid dump truck	Hydraulic Hybrid for Heavy Duty Vehicle	Power split for global market
Hybrid aircraft	ICE-Ultracap/battery hybrids	HCCI in 2-mode HEV
Design and control of power split hybrids	High performance hybrids	Hybrid Water-Coupled Jet Drive
Hybrid tug boat	Serial hybrid with a QUASITURBINE ENGINE	Fuel Cell Vehicle for City Use
AWD EV with battery/ultracap	Improve Efficiency of PHEV	Vibration Energy Regeneration
Hybrid for Emerging Market	Battery Management of Power Split Hybrid	Meeting the 2025 CAFE Target in performance hybrids
Hybrid Motorcycle	Feasibility Analysis of EV in the Andean Countries	GPS for EREV

In Winter 2013, this course was offered for the fifth time. It is also the first time the I-HES lab is ready to be used to support this course. The additional lab components helps students to acquire hands-on experience, including testing of motors, engines, pure electric vehicles and hybrid vehicles. We successfully offered 5 labs to the class cohort, which consists of 66 students. These labs provide hands-on experience on testing of motors, electric vehicles, engine, ICE-only vehicle and a parallel hybrid vehicle. The test data collected were used as the basis of homework questions as well as information to model the components of hybrid vehicles. Table 3 below shows the topics of the final course project proposed by the students. Similar to the previous years, again students in this class applied the knowledge they learned in this class to work on a very wide array of topics related to the design of electrified vehicles. We are very proud of the creativity demonstrated in these projects and think this is another anecdotal evidence of the effectiveness of this education grant.

Table 3 Topics of the final projects studied by students in the ME566 class in Winter 2013

Hybrid Drivetrain Application in a Marine Hydrofoil Vessel	Power split Chevy Volt with ECMS technique	Integration of Turbo-Generator to VOLT Driveline to optimize EV Driving range	Modeling and Control of an Extended Range Electric Military Vehicle
Hydraulic CVT for Semi-Trailer Truck Application	Effects of Hypermiling in a Conventional & Hybrid Vehicle	Power-Split Electric Hybrid Downsized Refuse Truck	Electric AWD Application
Efficient Integration of Waste Heat Recovery in a Power Split Hybrid'	Modeling and Control of a Power-Split Hybrid Vehicle	Modeling and Control of THS II Transmission for Power-Split Hybrid SUVs	Small Unmanned Ground Vehicles Series Hybrid Powertrain Design and Control
Torque-Assist and Electric APU Charging for Long Haul Diesel Trucks	Modeling, control and analysis of a Toyota Prius Based engine using Electromagnetic Induction Motor	Greener Deliveries: A Series Hybrid Study for USPS Long Life Vehicles	Performance Comparison of Optimized Flywheel System and Buick Lacrosse eAssist System
Analysis and design of a performance variant of the Chevy Volt Powertrain	Fuel Economy and Performance Analysis of a Power Split Hybrid Vehicle for Indian Market	The KERS Hybrid Cadillac ATS: Design of a Kinetic Energy Recovery System Flywheel Hybrid Vehicle	Hybrid Vehicle Optimization with Navigation and GPS
Hybridization of a Sports Car	Hybridization of Chevrolet Cruze to meet 2020 CAFE standards		

The final version of the course syllabus is shown in Appendix A.

<u>502 Vehicle Electrification (Part A): Battery Systems and Control:</u> This course was offered for the first time in Winter 2010 and was offered for the second time in Winter 2011. In its first offering, due to the lack of adequate time for promotion (the DOE project was awarded at the end of September of 2009, just 3 months before the semester starts), the course only had five students enrolled through distance learning (all of them are full-time employees of automotive companies). However, we have a large on-campus class of 54 students. For Winter 2011, the number of distance learning students doubled to 10 while the on-campus class size is 31.

Because of the departure of one of the two instructors—Dr. Hosam Fathy joined Penn State as an Assistant Professor in August 2010—the course has to be modified and is taught completely by Prof. Anna Stefanopoulou in Winter 2011. This change however also gave her the chance to include new and updated information and to revise the teaching plan to be more coherent.

In Winter 2012, this course was offered for the third time. The total number of enrollments is 52. This course now covers not only basic electrochemistry, but also Partial-differential-equations based and lumped parameter models. The concept of battery management systems is covered in depth with detail on battery state of charge and state of health estimation algorithms as well as cell—to-cell balance functions covered in details. A switching circuit has been designed and fabricated to emulate imbalanced cells and can be used to evaluate cell balancing in a battery pack. Finally, over the past year the course content on thermal model and management was developed and included in the course.

In the fourth quarter of FY2012, we tried to identifying an adjunct lecturer to cover the course for Winter 2013. The original course instructor, Prof. Anna Stefanopoulou will not be able to tech this course again. However at the end we cannot identify a qualified instructor. The course content is in very good shape and we do believe this course will be offered on a regular basis going forward.

The course content is shown in Appendix B.

503 Green Energy Manufacturing: Originally, this course was planned to be offered for the first time in Fall 2010. However, because the lead instructor, Prof. Jack Hu was promoted to the position of associate dean of academic affairs of the College of Engineering, his availability was negatively impacted. Therefore, we delayed the course development by one semester—this course was offered for the first time in Winter 2011, with a class size of 20. The course was offered involving another faculty, Professor Judy Jin of the Industrial and Operations Engineering department.

In the preparation of this course, a workshop was organized to invite regional industrial companies to provide inputs on the critical manufacturing challenges. This workshop was offered in October 2010, during which about 10 experts from the wind, solar and battery industries (including GM, Ford, DTE Energy, Johnson Controls, etc.) and academia presented the state of art in green energy manufacturing technologies. Forty attendees registered. Including the event speakers and local students, the size of the audience is more than 60. The outcome from this workshop helped to shape the final course content. In addition, invited guest speakers were identified. The Syllabus of the course and the flyer and the workshop agenda are shown in Appendix C.

504 Infrastructure for Vehicle Electrification: This course was developed by Prof. Ian Hiskens, and was offered for the first time in Fall 2010. This course covers an important topic that is receiving a lot of attention: the impact and interaction between electrified vehicles (plug-in hybrids or pure electric vehicles) and the electric power infrastructure. Prof. Hiskens and Prof. Huei Peng are also involved in a DOD research project (August 2011 to December 2011) for military microgrids, which is quite complementary to this course. The aim is to sustain electricity provided to military installments even under irregular events when the connection with the main grid is lost. In addition, to improve sustainability, the microgrid is envisioned to be equipped with renewable and intermittent power sources such as wind turbines. This new research project will help to ensure newest research and development knowledge is included in this important course. The main technical content for this course includes

1. Power system overview: Distribution supply systems; Reliability; Protection; Impact of high PEV penetration; Vehicle-to-grid integration.
2. Vehicle-grid interface: Grid-to-vehicle and vehicle-to-grid converter technologies; Standards; Safety systems; Quality-of-supply; Information transfer.

3. Business models for ubiquitous charging facilities: Cyber-infrastructure requirements for supporting smart/dumb charging.
4. System-wide control of charging: Time-based and price-based load shifting strategies; Optimal control of PEV demand; Hierarchical control structures; PEV control for smoothing renewable generation variability.

20 students enrolled in this course in Fall 2010. The course syllabus is shown in Appendix D. Originally the course was planned to be offered again in Fall 2011, however, due to the course planning in the EECS department, this graduate course was not offered. In the meantime, based on the curriculum assessment and benchmarking against our peer schools and industrial needs, a new graduate course "power system dynamics and control" was newly developed and offered in Fall 2012. The course is very complementary to the scope and content of the other DOE funded courses, even though it was not listed in our original plan.

A copy of the syllabus of this new graduate course (EECS 598, section 2, power system dynamics and control) is given in Appendix E. This new course has an enrollment of 26 in Fall 2012. <u>This number is reported in Table 1 as "Course 504".</u>

<u>Undergraduate courses</u>:
A total of six undergraduate courses were planned for this project—three of these are laboratory courses. The labs are the heart and soul of the proposed undergraduate curriculum. They were designed to provide critically needed hands-on experience and plays an important role in the offering of an undergraduate energy concentration (UMAA), undergraduate concentration in electric energy (UMD) and specialty in green Mobility engineering (Kettering). Three lecture-based courses have been created and will continue to be developed to fully utilize the labs as well as to provide rigorous analytical and design skills. Students receiving these training will be ready to work in new green mobility jobs developing advanced HEV/PHEV and FCEV; or well-prepared for graduate degrees in related field.

<u>401 Integrated Hybrid Electric System (I-HES) Laboratory:</u> This laboratory is truly a showcase piece of this DOE project and supports multiple courses (some of them already existed, or are being developed under the DOE support. The construction of this laboratory takes longer than originally planned and it was ready for instruction use for the first time in Winter 2013 (which is the last of the 10 courses developed within the scope of this project). We selected A&D to be the primary vendor to provide the equipment for this laboratory after lengthy and careful studies.

The College of Engineering of the University of Michigan—Ann Arbor is very supportive for the development of this laboratory, and assigned room 1070 of the Lay Automotive Laboratory for the purpose of this lab. This room is spacious (770 ft^2) but it does not have the exhaust, air handling, and fueling systems necessary for this lab. In addition, there was no control room available, and thus significant renovation is necessary. At the request of the PI, the College invested $1M to renovate this test cell (see Figure 1). The construction is very significant and separated the original room into a small control room and a test cell (see Figure 2). This major investment upgraded the lab space to accommodate the state of the art equipment capable of supporting three courses: ME438 (Internal Combustion Engines), ME 538 (Advanced Internal Combustion Engines), and ME566 (Modeling and Control of Hybrid Electric Vehicles). The design of the lab renovation (by Fishbeck, Thompson, Carr, & Huber, Inc. (FTC&H) of Farmington Hill, Michigan) finished in late 2011. The design project is completely funded by the College of Engineering , University of Michigan.

Figure 1. Renovation of "401 lab": in construction (left) and used for instruction (right)

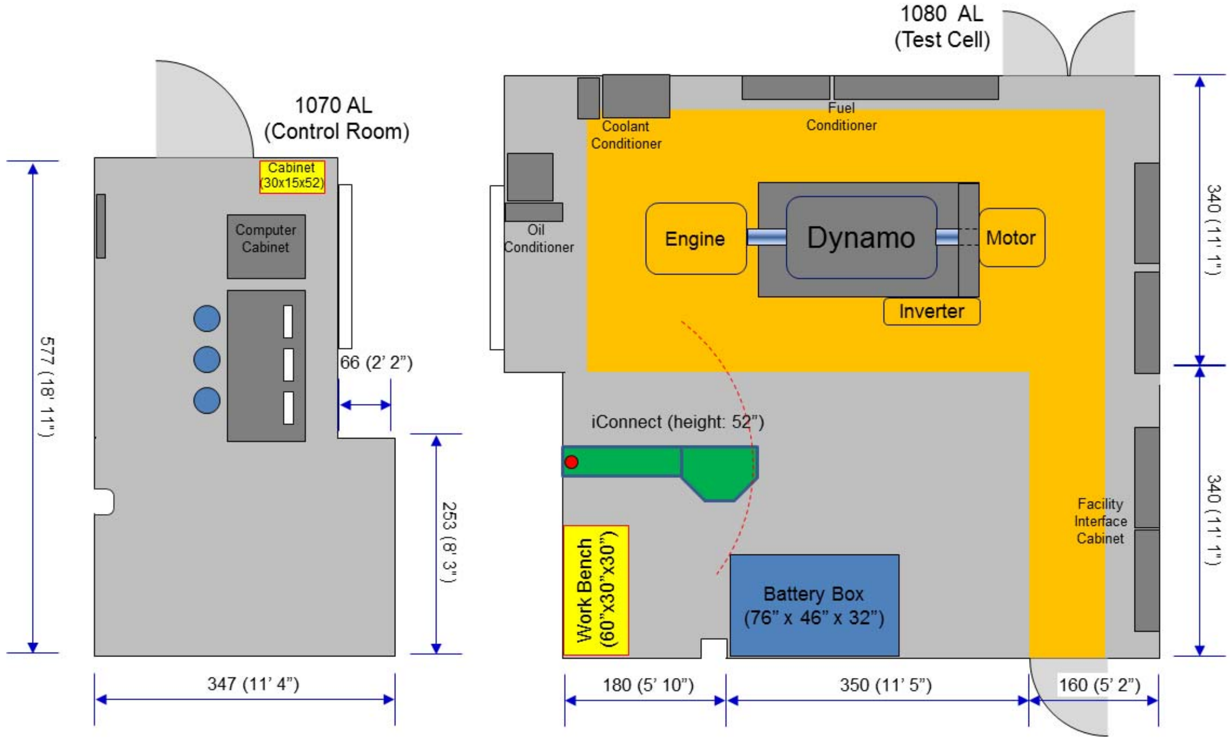


Figure 2. The renovated "401 lab" consists a control room and a test cell

The core equipment of this laboratory is the A&D dynamometer with associated iTest data acquisition and control system. The dynamometer has a double-ended design, and it was sized to test power components in future electrified powertrain. Because the dynamometer was designed to test both an engine and an electric motor (not simultaneously), the rotational speed range of the dynamometer is significantly higher than that typical of ICE- dynamometer. The top speed is 12,000rm and the rated power is 180kW. The speed and power of the dynamometer is adequate to test engines and motors used in the Chevy Volt, Ford Fusion and Toyota Prius. A schematic diagram of the system is shown in Figure 3. The major equipment is listed in Figure 4.

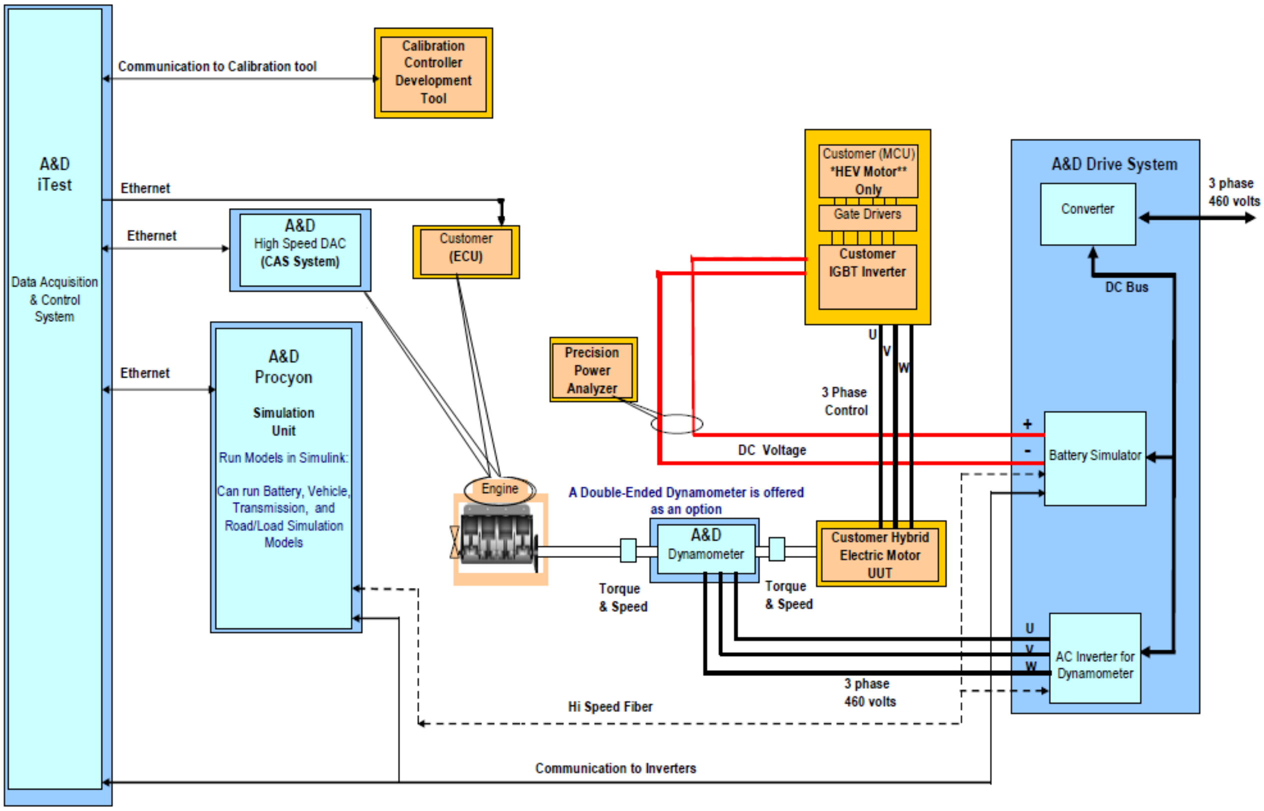


Figure 3. Schematic diagram of the test system for "Course 401"

Equipment		
1	241HP (180kW) AC Dynamometer System	A&D
2	180 kW Battery Simulation System	A&D
3	iTest Data Acquisition and Control System	A&D
4	iCentral Lab and Data Management Suite	A&D
5	High Speed Combustion Analysis System	A&D
6	Procyon Simulation and Control System*	A&D
7	(8) Compact ADX – AD70110EVA (Contingent Upon PO)	A&D
8	iConnect Distributed I/O System	A&D
9	Facilities Interface Cabinet (FIC)	A&D
10	Operator Control Console	A&D
11	A&D Coolant Conditioner (HEV only)	A&D
12	A&D Oil Conditioner (HEV only)	A&D
13	A&D Fuel Conditioner (HEV only)	A&D
14	A&D Battery Chiller	A&D
15	A&D Throttle Actuator (HEV only)	A&D
16	Interconnect Materials (cables, conduits, for A&D supply)	A&D
17	Yokagawa Power Analyzer / Probes	U-M
18	Bedplate(s) (if required for HEV ICE or Generator)	U-M
19	iCentral Server	U-M
20	Phoenix CAS PC or Laptop	U-M
21	Pods / Transducers for Cylinder Pressure Measurements	U-M
22	ECU / MCU / HCU (all control units)	U-M
23	Unit Under Test Motor / ICE / Generator / Inverters / Battery	U-M

Figure 4. Major equipment of "Course 401"

A 150kW electric motor from UQM and a 1.5L LNF internal combustion engine used for General Motors vehicles were purchased. The integration of this engine and electric motor is not trivial, and required intimate involvement from A&D and Bosch engineers to make this happen.

The lab instruction manual can be found in Appendix F.

<u>402 Automotive Power Electronics Laboratory:</u> This course covers the fundamentals of power electronics (devices, circuits, and systems) with a special emphasis on their automotive applications, including electric vehicle, plug-in HEV, HEV, and fuel cell vehicle powertrain applications. Upon completion of this course, students will develop a strong functional literacy in automotive power electronics; understand the basic operation of typical power converter circuits and their typical automotive applications, including battery energy management and motor drives; develop an appreciation for practical design issues including selection of power devices, thermal management, reliability, and EMC. A major renovation was undertaken to turn a classroom into the new power/energy undergraduate teaching laboratory. The basic laboratory equipment for nine benches were purchased, tested and integrated, including (see Figure 5)

- DC Electronic Load, 600W
- Power Supply ±25V, 1A
- Function Generator
- Digital Multi-Meter
- Oscilloscope 100 MHz
- Power measurement and analysis
- 50 MHz, AC/DC Current Probe
- 100 MHz Differential Voltage Probe
- 2MHz LCR meter
- IR and Thermometer
- Control Board

Figure 5 Equipment used in Lab of “Course 402”

This laboratory course was developed and offered in Fall 2010 as a course in the EECS department (EECS 498—section 009) with an enrollment of 24. The course is taught by another newly hired faculty member (Heath Hofmann). This lab course was updated in 2011 and is offered with a permanent course number EECS 419. 41 students are enrolled in this course in Fall 2011. Because of the increased number of students, three lab sections need to be offered. The increased lab hours enables the students to have more time to finish the labs.

In Fall 2012, this lab is offered again with a total enrollment of 47. The lab is taught by yet another newly hired faculty member Juan Rivas (he is not in the original proposing team). The lab content is very similar to what was covered in Fall 2011. From the increase in the class enrollment (from 24, to 41, to 47 in the last three offering), it is apparent this course is also now a healthy and popular course that we expect to offer regularly (most likely every year). The creation of this lab course is another success story of this DOE funded project. The syllabus of this course can be found in Appendix G.

403 Vehicle Electrification (Part B): Hydrogen and Fuel Cells: This course was developed and taught as a half-term course in Winter term 2010 (an accelerated course, students meet twice as often) with a total of 47 students, including a few from distance learning. This course is then offered in Fall 2011 as a regular (full-term) course. The instructors (Anna Stefanopoulou and Don Siegel) are continuing the development work of this course to prepare for its future offering. In its second offering, 30 students enrolled in this class in Fall 2011. The course was taught as a full-term course and this course is planned to be taught every other year after. The syllabus of this course is shown in Appendix H.

In Fall 2012, Prof. Siegel teaches an extended version of this (fuel cell and hydrogen) course, which is entitled "Atomistic Computational Modeling of Materials". This course is partly based on the course material he developed for the hydrogen and fuel cell course, but extends beyond. The course teaches molecular modeling, and covers theoretical methods and computational techniques used to predict the kinetic, thermodynamic, and mechanical behavior of materials. Students who take this course were able to use the techniques to simulate behavior in batteries, fuel cell stacks, hydrogen storage materials, and even combustion processes in internal combustion engines. Indeed, an important component of the course is a final project, wherein the students apply the introduced modeling techniques to an application of their choice. In several cases these projects have touched on technologies relevant for vehicle electrification. Although this course was not included in the original DOE proposal, it is clearly an important extension. The fact that this new course was developed so quickly is in part thanks to the DOE funding. The enrollments in this extended course were not included in the numbers we reported. The syllabus of this extended course is shown in Appendix I.

404 Electric Machines and Hybrid Drives: This course was developed and offered at the University of Michigan Dearborn campus in Winter 2010 with 47 enrollments. The course content was updated and offered again in Winter 2011. The scope of this course did not change much but the technical details were all updated. In Winter 2011 the enrollment is 25. Compared to the last year (47 students), enrollment is decreased.

However the course was first offered last year and many students among 47 students were juniors. Therefore, this year, enrollment decrease was somewhat expected. Based on the course evaluation and assessment, content on advanced AC motor drive section is shortened slightly and more time was spent on background and introduction on EV/HEV.

In Winter 2012 the course content is again refreshed. Currently the topics covered include characteristics of vehicle load, and all the popular electric machines used in electrified vehicles, including DC Motor Drives, Permanent Magnet AC Machine Drives, Induction Motor Drives, and Switched-Reluctance Machine Drives. The course ends with a few case studies including the integration of electric machines on EV, HEV, Plug-In Hybrid, and Fuel Cell Vehicles.

After the first two offering, it was decided that the course title and content should both be revised significantly. The plan was to offer the new course in Winter 2013 and the title will be changed to "Electric Machines and Drives". The main idea is to look on a broader scale the application of electric machines to automotive as well as non-automotive applications. Unfortunately, the plan to recruit a new faculty member to develop and offer this course fell short, and this course was not offered as expected in Winter 2013. However the faculty and the department are both committed to fill the position and offer this course, which has proven to be a popular and critical course. The syllabus of this course is shown in Appendix J.

405 Vehicular Power Systems and Loads: This course was developed by Prof. N. Natarajan at the University of Michigan Dearborn campus in Fall 2010. This is an introductory course on power systems and load analysis with focus on automotive applications. 20 students took this course in its first offering.

35 students enrolled in this course in Fall 2011. This is a fundamental course that covers vehicle energy analysis. The major contents include AC and DC circuits (6 hours), Concepts of real & reactive power (3 hours), Vehicular power system architecture (3 hours), AC and DC power generation and distribution (6 hours), Power flow studies (6 hours), Optimal operation (3 hours), Stability and real power control (5 hours), Reactive power control and voltage stability (3 hours), Grid control (3 hours), and
Short circuit analysis and power system protection (9 hours).

The course title and content were then revised and the new course is planned to be offered under a different title "Renewable and Efficient Electric Power Systems" every other year. Again similar to be course change planned for the 404 course, the plan is to generalize the course content to include non-automotive application to cover a wider array of applications. The topics that are currently being developed, and will be included in the next offering include: overview of power systems, power system stability, reliability, reactive power control, load flow analysis, short circuit analysis, DC and AC power grid, photovoltaic (PV) power systems, energy efficient lighting and energy efficiency in electronic systems, wind power systems, hybrid and electric vehicles.

The syllabus of this course is shown in Appendix K.

406 Green Mobility Laboratory and associated courses: At the Kettering University, the Green Mobility Laboratory was developed, together with the development of two courses that use this lab facility (see Figure 6). Kettering University has submitted a proposal to the State of Michigan to offer a certificate program that includes the two courses and laboratory funded by DOE. This certificate program will be used for retraining of unemployed engineers in HEV technology as well be part of the graduate program of Kettering. Because of the DOE support and related publicity, Kettering received two additional contracts, and that has spurred several proposals that have been sent to NSF, DOE and other companies in MI. In other words, the DOE support has created significant synergy and the impact of the lab development has gone much beyond its original scope.

Figure 6. Equipment of the Kettering "Green Mobility Laboratory"

Several courses at Kettering University were developed to take advantage of the new lab facility.

The Advanced Power Semiconductor course was developed and was taught Spring term of 2011 by Professor James Gover. This course will require relatively minor periodic updating in the future. The lectures were recorded and are available for Kettering University to use in future offerings of this course for on-line students and student in residence. Professor Gover also plan to record an 8 hour abbreviated version of this course that will be offered to all members of IEEE through its Vehicular Technology Society as a short course. He has previously recorded a 12 hour introductory course on power electronics and an 8 hour course on EV EMI that were recorded by IEEE and distributed to all members of the IEEE Vehicular Technology Society.

The Advanced Power Electronics course was taught in an exclusively classroom setting for the first time during Fall term of 2010 by Professor Gover. During summer term of 2011 Professor Gover made substantial upgrades to this course and taught it as an on-line course that again was recorded. Professor Gover also recorded an 8 hour version of this course for distribution by IEEE Vehicular Technology Society to its membership. In the Winter term of 2012 this lab course has an enrollment of 32, which is a significant increase from the previous two offerings.

The content of the Advanced Power Electronics course was revamped during the past semester. Currently, the course covers the following topics: Power Electronic Switches (Week 1~2), Power Electronics in Power Supply (Week 2~4), Power Electronics in Motor Control and Alternative Energy (Week 5~6), Power Electronics Solutions for EV/PHEV (Week7~8), and Reliability of Power Electronics Systems (Week 9~10).

Professor Bai and Professor Gover developed a new course on battery management systems (ME591) that are being offered by Professor Bai for the first time during the Fall 2011 term. The development of the laboratory component of this course is documented in the senior thesis of an undergraduate student, Mauri Yatsuri.

The enrollment of this course for Summer 2012 is 20, including 2 graduate students. The coverage of this course include Basic Concepts and Battery Chemistry (Lead-acid, Ni, and Li) (2 weeks), Battery State of Charge Estimation (1 week), Battery Modeling and Aging (1 week), Battery Charger Design (1 week), Battery Equalizer Design (1 week), Battery Thermal Management (1 week), Battery Management System Functions (1 weeks), and Battery in EV/PHEV (2 weeks).

Short courses:
Based on the content developed for the graduate courses (and to some extent, the undergraduate courses), we develop four short courses. These short courses were made available both face-to-face and through distance learning. Short courses were originally planned for the later part (3rd year) of this project. However, based on feedback we received regarding industrial needs, we developed a modular face-to-face short course series earlier in this project. The course series include education modules on hybrid powertrain, green manufacturing, battery fundamentals, battery management systems and hybrid power-train EMC, and a few others that are not related to electrified powertrain.

Prof. Chris Mi lead the first wave of short courses offering. In 2010, he developed and offered "Battery Management Systems for EV and PHEV", an 8-hour short course, to two companies. The first offering is to Delphi, with an enrollment of 50. He subsequently offered it to GM, and the enrolment is 17. In the same year, he also offered a short course "Energy efficient motors and power electronics for EV, HEV and PHEV" through SAE. This course is open to the public and the enrollment is 50.

A distance-learning version of the short course series was first offered in October 2011. Out of the eight modules (around 6 hours each), four of them were developed and taught by the ARRA project team (innovation in MFG: Jack Hu, Intro to Electrical Energy Storage: Don Siegel, Hybrid Vehicles: Huei Peng, Energy Storage, Battery Management and Battery Safety: Chris Mi). A total of 13 students participated in this short course series. These students took 4 of the 8 modules to receive a certificate.

This short course series was offered again in January-March of 2012. 14 students enrolled in this offering. There was no major content update. However we collected the feedback from the two batches of students (October 2011 and February 2012) and later revise and update the course content accordingly. In the summer of 2012, we re-captured some of the lectures, and enhanced the questions and pre-lecture materials. The modular short courses were again offered in Fall 2012 (September to December) for the third time. In the last few offerings, most of the students come from General Motors. We are working on the marketing materials to reach out to other students, and hope to see the short course cohort to grow this year.

A slightly different version of the short course was also offered at the end of September in the face-to-face format to 18 students. This short course has a little more strategy/business flavor because of the fact the course was targeting higher level managers. However, two modules (hybrid vehicles and advanced manufacturing) developed by the DOE education team participated in this short course.

Finally, in Winter 2013, the distance learning format of the short course series were offered, and the enrollments are as follows: 15 in hybrid vehicles, 16 in introduction in electrical energy storage, and 13 in innovation in manufacturing.

On retrospect, the total offering in short courses far exceeded our original plan. However, the number of students registered in each offering is lower than what we hoped to see. To enhance discussions and learning from other students, it is desirable to have 20-25 students in each cohort. The smaller class size made it harder to run these courses as the target of running short courses is to break even (not losing money). The soft demand indicates the automotive industry is still conservative financially, even for important functions such as education and training.

K-12 and Consumer Education:

<u>101 K-12 Outreach:</u>

Summer schools for high school students:
We successfully offered a summer camp for high school students for the first time in August 2010. The 3-day summer camp was held at the Ann Arbor campus of the University of Michigan. The camp is mainly staffed by the faculty members of the DOE ARRA proposal team. There were three main parts of the camp: (1) highlight transportation electrification related activities, both research and education, from the Ann Arbor campus; (2) field trip to selected local companies to give the campers first-hand experience about the current state of development related to electrified vehicles; and (3) a lab for putting together an electrified vehicle and competition. Thirteen students attended this camp in 2010.

Figure 7 Snap shots of the 2010 summer camp activities

The agenda of the summer camp is attached in Appendix L for reference. Figure 7 shows snap shots of the activities taken during the summer camp. We did not have any photos taken during the field trip to GM, Ford and ISC Transco because no cameras were allowed on those corporate properties during the visit. From the smile of these kids, it is apparent they have lots of fun, especially when their electric vehicles successfully run over mini chocolate bars—which they got to keep! The faculty members who helped with the lectures of the summer camp all comment on one thing: the kids are bright, enthusiastic, and they are so much fun to work with.

For 2011, we kept the duration of the camp at 3-day but have recruited instructors from a broader range. We were able to accommodate 17 students in the 2011 offering, with students from a wider geographical region. The camp again has a moderate size because of the limited laboratory space. We continued to emphasize on recruiting female and URM students with the goal of attracting more of them to study in the Science, Technology, Engineering and Mathematics fields. To reach that goal we again worked with regional public school systems and science teachers and target 11th graders as the main audience.

In 2011 we made many changes to the content of the summer camp. Instead of relying mostly on the proposing team, this year we have replaced many of the lectures with topics that are broader in scope and many of these new lectures were delivered by practicing professionals in the region, including lecturers from GM, Ford, Clean Cities Coalition, City of Ann Arbor transportation planning office, etc. We also decided to include a module on basic concepts, delivered by the graduate student who is designing the education kit. His lecture is very fundamental and is an excellent background introduction to the students. The response from the students was also assessed to help providing feedback for the education development team at Pennsylvania State University.

In Summer 2012, we did offer the summer camp. This is because we needed to focus our human resources (especially that of the PI) on the development of the hybrid powertrain laboratory.

It is difficult to assess the effectiveness of the summer camps, but there seems to be some anecdotal evidence. The PI has been contacted by two campers afterwards when they were applying to the College of Engineering of the University of Michigan for advice. Another camper, a 2013 Presidential Scholar winner (representing the State of Michigan) is heading to MIT to study engineering this Fall.

<u>102 Development of an Education kit for Electric Automobiles:</u> This task takes a three-prone approach, and will introduce K-12 students to vehicle electrification and hybridization. The educational outcome consists of three complimentary components: (i) a toy kit that gives users a hands-on introduction to electrified vehicles (see Figure 8), (ii) Information-rich "Educational Videos" (see Figure 9); and (iii) an educational videogame (see Figure 10) that introduces them to the components, synergies, and tradeoffs in electrified vehicle design. The overarching goal of the toolkit is to excite and educate the public about electrified vehicles, with a particular focus on outreach to K-12 institutions and the recruitment of future electrified transportation experts and engineers.

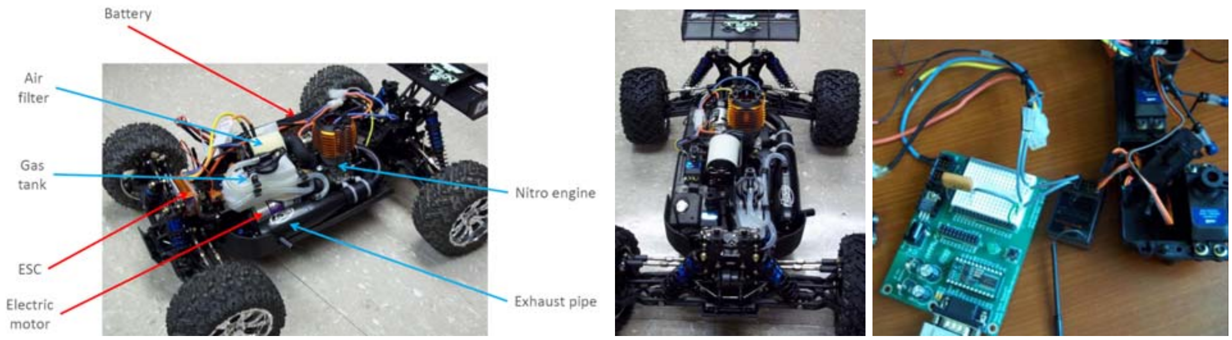


Figure 8 Developed toy kit for electrified vehicles

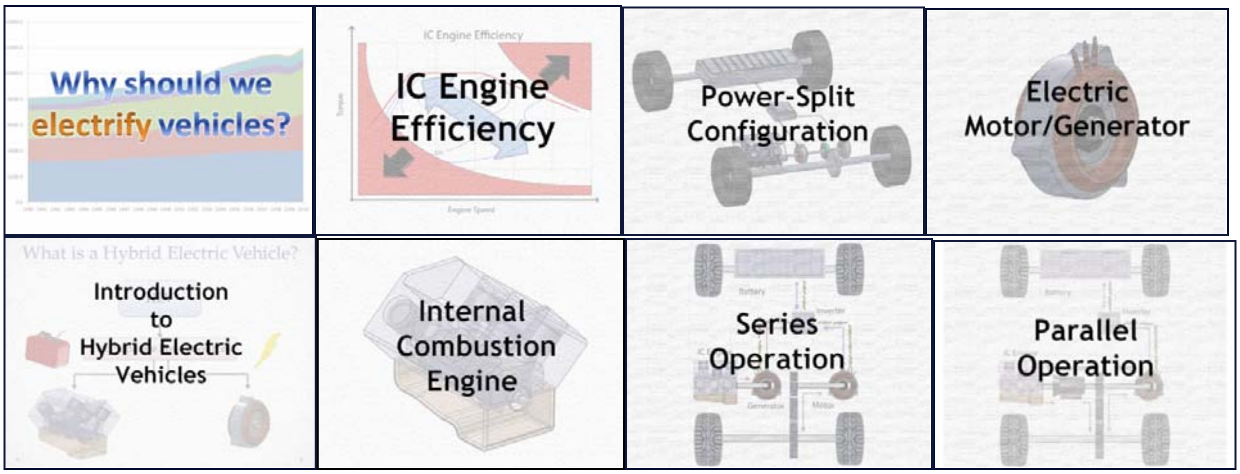


Figure 9 Educational videos

Figure 10 Developed Educational videogame

In all three elements of this educational activity, the major benefits and working principles of electrified powertrains were explained and demonstrated in simple facts and in a way that is acceptable to K-12 students. Among these three products, the design of the toy kit is by far the most challenging, and yet perhaps has the highest potential to excite kids. An ideal toy kit should allow players to construct different hybrid powertrain configurations (e.g., series, parallel, power split, etc.) from the same slate of components. We recruited two undergraduate Schreyer Honors students at the Pennsylvania State University, Mr. Nate Michaluk and Ms. Lindsay Johannes, to develop this toy kit as part of their undergraduate honors theses. A master student Michael Rothenberger leads the effort in putting the educational videos together. He also wrote his master thesis on the topic "An Interactive Multimedia Framework for Education on Vehicle Electrification".

The major achievements of this K-12 education activity are summarized in Appendix M.

Budget and Cost Share
The financial details can be found in the financial report. Regarding the required cost share, the University of Michigan has committed far more than the 20% originally required for this education grant. Just for the renovation of the laboratory for the hybrid-in-loop system laboratory, the construction cost is close to 1 Million dollars (see Appendix N), far more than the 500k required for this 2.5M project. This demonstrated the full and enthusiastic support from the University of Michigan.

Conclusion

Through this DOE supported education grant, we have developed ten courses: 4 graduate courses and 6 undergraduate courses. This includes 3 laboratories that are used to support several existing or newly developed courses. These courses significantly strengthened the curriculum of UM Ann Arbor, UM Dearborn and Kettering university in the field of electrified transportation. More than 70% of the project fund was used on infrastructure: to establish 3 laboratories. The ARRA money is thus going to have significant and lasting impact for many years to come. Over the last 7 semesters, more than 1,000 students have enrolled in these newly developed courses and received urgently needed training in the emerging field of electrified vehicles.

The course content developed for these ten courses were also used to develop several short courses that cover state of the art development in the field such as hybrid vehicles, battery systems, and innovative manufacturing. These short courses have been offered both in face-to-face and distance learning settings. More than 300 students attended these short courses.

We offered summer camp to high school students. A total of 30 students joined the camp. They not only learned from a broad range of energy related lectures, they also got a chance to visit sites in their own neighborhood to witness the cutting edge development of clean energy and clean vehicles, they also participated in model electric vehicle competitions. Attracting high school students to get engaged in these activities and make them excited about STEM as a career choice is important to ensure we will continue to have the best engineers to develop and produce future clean vehicles. This is also why we engage in the educational activities to develop toy kit, videos and videogames for K-12 students.

Appendix A. Syllabus of "Course 501" Modeling, Analysis and Control of Hybrid Electric Vehicles

The University of Michigan
Department of Mechanical Engineering
ME566 Modeling, Analysis and Control of Hybrid Electric Vehicles
Winter 2013

Instructor: Huei Peng, Professor, ME, G036 AL, hpeng@umich.edu, 734 936 0352

Objective: To cover the modeling, analysis and control of electrified vehicles, with focus on hybrid electric vehicles. Introduce the state-of-the-art development in energy conversion and storage options, modeling, analysis, system integration and basic principles of vehicle controls. Upon completion of this course, students should be able to follow the literature on these subjects and perform modeling, design, analysis and development work in this field.

Time: Mon and Wed 2:00-3:30pm (165 Chrysler)

Office hours: Tue 3:30-4:30pm (Peng, F2F), Thu 12:00-1:00pm (Peng, F2F+WebEx)
Mon 4:30-6pm (Li, F2F)
Mon 8-9pm (Peng, WebEx), Wed 10:30am-12:00noon (Li, WebEx)

Prerequisite: Knowledge in Automatic Control (ME461) is helpful but is not required. The computer package MATLAB/SIMULINK will be used extensively for example problems and homework problems. Therefore, prior experience with MATLAB is strongly recommended.

Website: The course web site will be in Ctools

Laboratory: Tu and Th 6:00-7:30pm (week 2, 3, 5, 7 and 9) Optional but highly encouraged

Grading:

4-6 Homework sets	40%
Midterm	15%
Final Project	45%

Homework: Must be handed in on the due date in class (on-campus students) or uploaded to Ctools before the specified time (distance students). Late homework will be accepted up to 48 hours late with a 20% penalty for each 24 hours (rounded up, i.e., 0 to 24 hours late = 24 hours late). All problem sets (homework assignments) are to be completed on your own. You may discuss homework assignments with your fellow students at the conceptual level, but must complete all calculations and write-up, from scrap to final form, on your own. Verbatim copying of another student's work is forbidden. If you have any questions about this policy, please do not hesitate to contact the instructor.

Project: A team project report is due by 9pm EST on April 26 (Friday).

Exams: In-class midterm on energy/combustion/control concepts. No make-up examinations will be scheduled.

Course Outline:

Lec.	Date	Lecture contents
1	1/9	Introduction, motivation
2	1/14	Introduction of electrified powertrain concepts. Final project ideas
3	1/16	Introduction of hybrid vehicles, current technologies
	1/21	**MLK day, no lecture**
4	1/23	MATLAB-SIMULINK review
5	1/28	MATLAB-SIMULINK review
6	1/30	Modeling of power split devices for hybrid vehicles
7	2/4	Modeling of power split devices for hybrid vehicles
8	2/6	Power split systems – two mode hybrids
9	2/11	Power split systems – two mode hybrids
10	2/13	APUs for hybrid electric vehicles – IC engine fundamentals, challenges and opportunities (guest lecturer: Jason Martz)
11	2/18	Vehicle control hierarchy and power management
12	2/20	Vehicle control hierarchy and power management
13	2/25	Hydraulic hybrids (guest lecturer: Simon Baseley)
14	2/27	Hydraulic hybrids (guest lecturer: Simon Baseley)
15	3/11	**Midterm**
16	3/13	Modeling and analysis of power split hybrid power-trains
17	3/18	Modeling and analysis of power split hybrid power-trains
18	3/20	Control of power split hybrid vehicles
19	3/25	Control of power split hybrid vehicles
20	3/27	Modeling and control of batteries
21	4/1	Modeling and control of batteries
22	4/3	Vehicle Controls Fundamentals for Power Split Hybrid (guest lecturer: Ming Kuang, Ford)
23	4/8	Major design issues and consideration of Hybrids
24	4/10	Emission issues, environmental impact of hybrids
25	4/15	Fuel economy test of PHEV
26	4/17	Grid integration
27	**4/22**	**Final Project Presentation**

Appendix B: Content of “course 502” Modeling and Control of Battery Systems

ME 599 Course Schedule

Overview and Attributes of Storage Systems, Batteries, Li Chemistries
Battery Equivalent Circuit Models (HW1)
Characterization of OCV-R Battery Model (HW2)
Constant Curent Constant Voltage (CCCV) Protocol
Battery Parameterization – HW3
Electrode Thermodynamics & Kinetics (Bulter Volmer)
Potentiostatic Operation (HW4)
Electric Potential & Diffusion + Electrochemical Model Summary
The Evolution of Diffusion - Spherical Diffusion Dynamics
Review and loose ends
MID-TERM
Single Particle Diffusion Model (HW5)
Potentials and Voltage Response of the Single Particle Model (HW6)
SOC definitions in Electrochemical Model + Battery SOC- Fuel Gauge (Open Loop)
SOC Estimation (Closed Loop) + Tuning the SOC Estimation Gain (HW7)
Cell-to Cell Balancing (HW8)
Thermal Dynamics
Thermal Management (HW9)
Neutron Imaging and other Diagnostic Techniques
Laboratory Visit & Electrodes & Fab in Glove Box
Field Trip: Pack Assembly annd Manufacturing Plant
Final Lecture: Review and Q&A
Final Exam

Appendix C. Syllabus and the Agenda and flyer of the Workshop for "Course 503"

ME599/IOE591 Green Energy Manufacturing (2 credits)

3:30 - 5:30pm, Tuesday and Thursday (EECS 1008)

Winter 2011

Instructor: S. Jack Hu, Professor, ME & IOE, jackhu@umich.edu, 734 615-4315
Judy Jin, Associate Professor, IOE, jhjin@umich.edu , 734 763-0519

Objective: To introduce the physics and manufacturing processes of clean energy generation, storage and conversion devices, such as solar cells, lithium batteries, wind power, electrification vehicles, etc. To cover in detail the manufacturing and assembly processes of components and systems, and quality and reliability testing methods for these devices.

Course Outline:

Lecture		Topic
		Part I: PV manufacturing
1	3/8	Introduction: motivation, PV principles, and materials
2	3/10	PV system, performance metrics
3	3/15	Thin film cell production: TCO sputtering process
4	3/17	Thin film cell production: CIGS deposition process
5	3/22	Module assembly process: gridline printing process
6	3/24	Efficiency testing and accelerated life testing
		Part II: Lithium batteries
7	3/29	Introduction: Battery types and structure
8	3/31	Cell manufacturing
9	4/5	Assembly and packaging
10	4/7	Quality assurance
11	4/12	Testing and performance
		Part III: Others
12	4/14	Guest lecture: Electrification vehicle and fuel cell (Prof. Huei Peng in ME)
13	4/19	Guest lecture: Wind turbine system (Joseph Abbud, VP, Danotek Motion Technologies)

Course grading policy:

- Homework: 40%
- Exam (open notes): 30%
- Project: 30%

GREEN ENERGY

MANUFACTURING WORKSHOP

Co-chairs: Jack Hu jackhu@umich.edu | Judy Jin jhjin@umich.edu

UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING

ATTEND THIS ONE-DAY WORKSHOP TO BE PART OF A FORUM THAT BRINGS TOGETHER INDUSTRY AND ACADEMIA TO FOCUS ON GREEN MANUFACTURING OPPORTUNITIES, CHALLENGES, AND EDUCATIONAL AND TRAINING NEEDS

SPEAKERS

Welcome Remarks
- Huei Peng, InterPro Director, Professor ME, U-M

Session 1 Wind Energy System Manufacturing
- Dawn White, CEO, Accio Energy, Inc.
- Joseph Abbud, VP Manufacturing, Danotek Motion
- Chandra Yerramalli, GE

Session 2 Lithium Battery Manufacturing
- Jeff Abell, Lab Group Manager, General Motors Corp.
- A123 (invited)

Session 3 Solar PV Manufacturing
- Jay Guo, Associate Professor EECS, U-M
- Michael Mills, Chief Scientist, Dow Solar Solutions
- Jeff Yang, Vice President, Technology, Uni-Solar
- John Wakeman, Owner, SUR Energy

Session 4 U-M Research and Educational Activities for Manufacturing Scale Up
- Jack Hu, Professor ME and Associate Dean CoE, U-M
- Judy Jin, Associate Professor IOE, U-M

Concluding Roundtable Discussion

A University of Michigan College of Engineering event, the Green Energy Manufacturing Workshop is made possible by a grant from the U.S. Department of Energy.

OCTOBER 19, 2010

8:30 a.m.–5:00 p.m.
University of Michigan
Room 1670, Computer Science
Engineering Building (CSE)
2260 Hayward
(registration begins at 7:30 a.m.)

WHO SHOULD ATTEND

The workshop will be of interest to a wide range of business leaders, researchers, engineers, students, non-profit organizations, and others who are interested in advancing education and technology for mass production and sustainable energy system development.

THIS WORKSHOP IS FREE BUT BY INVITATION ONLY.

If you did not receive an invitation and would like to attend, we encourage you to submit your request at **GreenEnergyMfg.engin.umich.edu**
You will be notified if seating is available. You may also call (734) 647-7200 or send an email to meonline@umich.edu.

See reverse for workshop schedule

Visit **GreenEnergyMfg.engin.umich.edu** for more information and to register. You may also call (734) 647-7200 or send an email to meonline@umich.edu

Michigan**Engineering**

Part I: PV manufacturing
Introduction: motivation, PV principles, and materials
PV system, performance metrics
Thin film cell production: TCO sputtering process
Thin film cell production: CIGS deposition process
Module assembly process: gridline printing process
Efficiency testing and accelerated life testing
Part II: Lithium batteries
Introduction: Battery types and structure
Cell manufacturing
Assembly and packaging
Quality assurance
Testing and performance
Part III: Others
Guest lecture: Electrification vehicle and fuel cell (Prof. Huei Peng in ME)
Guest lecture: Wind turbine system (Joseph Abbud, VP, Danotek Motion Technologies)

Appendix D. Syllabus of "Course 504" Infrastructure for Vehicle Electrification

University of Michigan
Department of Electrical Engineering and Computer Science

EECS598 - Infrastructure for Vehicle Electrification
Fall 2010

Course Administration and Outline

Instructor: Professor Ian Hiskens
4437 EECS Building
Phone: (734) 615-7076; Email: hiskens@umich.edu
Office hours: Wednesday and Friday 10:30-11:30am

References: Course material will build primarily upon technical reports and papers, which will be made available throughout the course.
J.D. Glover, M.S. Sarma and T.J. Overbye, *Power System Analysis and Design, 4th Edition*, Thomson, 2008.

Web Site: All course material will be published on CTools.

Assessment: Four homework assignments (30%)
Project (40%)
Final exam (30%)

Topics:

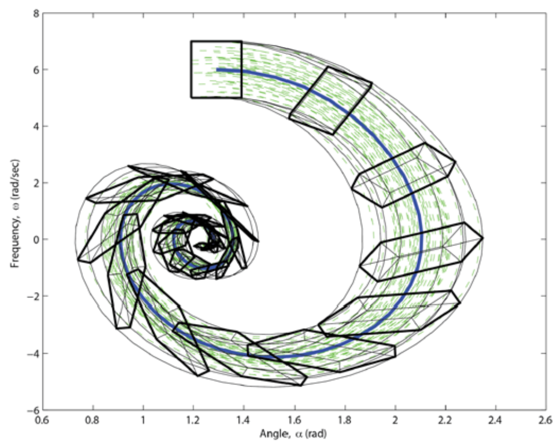
1. Overview of power systems
2. Local power system infrastructure
   - Distribution system topology; Supply connections; Transformers: tapping, heating/cooling; Protection; Voltage regulation; Reliability; Vehicle-to-grid integration.
3. Vehicle-grid interface
   - Grid-to-vehicle and vehicle-to-grid converter technologies; Standards; Safety systems; Quality-of-supply; Information transfer.
4. Global power system infrastructure
   - Daily load variation; Generation scheduling; Large-scale integration of PEVs.
5. Communications infrastructure
   - Information requirements for smart/dumb charging; Advanced metering infrastructure; Smart meters; In-home networks; Data management.
6. Control
   - Time-based and price-based load shifting strategies; Direct control; Hierarchical control structures; Valley filling control; Tracking control: smoothing renewable generation variability.
7. Business models for ubiquitous charging.

Appendix E. Syllabus of a new undergraduate course, developed to complement "Course 504".

EECS 598-2 Special Topic

Power System Dynamics and Control

Wednesday and Friday, 10:30am-12:00pm
Fall 2012



The course will introduce angle and voltage stability concepts and consider control strategies for improving dynamic performance. It will provide an overview of nonlinear dynamical systems, including geometrical properties of solutions, Lyapunov methods for approximating the region of attraction, and bifurcation analysis. Models of dominant dynamical devices, including synchronous machines, wind-turbine generators and tap-changing transformers, will be developed. The switched differential-algebraic structure of these models will be considered in the context of hybrid dynamical systems. Small distrubance (linear) analysis techniques will be developed, and applied to tune stabilizers for damping improvement. Methods for assessing large disturbance (nonlinear) behavior of power systems will be considered. Numerical integration forms the mainstay for such analysis. The variational equations describing the evolution of trajectory sensitivities will be developed, and methods for their efficient computation will be established. It will be shown that these sensitivities underpin shooting methods for solving a range of inverse problems relating to parameter estimation, grazing phenomena and limit cycles. Future control strategies will be considered, including coordinating the response of large numbers of loads to fluctuations in renewable generation, and the use of model predictive control for alleviating cascading outages.

Syllabus:

1. Overview of angle and voltage stability concepts, nonlinear dynamical systems, geometrical properties of solutions, Lyapunov methods, bifurcation analysis.
2. Modeling, differential algebraic systems, hybrid dynamical systems.
3. Small disturbance (linear) stability analysis.
4. Large disturbance (nonlinear) analysis, numerical integration, trajectory sensitivities, shooting methods, parameter estimation, grazing, limit cycles.
5. Future grid responsiveness, non-disruptive load control, model predictive control.

Prerequisites: EECS 463 (or Permission of Instructor).

Course Director: Prof Ian Hiskens, Electrical Engineering and Computer Science.
For additional information contact <hiskens@umich.edu>.

Appendix F. Lab document for 401 I-HES which shows the detailed lab design and work

Instruction to Hybrid Vehicle Dynamometer Lab

October 24 1012

The purpose of this document is to provide an introduction of the overall design of the test cell. Some technical details such as engineering sketch can be found in "Final tech proposal from AND.pdf" and "11-SYS-000096_P6_2011-11-02.pdf"

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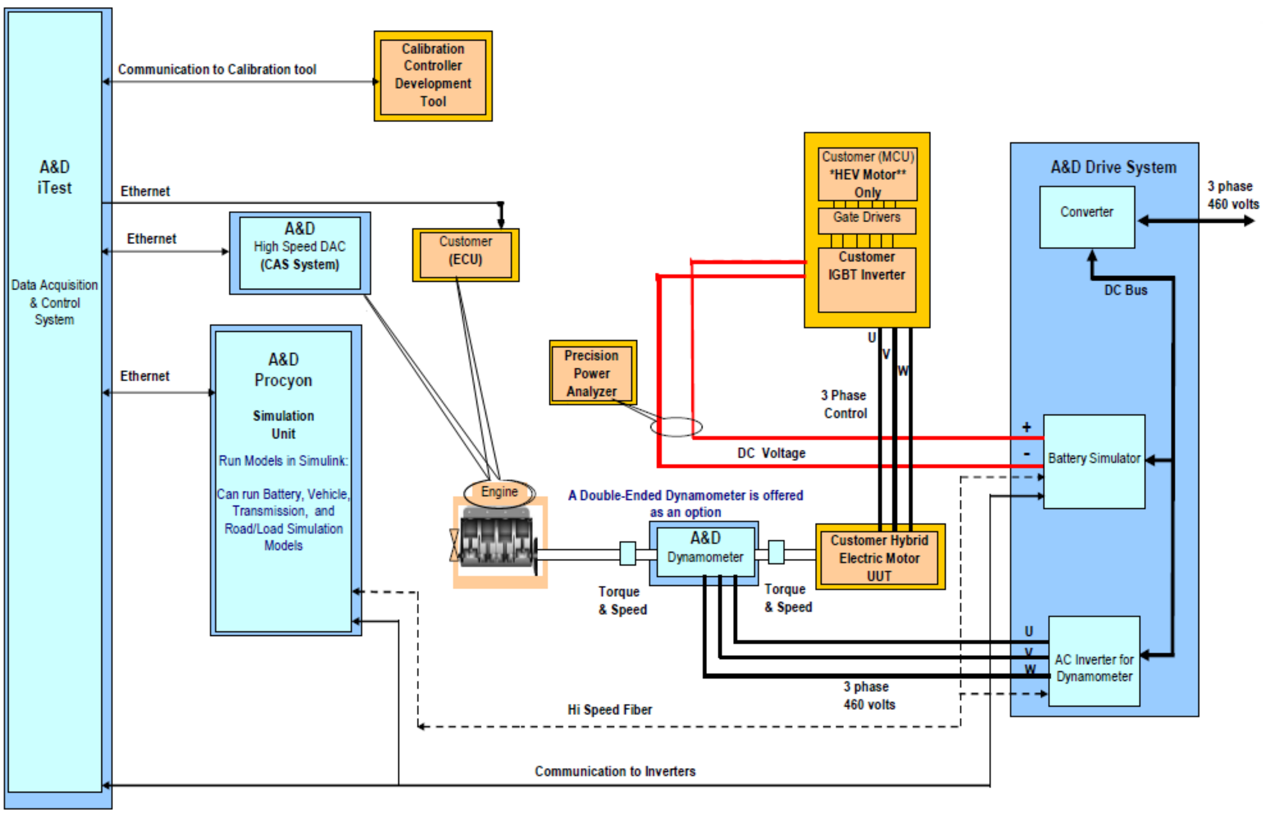
1. System Schematic – HEV Test Stand Configuration[1]

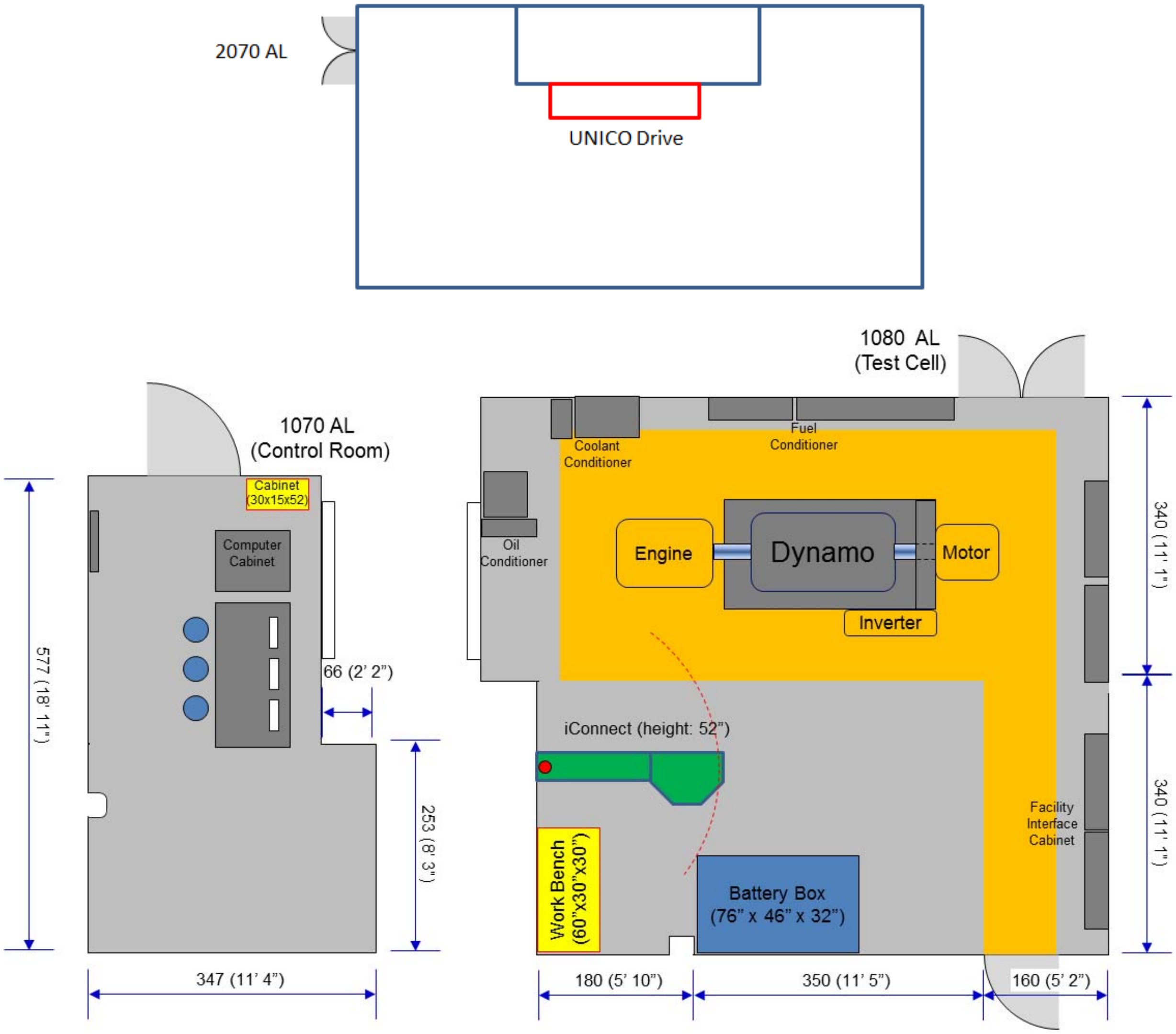
The HEV Lab consists of a control room (1070 AL), a test cell (1080 AL), and a power supply system (located inside the large storage room 2070 AL). The control room contains four computers for user interface and data acquisition, including the A&D iTest computer (user interface), the A&D High Speed DAC (CAS computer), the A&D Procyon, and the RT-PC (the computer running in background together with iTest). The test cell contains the powertrain elements (engine, motor), their controllers (ECU, MCU, and motor inverter), accessary equipment (coolant, oil, and fuel conditioners), and safety equipment. The power supply system includes an AC inverter for Dynamometer, a battery simulator, and a converter.



[1] Basic and advanced test cell configurations are shown in Appendices A and B. More details about the operation of the software can be found in a separate document "iTest iConnect Overview.ppt"

2. Hybrid Vehicle Dynamometer Lab. Configuration

The HEV Dynamometer Lab consists of three rooms. Control compenents are in Control room (1070AL). Test Cell compoents are in Test Cell (1080AL). Power Supply(Unico Drive) is in 2070AL. The overview of these three rooms can be found in the figure below

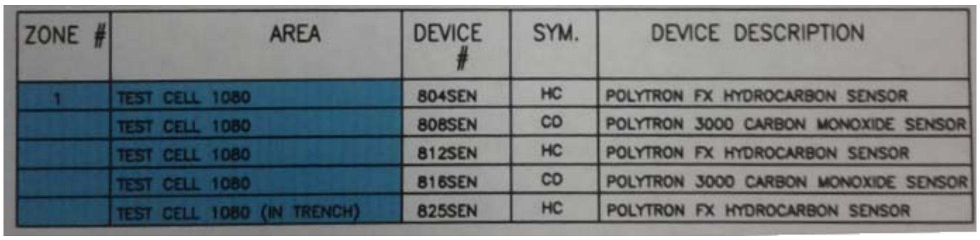


3. Lab Safety Systems

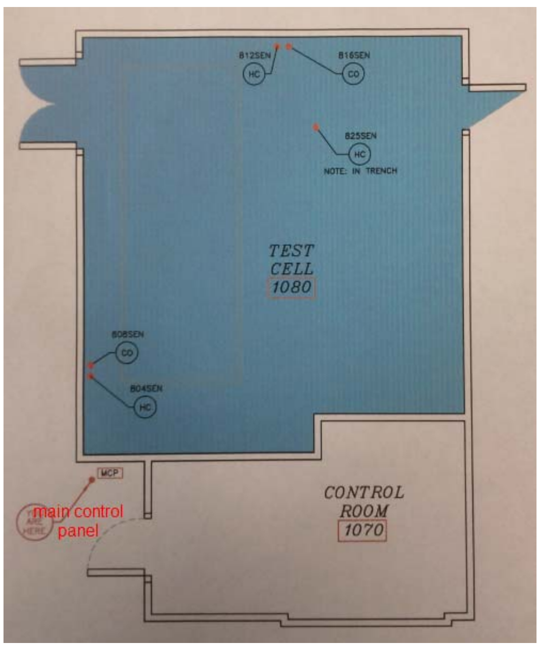
3.1. Gas Detection System

3.1.1. Gas detectors

A total of 5 gas detectors were installed in the test cell. The list of detectors and their locations are shown in the following figures:



ZONE #	AREA	DEVICE #	SYM.	DEVICE DESCRIPTION
1	TEST CELL 1080	804SEN	HC	POLYTRON FX HYDROCARBON SENSOR
	TEST CELL 1080	808SEN	CO	POLYTRON 3000 CARBON MONOXIDE SENSOR
	TEST CELL 1080	812SEN	HC	POLYTRON FX HYDROCARBON SENSOR
	TEST CELL 1080	816SEN	CO	POLYTRON 3000 CARBON MONOXIDE SENSOR
	TEST CELL 1080 (IN TRENCH)	825SEN	HC	POLYTRON FX HYDROCARBON SENSOR



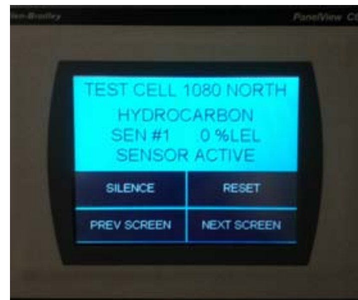
The gas detection levels are programmed as follows:

	Sensor Color	Warning	Danger	Sensor #
HC	Blue	10% (5 sec)	20% (5sec)	1, 3, 5
CO	Black	25 ppm (5min)	35 ppm (30sec)	2, 4

If the detection system is in warning status, the dynamometer will have a power-off coast down and the warning light on the wall will flash. If the gas level reaches the danger level, alarm will sound. The alarm sound will continue until someone presses the silence button on the control panel outside of 1070 AL. Once the alarm sounds, the building manager and university public safety office will also receive calls and they will arrive at the test cell to investigate the cause of the alarms.

3.1.2. Control Panel

The main control panel is in the hallway (see the above figure) outside of 1070 AL. You can see the current levels of detected gases. You can also reset the system.



3.2. Ventilation

The test cell and control rooms have a strong air ventilation system. The control panel is in Control Room. All three knobs should be set to the ‘on’ position whenever a lab is in session.

3.3. E-Stop Buttons

There are several E-Stop (Emergency Stop) buttons. The yellow one in the control room is a soft stop button (see photo below, system will coast down). The detailed functions of this stop button are defined in iTest.

There are two red buttons in the test cell, located on the East side and the West side of the room, respectively. Both will shut down the power to the AND power/signal when pressed.

4. Hardware

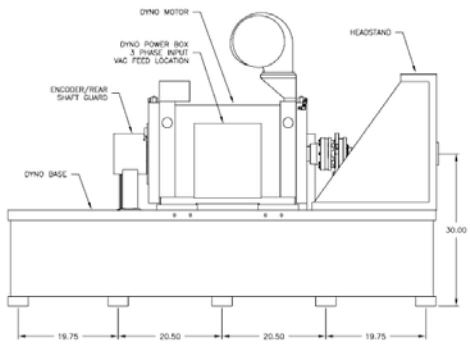
4.1. List of Hardware

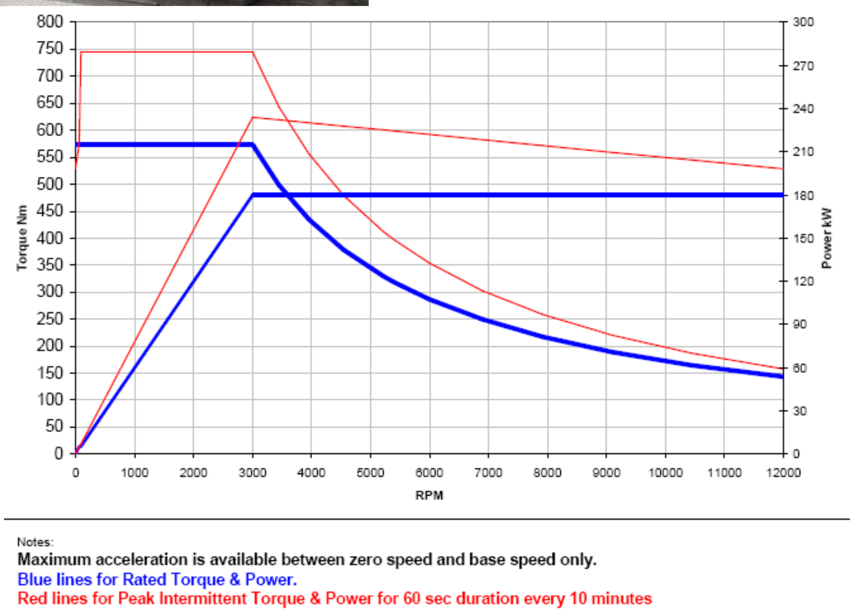
1) **241HP (180kW) AC Dynamometer System**
2) **180 kW Battery Simulation System**
3) **Test Motor/Inverter for Test Motor**
4) **Engine**
5) **iConnect Distributed I/O System**
6) **Facilities Interface Cabinet (FIC)**
7) **A&D Coolant Conditioner**
8) **A&D Oil Conditioner**
9) **A&D Fuel Conditioner**
10) **Procyon Simulation and Control System**
11) **High Speed Combustion Analysis System (CAS)**
12) ECU
13) ETAS
14) **Electric/Electronic Rack**
15) Operator Control Console
16) iTest Data Acquisition and Control System
17) Interconnect Materials (cables, conduits, for A&D supply)
18) Bedplate
19) Phoenix CAS PC
20) Transducers for Cylinder Pressure Measurements
21) ~~A&D Throttle Actuator (Not used)~~

4.2. Dynamometer[2]

The dynamometer is built on a cast iron foot mount frame with the following features:

- Air cooling fans installed directly on the dynamometer
- Fitted with an in-line torque flange and an optical shaft encoder.
- Protected with temperature switches with an alarm at 130 degree C and shutdown at 150degree C.
- Equipped with bearing temperature sensors.





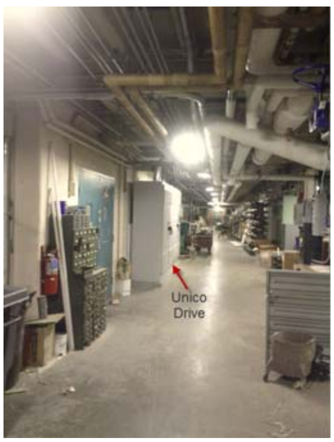
Base Speed	3,000 rpm
Max. Speed	1,2000 rpm
Inertia	0.68 kg-m^2

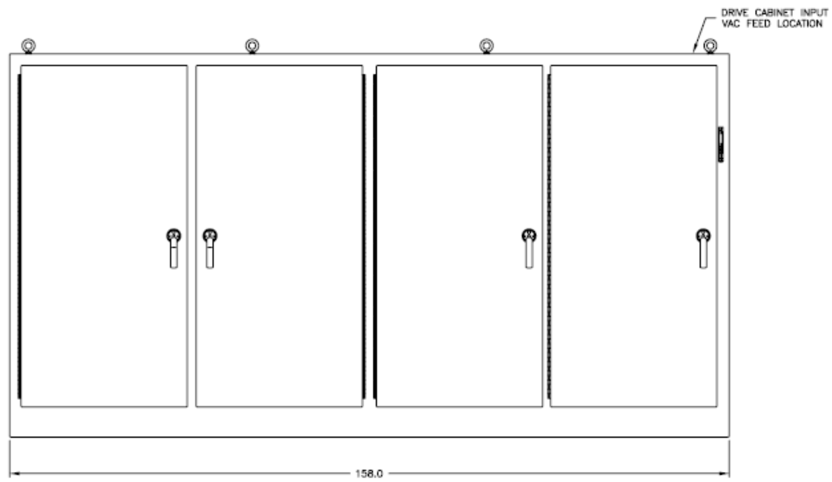
[2] See more detail at 11-000096-A15 of the drawing file (11-SYS-000096_P6_2011-11-02.pdf) and the page 80 of "Final tech proposal form AND.pdf"

Max. Acceleration	10471 rpm/s	
Rated Power	180 kW	241 hp
Max. Power	234 kW	314 hp
Rated Torque	573 Nm	423 lb-ft
Max. Torque	740 Nm	550 lb-ft
Max intermittent power tapers off from base to max speed		

4.3. Drive System (Unico Driver)[3]

The Unico driver is located in 2070 AL. If the room is locked (very rare), ask Bill Kirkpatrick (1058 AL) to help to open the room.





The driver consists of an AC/DC converter, a DC/AC inverter for the dynamometer, and a battery simulator for the test motor.

- The AC/DC converter transforms 460VAC to DC.
- The inverter in Unico driver converts DC to 3-phase AC (460 Volts) to supply it to the motor of the dynamometer. It has a regenerative capability.
- The battery simulator can modulate the DC voltage (600A, 200-600VDC). It supplies the DC to the inverter located next to the UQM motor (test motor).

4.4. Motor Specifications[4]

SPM286-149-2 Motor/Generator

[3] See more detail at 11-000096-A14 of the drawing file (11-SYS-000096_P6_2011-11-02.pdf) and the page 83 of "Final tech proposal form AND.pdf"

[4] See "PP150 Spec Sheet 7.14.10.pdf" for more information

Peak Power:	200 hp 150 kW
Continuous Power at 3000 rpm	134 hp 100 kW
Peak Torque	480 lbf-ft 650N-m
Continuous Torque	295 lbf-ft 400N-m
Maximum Speed	5000 RPM
Maximum Efficiency	95%
Power Density (based on 150kW)	0.96 hp/lb 1.57 kW/kg

4.5. Engine Specifications[5]

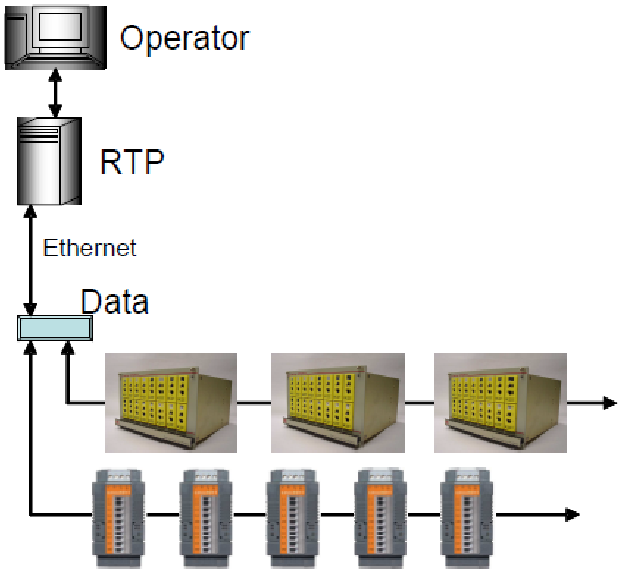
Ecotec 2.0L I-4 VVT DI Turbo

Type:	2.0L I-4 VVT DI Turbo
Displacement (cu in / cc):	121.9 / 1,998
Bore & stroke (in / mm):	3.4 x 3.4 / 86 x 86
Compression ratio:	9.2:1
Output (kW / hp @ rpm):	194 / 260 @ 5300 (est.)
Torque (lb-ft / Nm @ rpm):	260 / 353 @ 2000 (est.)
Max engine speed (rpm):	5500 (est.)

[5] The hard copies of the engine manual are on the table of control room. We may place the books in some of the cabinets.

4.6. iConnect Distributed I/O System [6]

The basic system architecture includes an Ethernet connection to the host controller from the e.Gate (data concentrator), which supports four Localbus networks to individual I/O modules. The I/O modules are offered in two distinct packaging options: DINrail modules with screw terminal connections (inside the Facility Interface Cabinet, FIC) and iConnect modules with quick connector jacks (in the Boom).



System Diagram

4.6.1. e.Gate Data Concentrator

The data concentrator that gathers channel values from individual I/O modules. It provides data synchronization of all local I/O to a 10 µs window, and 1 ms for system level I/O if more than one concentrator is used in the system. All data samples are time-stamped at the concentrator to ensure data alignment at the host controller regardless of the number of I/O channels deployed.

4.6.2. I/O Modules

- **DINrail Mounting** with screw terminals for individual module placement in the test cell
- **19" Rack Mount** configuration packaged in an iConnect enclosure
- **Thermocouple Types B, E, J, K, L, N, R, S, T, U**
    - 19 Bit A/D Resolution
    - Cold Junction Compensation
    - Accuracy 0.01%
    - Common Mode 100V
    - Galvanic Isolation 500V

[6] For more information, see p. 44 of "Final tech proposal form AND.pdf"

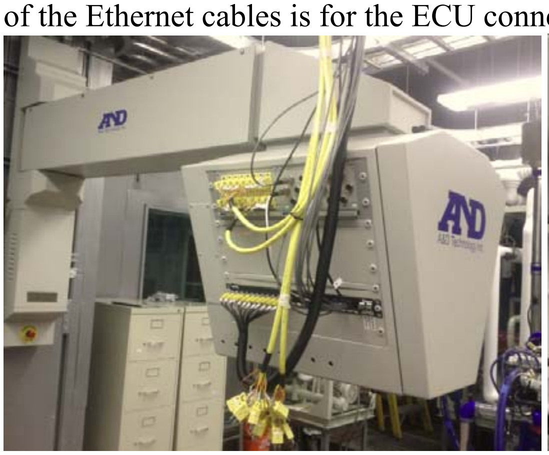
- **Voltage Analog Input: ±10VDc**
    - Built-in Signal Conditioning: Common mode 500V
    - 19 Bit A/D Resolution: Accuracy 0.01%
    - Galvanic Isolation: Analog Output: ±10VDc or 0 – 20mA
    - 16 Bit A/D Resolution at 100 samples/sec
    - Common mode 100V
    - Galvanic Isolation 500V
    - Refresh Time 1mS per Output Channel
- **Digital I/O**
    - Switching Capacity 250VAC/8A, 30VDC/8A
    - Galvanic Isolation
    - Common Mode 100V
    - Galvanic Isolation 500V
- **RTD Analog Input**
    - Pt 100, Pt 1000 Resistance
    - 19 Bit A/D Resolution
    - 10Hz Sample Rate Per Channel
    - Accuracy 0.01%
    - Galvanic Isolation 500V
    - Common Mode 100V

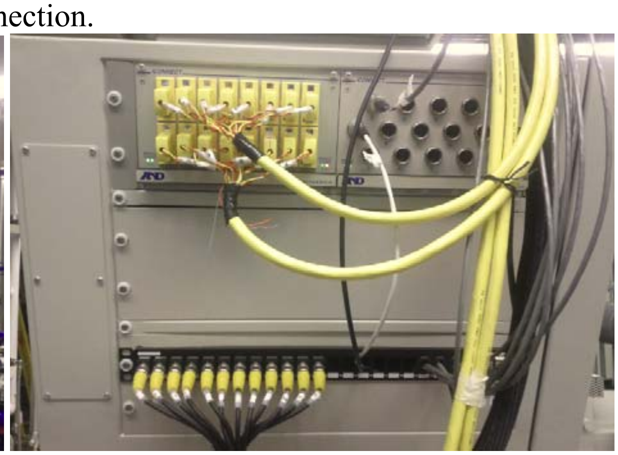
- Sigma-Delta Conversion Method

- **Additional Features**
    - Frequency, Counter and Quadrature (with direction)

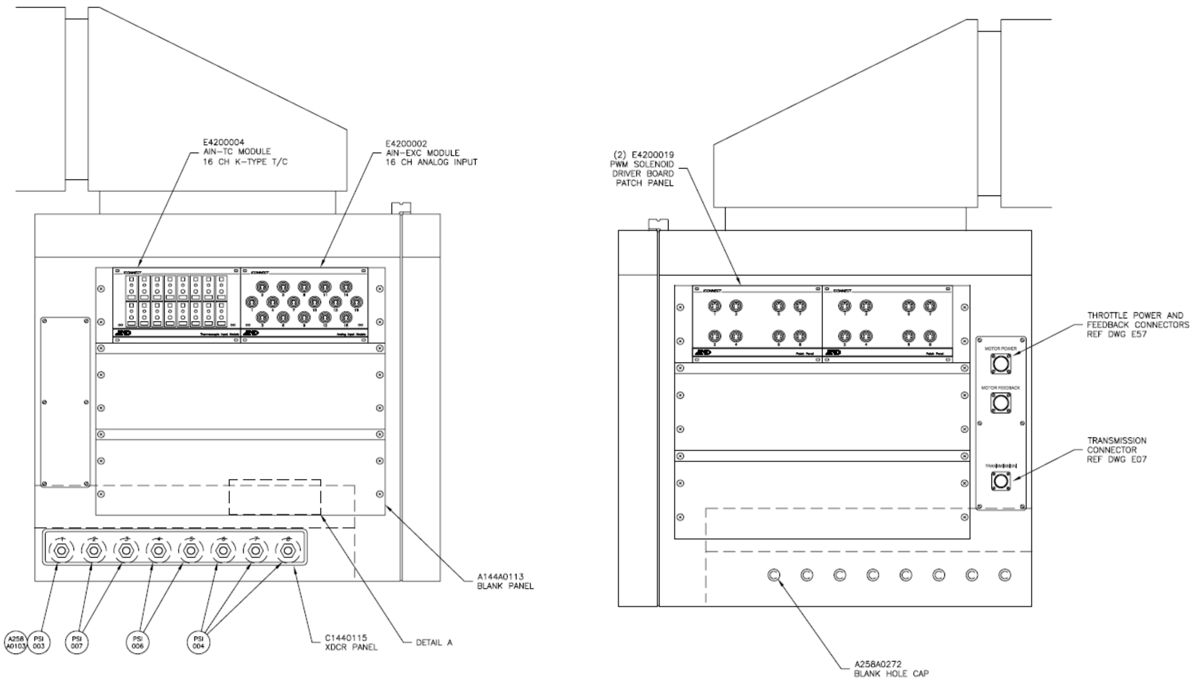
4.6.3. iConnect Boom Arm Assembly

It is a modular signal interface system that is an in-cell unit and contains signal input and output connections to/from the iTest DAC System (FIC). The boom arm rotates 180 degrees. We added 12 BNC connectors and 2 Ethernet connectors. 12 BNC cables and 2 Ethernet cables are linked to the control room (not to FIC). The BNC cables are for high speed measurements (CAS)[7]. One of the Ethernet cables is for the ECU connection.

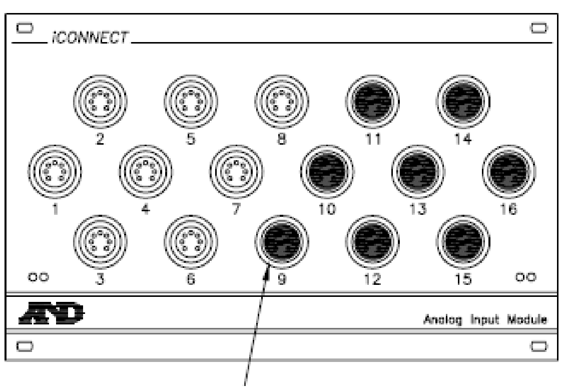




[7] The signal list for CAS is in "signal list.xlsx"



- Only 8 analog input plugs are available (as of Oct 2012, two are used, for intercooler water valve position feedback, and the lambda sensor). The rest (8 channels) are already used for pressure transducers (see figure below, connected inside the boom head but not from the outside). The pin map of the plug is in the drawing file[8].



The balck colored channles are for pressure transducers.

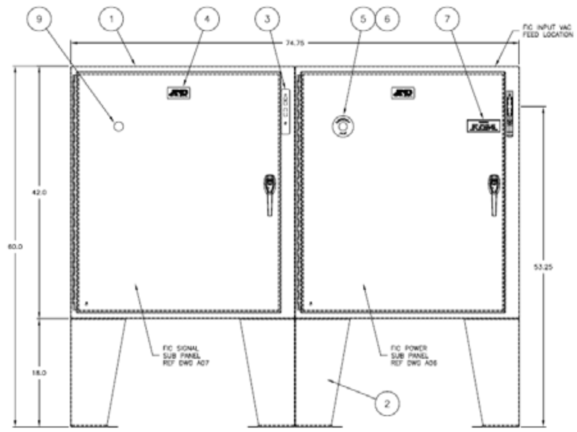
The channel names for the plugs are as follows:

Number	Channel Name
1	ai_01_03_15_01
2	ai_01_03_15_02
3	ai_01_03_15_03

[8] See more detail at 11-000096-E33 and E34 of the drawing file (11-SYS-000096_P6_2011-11-02.pdf).

4	ai_01_03_15_04
5	ai_01_03_16_01
6	ai_01_03_16_02
7	ai_01_03_16_03
8	ai_01_03_16_04

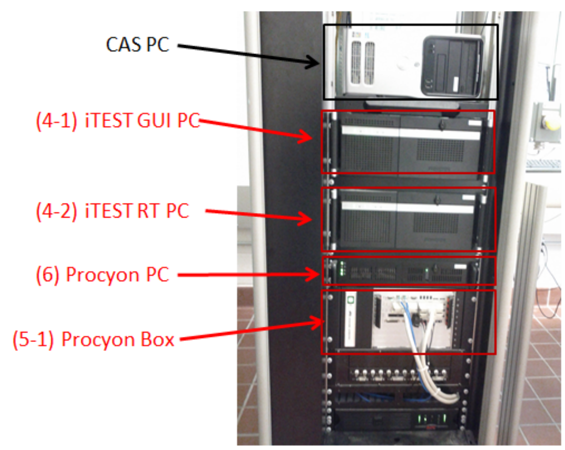
4.6.4. Facilities Interface Cabinet (FIC) [9]



Facilities Interface Cabinet (FIC) is an integral part of our transmission dynamometer equipment. It consists of

· e.Gate Data Concentrator
· CellMinder Safety System
· Instrumentation Power Supplies
· (12) K-Type Thermocouple Channels
· (24) Digital Output Channels
· (32) Digital Inputs Channels
· (24) Analog Output Channels
· (26) Analog Input Channels

4.6.5. Real-Time Processor (RTP)



RTP run the tests, schedule, read/write the I/O values, monitor limits and log real-time test data. Once the test is selected, the schedule, limits and I/O channel lists are downloaded to the PC processor the user has full control over the test article.

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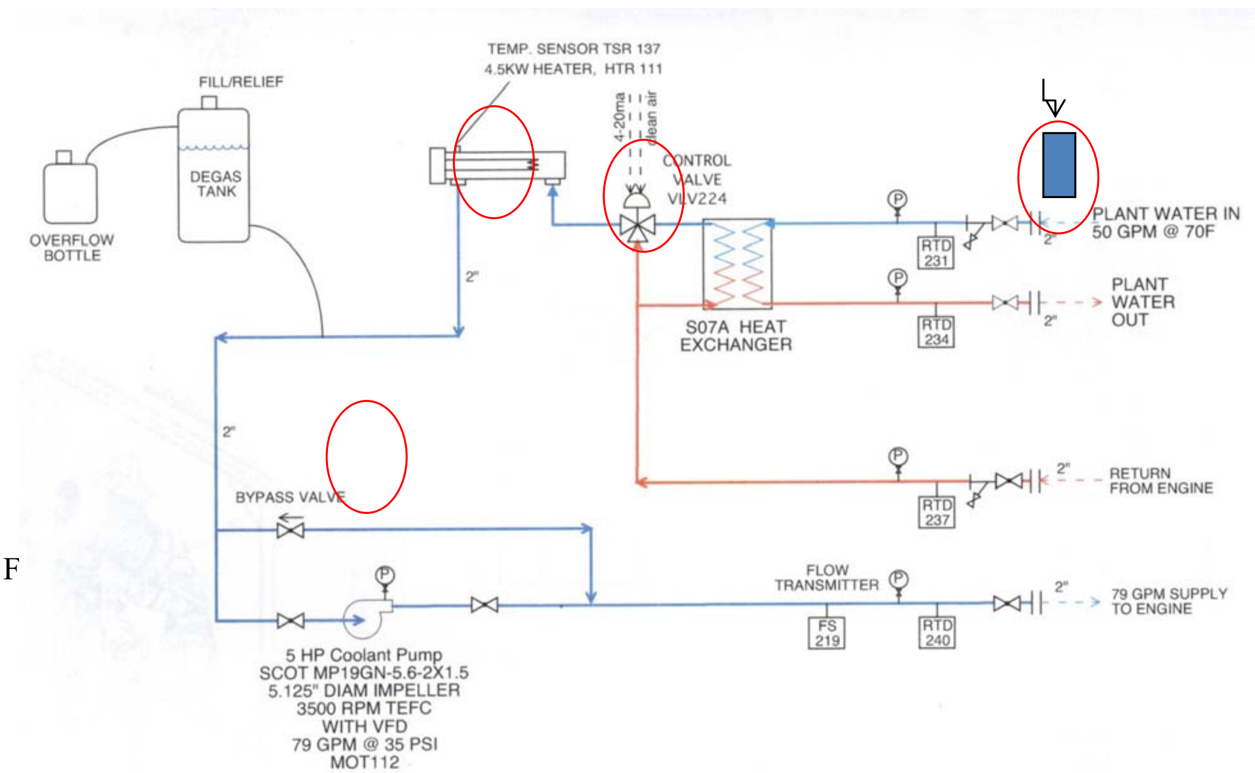
[9] See more detail at 11-000096-A05, A06, A07 of the drawing file (11-SYS-000096_P6_2011-11-02.pdf). The channel drawings are in 11-000096-E41 ~ E55.

4.7. Coolant Conditioner [10]

The coolant conditioner controls the temperaure of the coolant. In iTest, the temperature controlled at the temperature set-point or valve position set-point. It provides coolant to the test motor or test engine. To open the cabinet door, use a large "–" driver to turn

Water valve: remotely controlled



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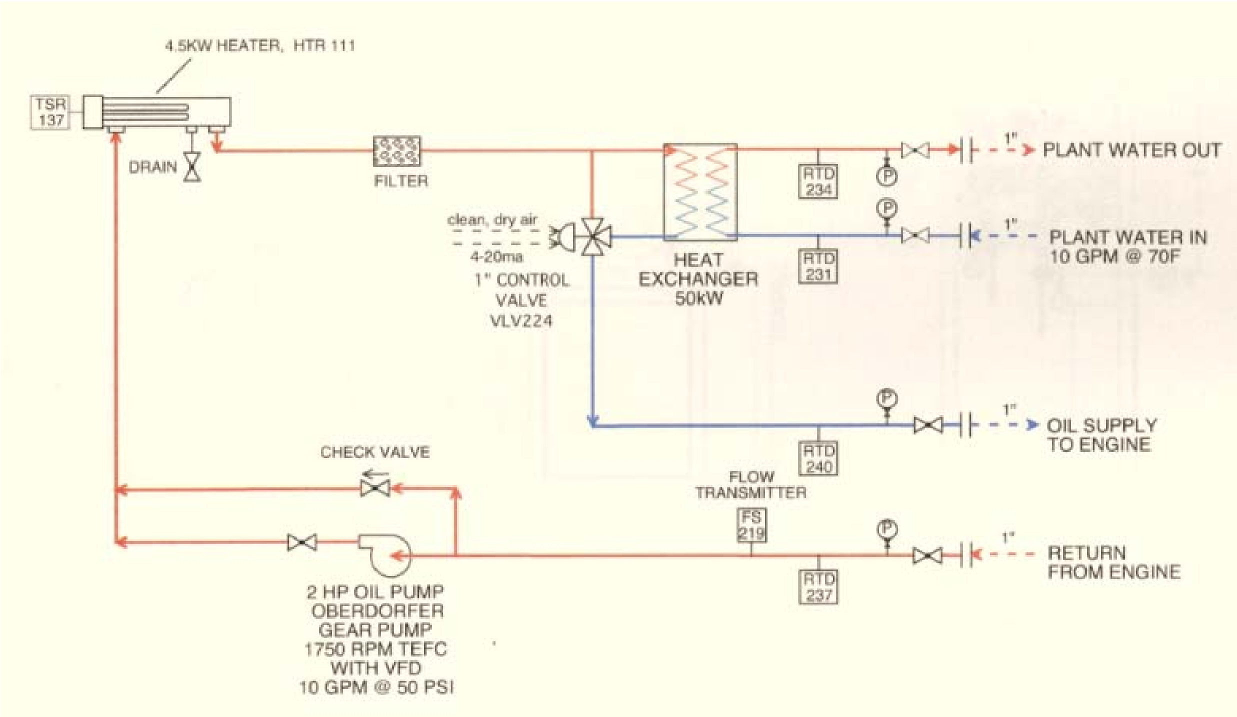
[10] The manual and drawings are in the control cabinet. More information is in the page 95 of "Final tech proposal form AND.pdf"

4.8. Oil Conditioner[11]

The oil conditioner regulates the temperaure of the engine oil. In iTest, the temperature controlled at the temperature set-point or valve position set-point. The oil ciculation starts when the engine runs.



Four controllable devices:

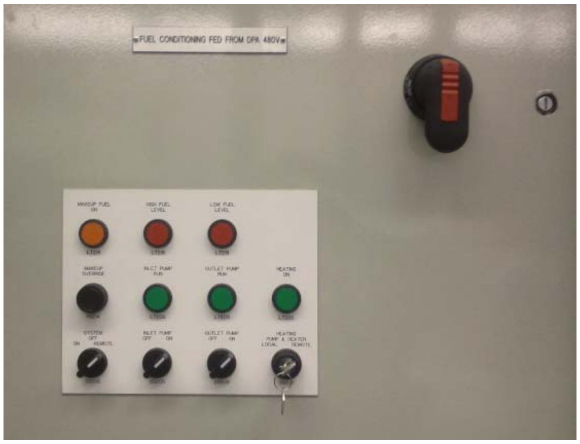
1. Water valve: on/off (set at fixed value in iTest)
2. Heater: on/off (for heating, turned off)
3. Oil Pump: 4mA-20mA (set at fixed value in iTest)
4. Heat exchanger valve (for cooling)

[11] The manual and drawings are in the control cabinet. More information is in the page 97 of "Final tech proposal form AND.pdf"

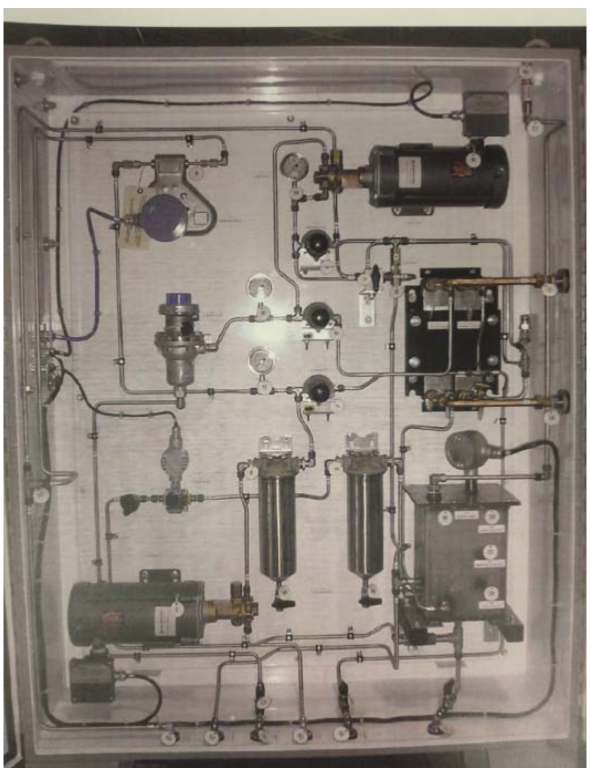
4.9. Fuel Conditioner[12]

The fuel conditioner regulates the temperaure and pressureof the fuel. The electric circuit and the fulid circuit drawings are in the test cell.

Control panel:



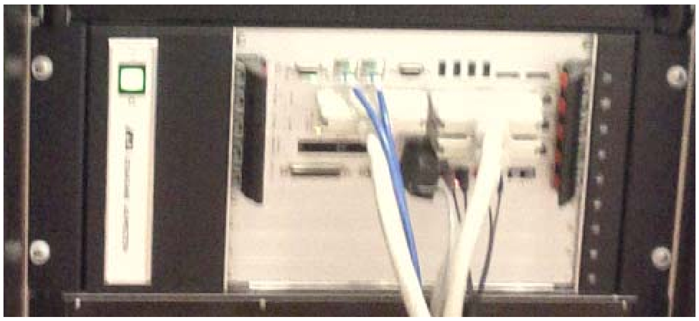
Fuel conditioning cabinet



[12] More information is in the page 99 of "Final tech proposal form AND.pdf"

4.10. Procyon Simulation and Control System[13]

Procyon is a ultra-high-performance real-time simulation and control platform. With A&D's VirtualConsole as a visual front end, Procyon offers the real-time solution for the model-based development environment and with MATLAB/ Simulink, offers a flexible and customizable architecture. Procyon connects to the UNICO drives using a high speed fiber optic interface.



[13] For more information, see p. 65 of "Final tech proposal form AND.pdf"

4.11. High Speed Combustion Analysis System (CAS), Phoenix[14]

It performs continuous data acquisition for all cylinders cycle-by-cycle. The acquired data is then processed and analyzed using CAS combustion analysis software running on aWindows XP professional PC. The results of all calculations may be logged and displayed on the host PC for instant interpretation. Calculated results can also be sent to a data acquisition and control system for closed loop control using combustion data for automated or lights out engine mapping applications. The standard Phoenix system can perform combustion analysis on up to eight cylinder engines at encoder resolutions up to 0.1degrees.
Every Phoenix system includes a 12 channel high-speed data acquisition system and CAS combustion analysis software. The high speed data acquisition system will digitize signals from in-cylinder pressure sensors and other transducers on the engine while transferring the digitized data to the host PC for analysis and display providing instantaneous feedback to changes in engine operating conditions.

Phoenix Data Acquisition System

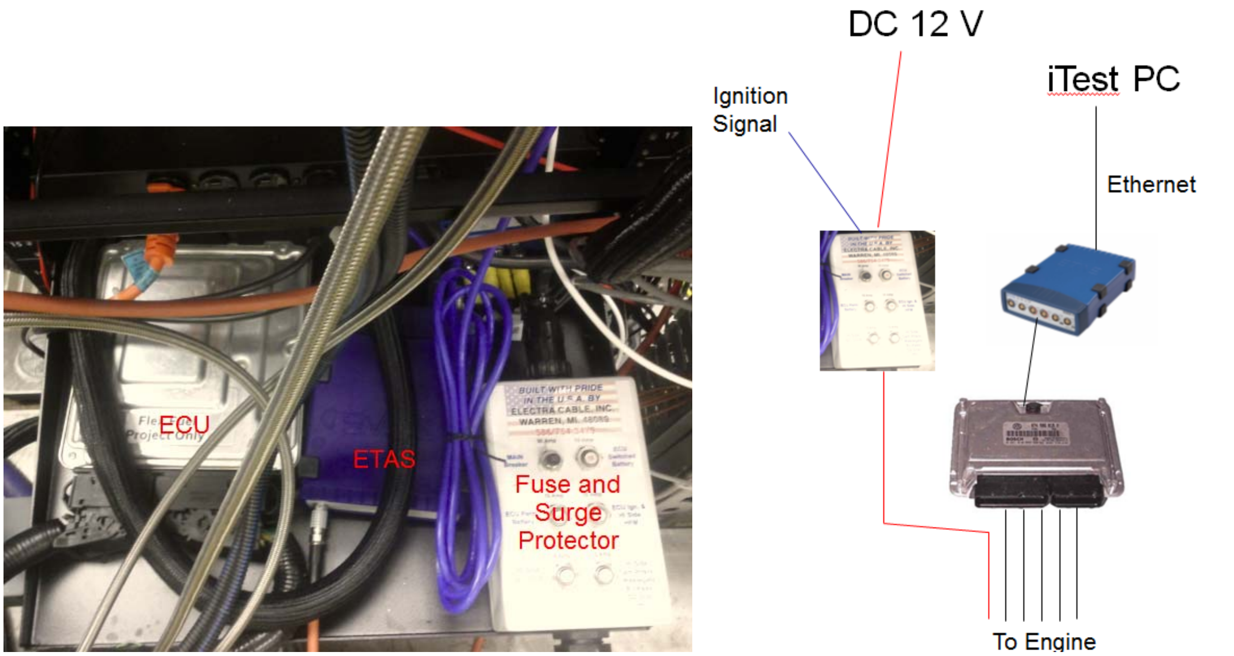
- 12 15-bit **2MHz** parallel analog input channels
- Input ranges; +/-1, +/2.5, +/-5, +/-10 and +/-50 V
- 200 KHz anti-aliasing filters on each channel
- User selectable low-pass filters at 12.5 KHz, 25 KHz, 50 KHz or none
- 256 Mb of data storage
- Encoder inputs for Trigger, Clock, Direction with built-in pulse multiplication
- 6 high speed digital inputs
- 1,000 M-bit Ethernet interface to host PC
- Complete power on self test with diagnostic indication
- Front panel BNC connection for all analog inputs
- Supports up to eight cylinders with four additional inputs for pressure referencing, spark, injection, etc.

4.12. ECU and ETAS

The ECU we are using is a prototype ECU given by Bosch. If there is a problem with the ECU contact Jason Martz or Jeff Sterniak (10?? AL, He is a Bosch employee and not affiliated with this project or this lab.)

[14] For more information, see p. 59 of "Final tech proposal form AND.pdf"

The ETAS ES592[15] is an ECU and bus interface module. The ES592 module has an upstream Ethernet interface that guarantees data exchange with the host PC or with a Drive Recorder.



Through ETAS ES592, we can access the variables of ECU. We can send control signals, modify some parameters, and perform data logging. Software (INCA) has to be installed in iTest PC.

The signals defined in iTest Solution include.

Channel	a2I name	Description	Units	Remark
1	nmot_w	Engine speed	RPM	
2	wdkba_w	Throttle position, actual. 100%=90 deg (open), 0% = 0 deg (closed)	% throttle	
3	wdks_w	Throttle position, commanded	% throttle	
4	zwist	Spark timing, deg CA BTDC combustion	deg	
5	wnwe_w	IVO, deg CA ATDC gas exchange	deg	
6	wnwse_w	IVO, commanded	deg	
7	wnwa_w	EVC, deg CA ATDC gas exchange	deg	
8	wnwsa_w	EVC, commanded	deg	
9	prist_w	Rail pressure	Mpa	
10	wbhxxs1_w	SOI 1, gas exchange, deg CA BTDC combustion	deg	
11	wehp2k1_w	SOI 2, gas exchange, deg CA BTDC	deg	

[15] For more information, see “ES592.1_UG_R03_EN.pdf”.

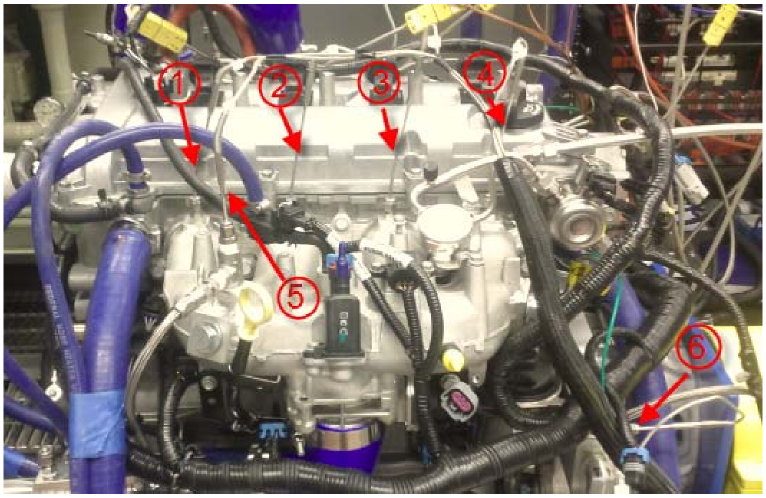
		combustion		
12	tihxxsL1	Inject on duration, first injection	ms	
13	tihp2k1_w	Inject on duration, second injection	ms	
14	rk_w	Modeled injection mass, reactive to the displaced volume filled with a stoichiometric fuel air mixture at 101.3 kPa and 20 deg C	%	
15		Modeled delivered fuel mass = 1.e6*rk_w/(2578*AF_stoich*60)	mg/cyc-cyl	AF_stoich = 14.6
16	ldtvm	Waste gate duty cycle, 100%: Waste gate closed, 0%: Waste gate open if boost high enough to overcome spring force	%	
17	mshfm_w	MAF: mass airflow sensor, intake - precompressor	kg/hr	
18	tasr_w	MAT: mass airflow sensor, intake - precompressor	mbar	
19	pvdk_w	Boost pressure, compressor out	deg C	
20	tavdk_w	Boost temperature, compressor out	mbar	
21	psrg_w	MAP: intake manifold pressure, post throttle	-	
22	lamsoni_w	Lambda from O2 sensor	%	
23	o2adap_w	O2 % in exhaust from O2 sensor	deg C	
24	tmot	Jacket water coolant temperature		
25	wdks_w	Throttle command setpoint		
26	CWEVAB	0: injectors enabled, 255: injectors off		
27	upwgl_u	pedal position high volt		
28	upwg2_u	pedal position low volt		
29	fcmActoNbr	Num of error message		

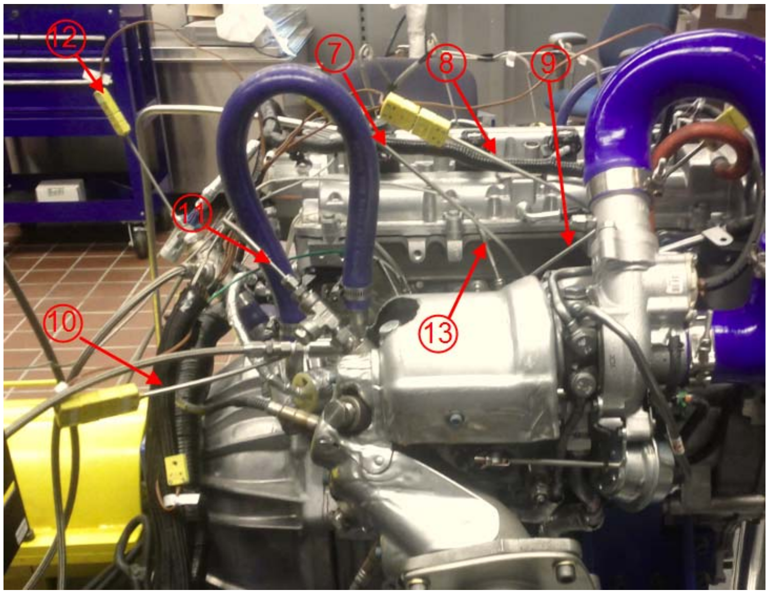
4.13. Additional Sensors and Actuators

4.13.1. Temperature (Thermocouples)

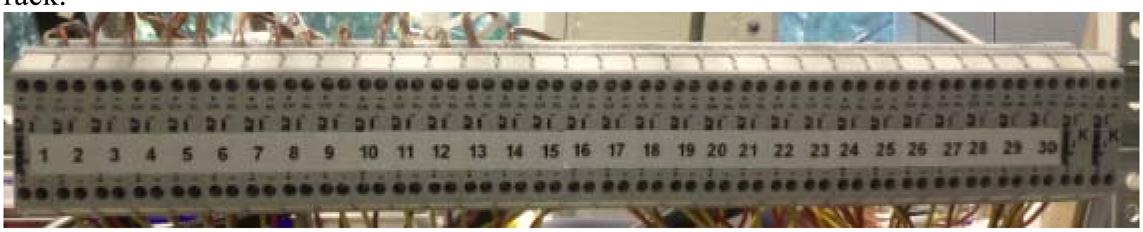
Thermocouples are installed mainly in the engine. The connections go to the boom via the electric rack. The list of the signals and channel names are as follows:

Number	Description	Channel Name	Module Name	Remark
1	Intake #1	t_01_03_11_01	tEng1Cyl1Intake	
2	Intake #2	t_01_03_11_02	tEng1Cyl2Intake	
3	Intake #3	t_01_03_11_03	tEng1Cyl3Intake	
4	Intake #4	t_01_03_11_04	tEng1Cyl4Intake	
5	Intake manifold	t_01_03_12_01	tEng1IntakeManifold	
6	Lubricant oil in	t_01_03_12_02	tEng1LubricantOil	
7	Exhaust #1	t_01_03_12_03	tEng1Cyl1ExhaustMan	
8	Exhaust #2	t_01_03_12_04	tEng1Cyl2ExhaustMan	
9	Exhaust #3	t_01_03_13_01	tEng1Cyl3ExhaustMan	
10	Exhaust #4	t_01_03_13_02	tEng1Cyl4ExhaustMan	
11	Turbo out	t_01_03_13_03	tEng1TurboOut	
12	Jacket water out	t_01_03_13_04	tEng1CoolantOutlet	
13	Scroll A	t_01_03_14_01	tEng1ScrollA	
14	Scroll B	t_01_03_14_02	tEng1schollB	Sensor is not connected
15	Dyno Bracket Bearing Front	t_01_03_14_03	tDt1LBraketBearFront	Sensor is not connected
16	Dyno Bracket Bearing Rear	t_01_03_14_04	tDt1LBraketBearRear	Sensor is not connected

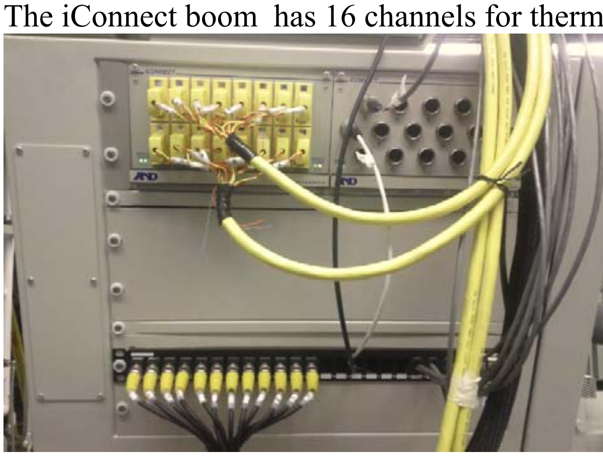




The sensors(K-type thermocouple) are terminated to the thermocouple connector blocks in the rack.



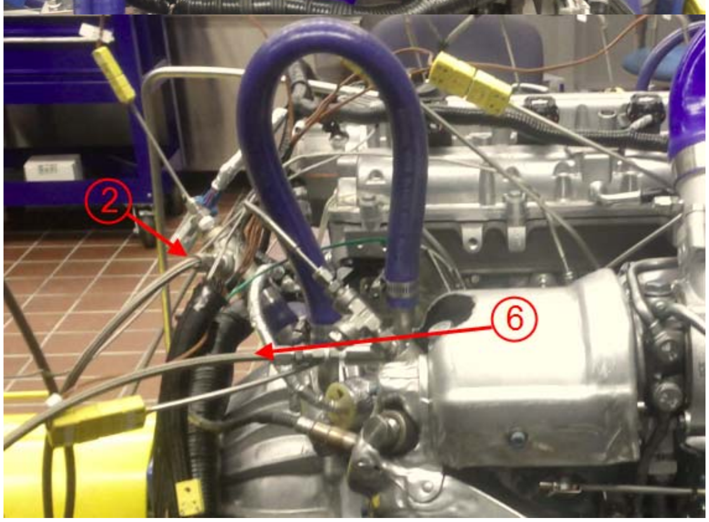
The connector blocks are connected to the iConnect boom.
The iConnect boom has 16 channels for thermocouple inputs.

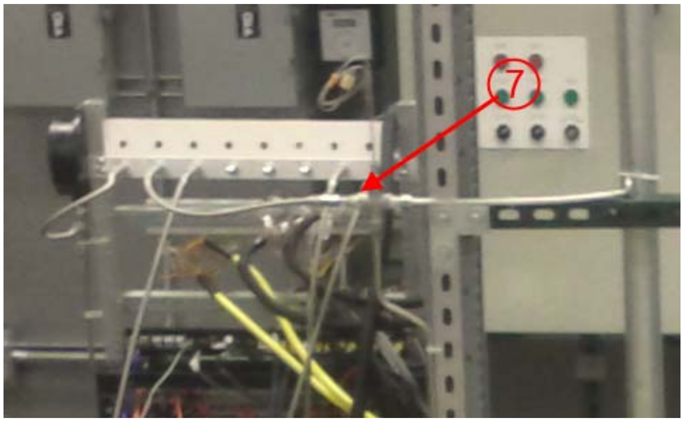


4.13.2. Pressure Sensors

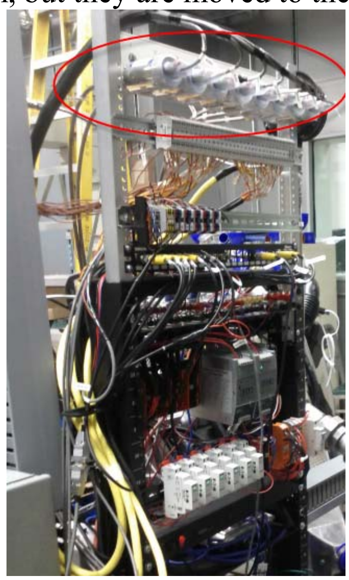
The iConnect instrumentation has eight transducers.
It uses variable capacitance transducer.

Channel	Description	Channel Name	Module Name	Remarks
1	Intake	ai_01_03_17_01	pgEng1IntakeManifold	
2	Coolant	ai_01_03_17_02	pgEng1CoolingSystem	
3		ai_01_03_17_03		
4		ai_01_03_17_04		
5		ai_01_03_18_01		
6	Exhaust	ai_01_03_18_02	pgEng1Exhaust	
7	Fuel	ai_01_03_18_03	pgEng1Fuel	
8	Oil	ai_01_03_18_04	pgEng1Oil	



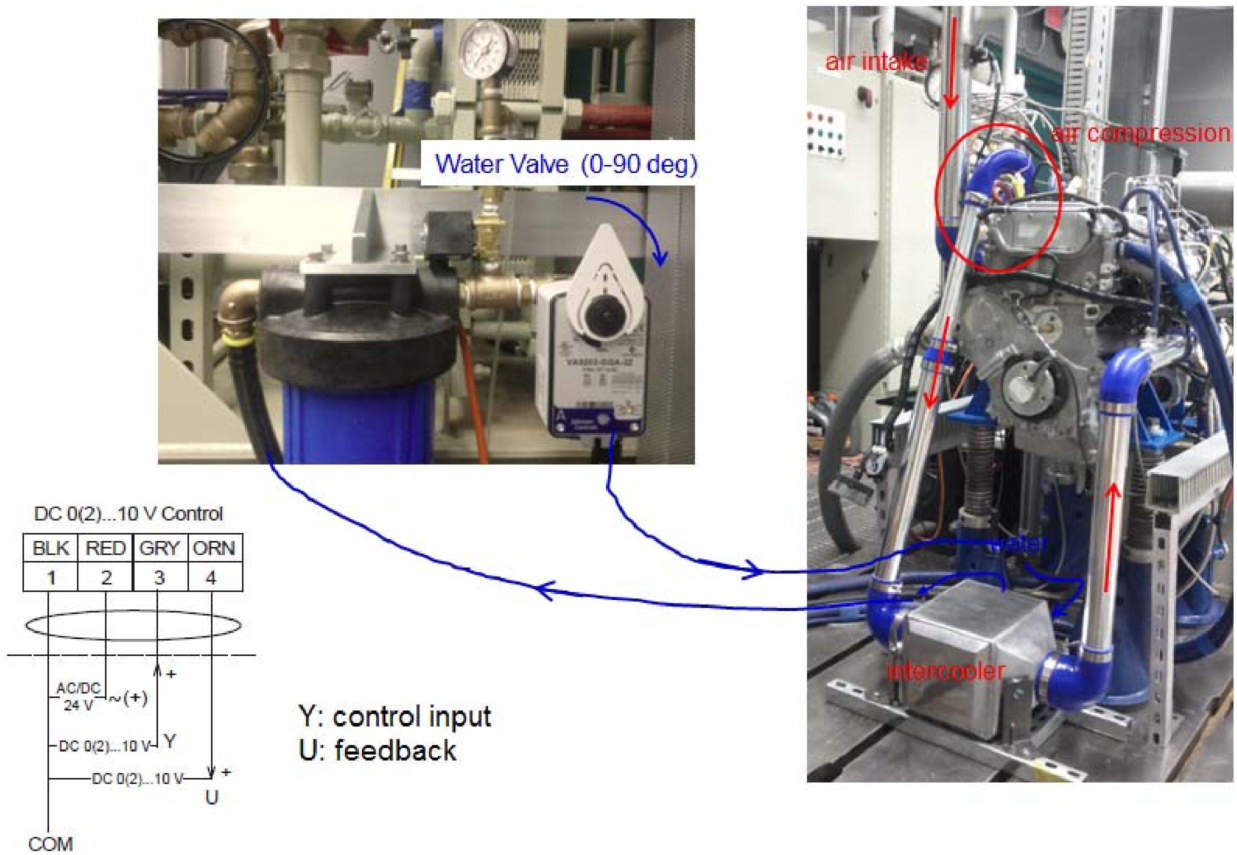


Transducers: They were inside of the boom, but they are moved to the rack.



4.13.3. Water valve for intercooler system[16]

There is an intercooler system to cool down the compressed air going to the intake manifold. The cooling is done by cold water. The water flow is controlled by a proportional electric spring return valve actuator.

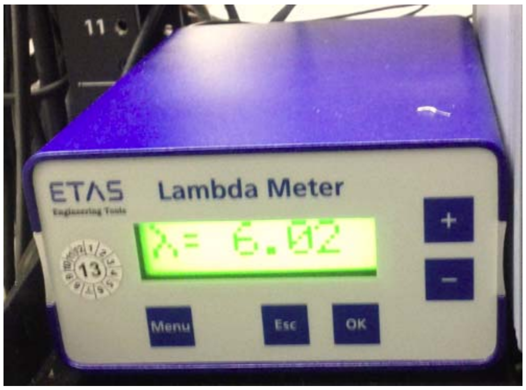


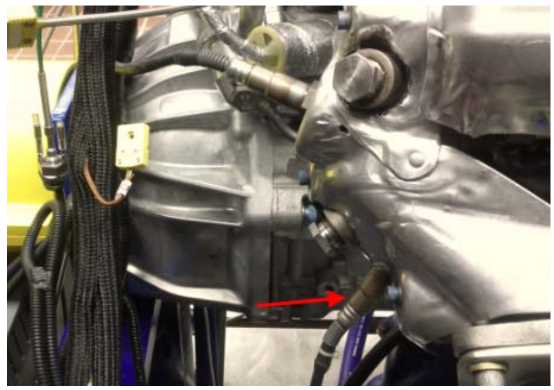
Description	Channel Name	Module Name
Intercooler coolant valve feedback	ai_01_03_15_01	aiEng1IntercoolerValvePos
Intercooler coolant valve feedback, 10V: 100%, 0V: 0%	ao_01_02_14_02	aoEng1IntercoolerValvePos

[16] For more information, see “VA9208-GGx-x.pdf”

4.13.4. Lambda Sensor (Lambda Meter LA4)

The LA4 Lambda Meter[17] is a precision measuring instrument that measures exhaust gases in gasoline, diesel and gas engines in conjunction with the Robert Bosch LSU Broadband λ sensor[18]. The instrument uses fuel-specific maps to convert the oxygen content and can display both the current λ air ratio and the air/fuel ratio (A/F).





Channel	Decription	Channel Name	Module Name	Remarks
1	Lambda (AF ratio)	ai_01_03_15_02		

The sensor output is connected to the 2nd analog input plug in the iConnect boom.

[17] "LA4_UG_EN_R1.0.6.pdf"
[18] "Y258E00015e Technical Product Information LSU4.9.pdf"

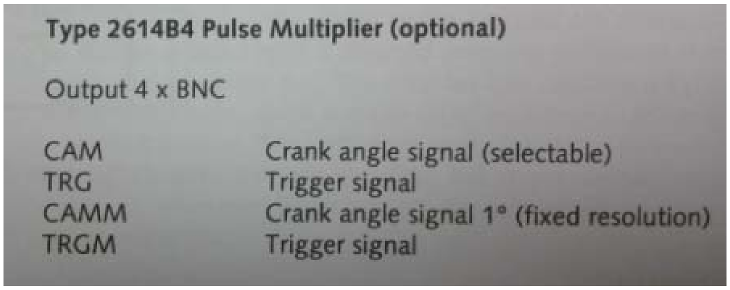
4.13.5. Crank Angle Encoder Set[19]

The crank angle encoder set Type 2614B provides measurements related to crank angle. The outputs should be connected to high speed measurement system. In our case, we connect the output to CAS. The output type is BNC.

Crank angle sensor and Amplifier	Pulse multiplier (2614B4)
	

It requires a separate power supply (6 ~ 26 VDC / 200mA)

There are four outputs from pulse multiplier.

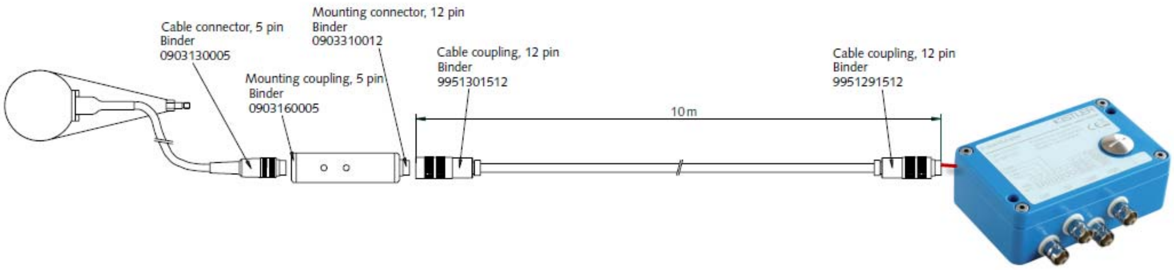


Type 2614B4 Pulse Multiplier (optional)

Output 4 x BNC

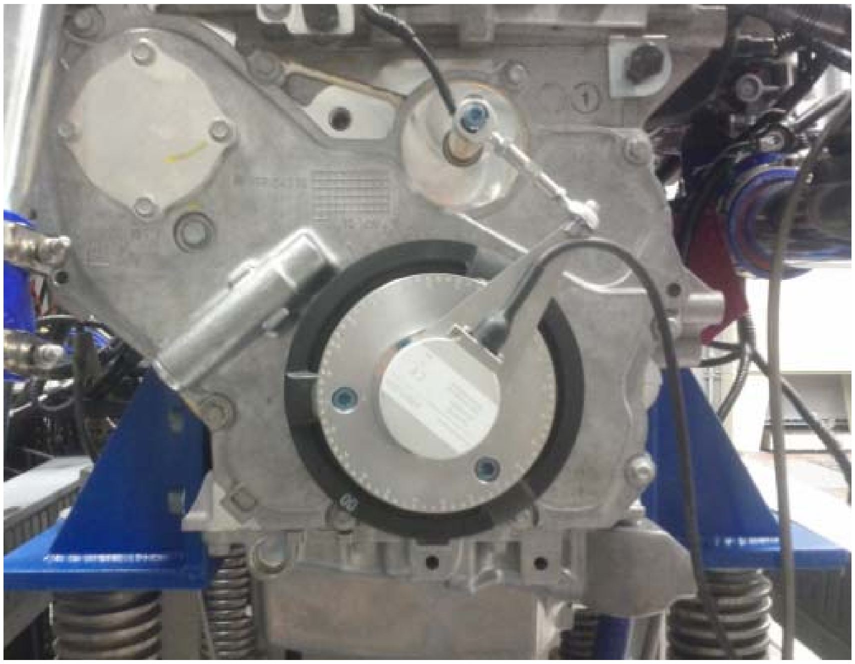
CAM	Crank angle signal (selectable)
TRG	Trigger signal
CAMM	Crank angle signal 1° (fixed resolution)
TRGM	Trigger signal

Connection diagram



The encorder is intalled the free end of the engine.

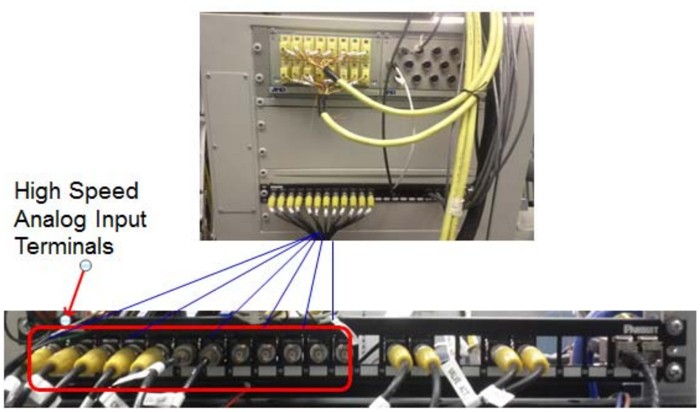
[19] "2614B.pdf"



Channel assined (high speed signal panel):

Channel	Description
1	Crank Angle Sensor TRG
2	Crank Angle Sensor CAM
3	Crank Angle Sensor TRGM
4	Crank Angle Sensor CAMM

This signals go to CAS system via the iConnect boom.

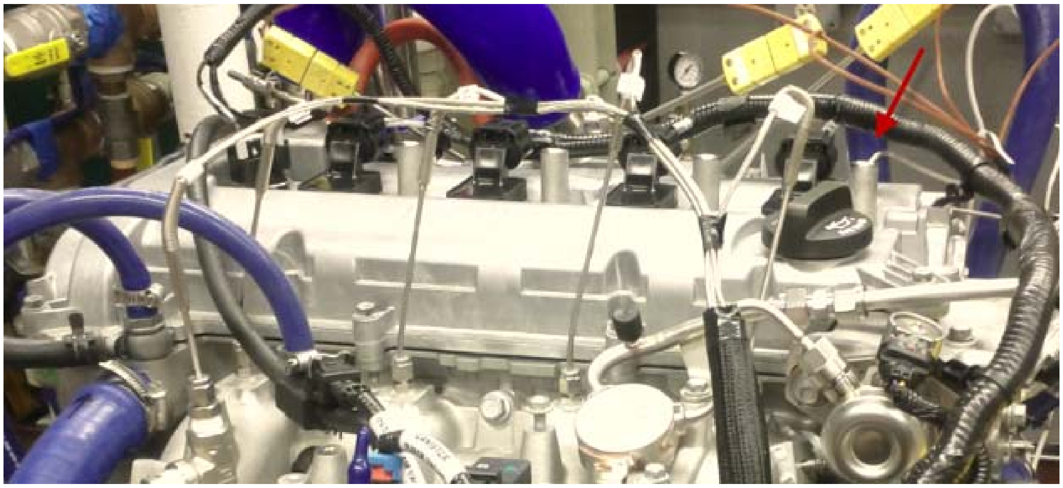


4.13.6. Cylinder Pressure Sensor

Ground-isolated high-temperature pressure sensor with integral connecting cable for measuring cylinder pressures in combustion engines.

PiezoStar® Pressure Sensor[20]	Charge Amplifier[21]
	

The output cable is a BNC type.



The sensor is installed in Cylinder # 4 only.
This signals go to CAS system via the iConnect boom.

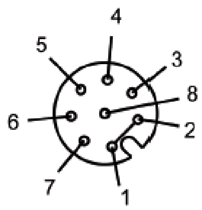
[20] "6125C11__000-695e-10.11.pdf"
[21] "Data sheet_000-387a-07.09.pdf"

4.13.7. Water Cooled Absolute Pressure Sensor[22]

Sensor	Amplifier
	

The outputs from the amplifier are pressure and temperature.

Pin Allocation at Amplifier Type 4622A... (Lumberg 8-pol, M12x1)

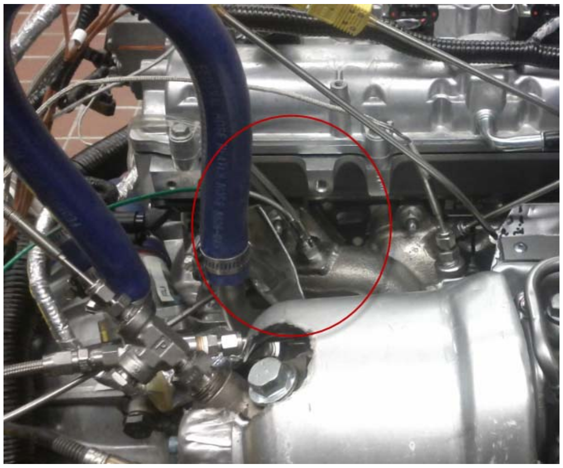


Pos.	Signal	Wire colors cable Type 4777A...
1	Excitation GND	brown
2	Signal GND	white
8	Excitation (+11 ... 30 V DC)	gray
4	Pressure output	blue
5	Temperature output (10mV/°C)	black

Channel assined:

Channel	Description
1	Exhaust #4 Temperature
2	Exhaust #4 Pressure

This signals go to CAS system via the iConnect boom.

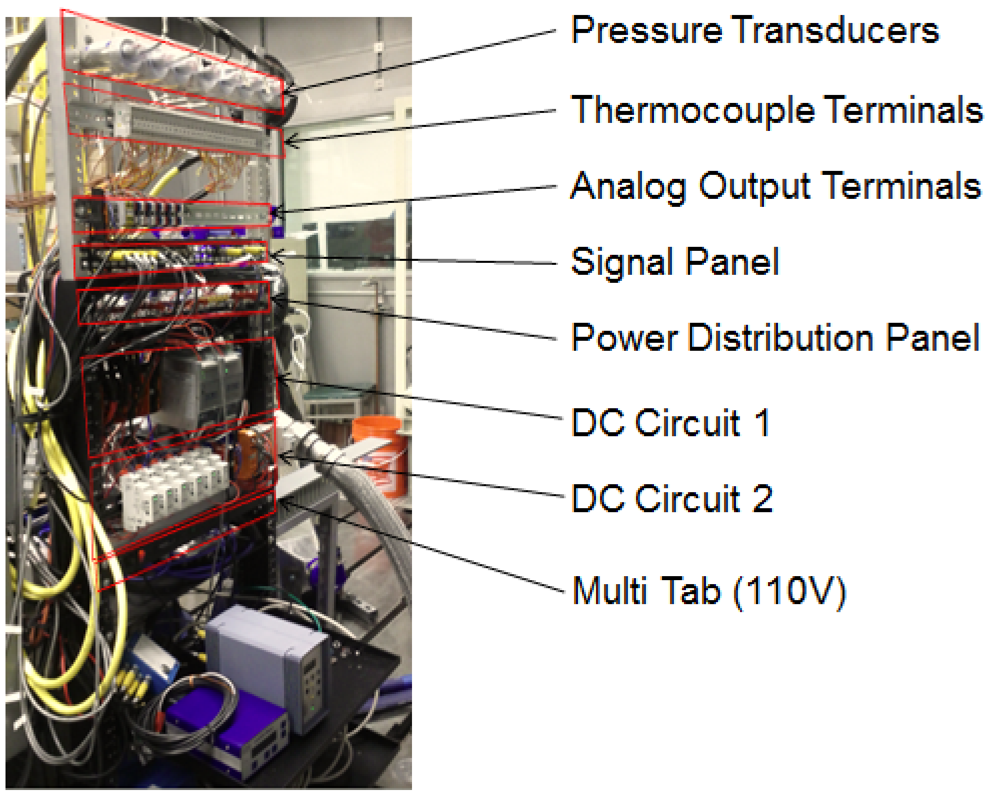


[22] "4049A.pdf"

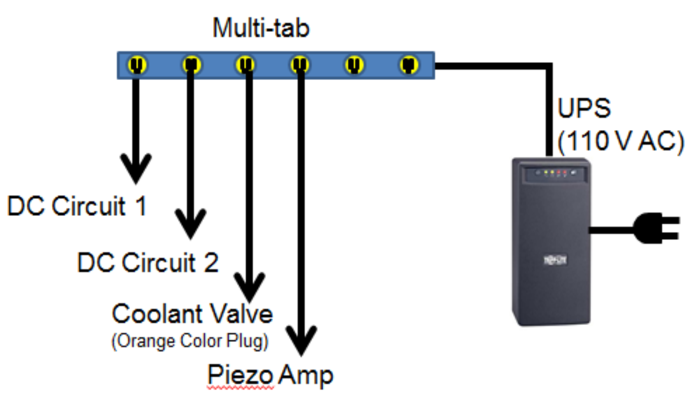
This sensor requires water cooling. Water is supplied through a thin plastic tube. The water flows once 110V switch on the rack is ON.

4.14. Electric/Electronic Rack

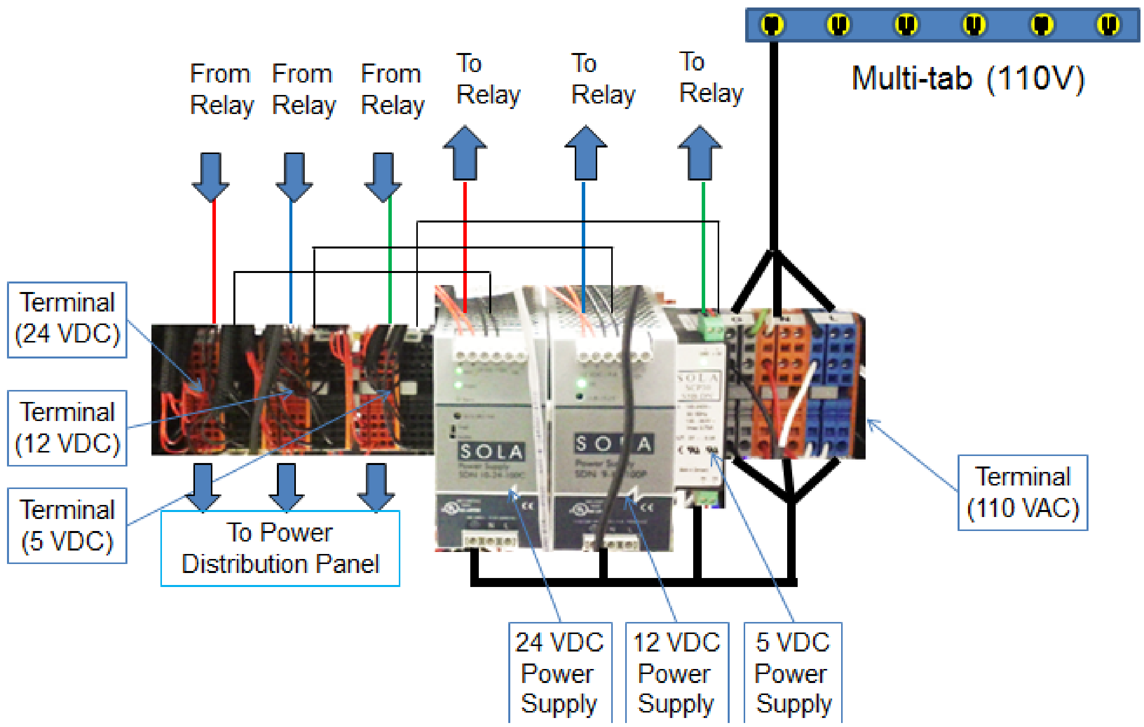
It provides 19” din rail for sensors, power connectors, and signal connectors. All signals and power for the customized (user added) sensors go through the rack.



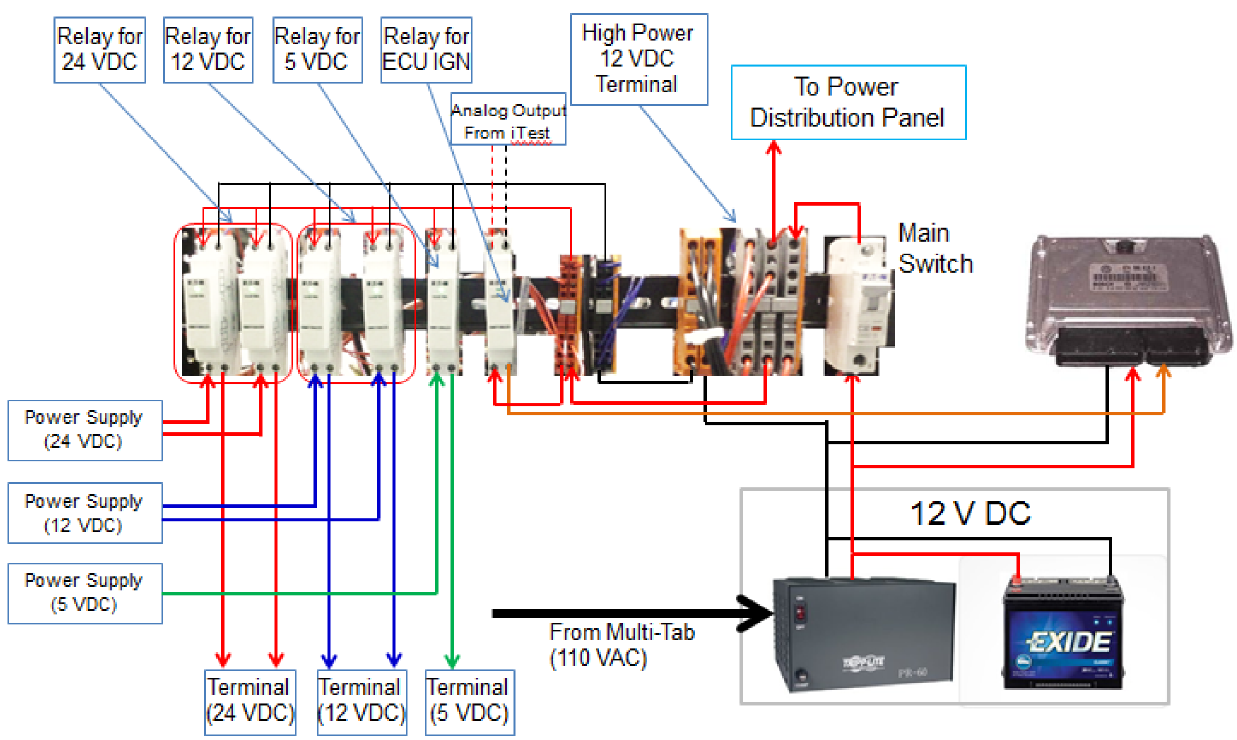
4.14.1. AC Circuit



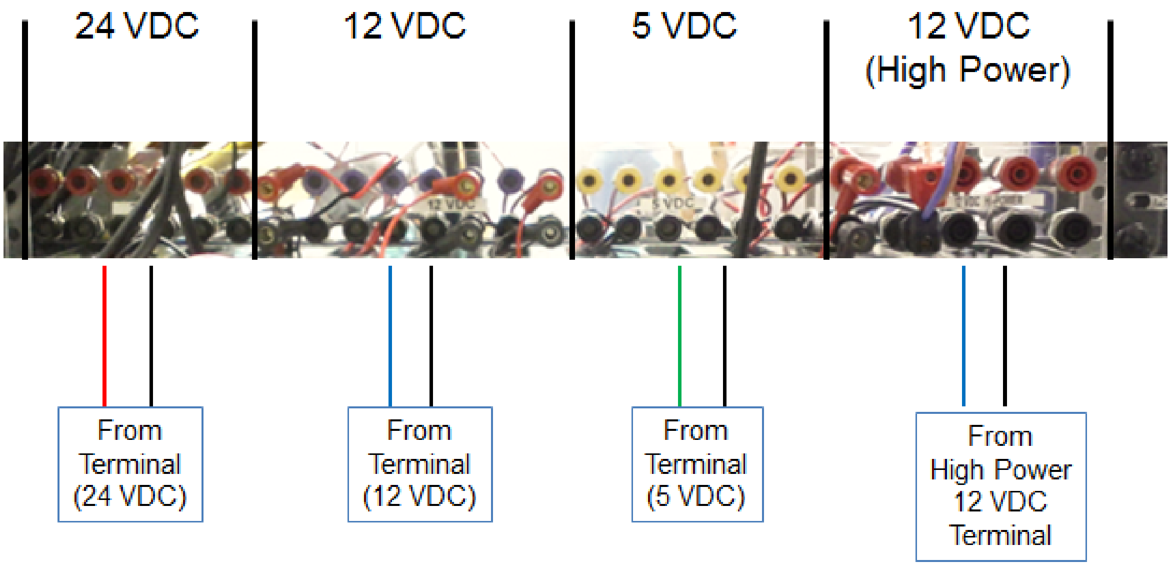
4.14.2. DC Circuit 1 (Low Power 5V/12V/24V DC)



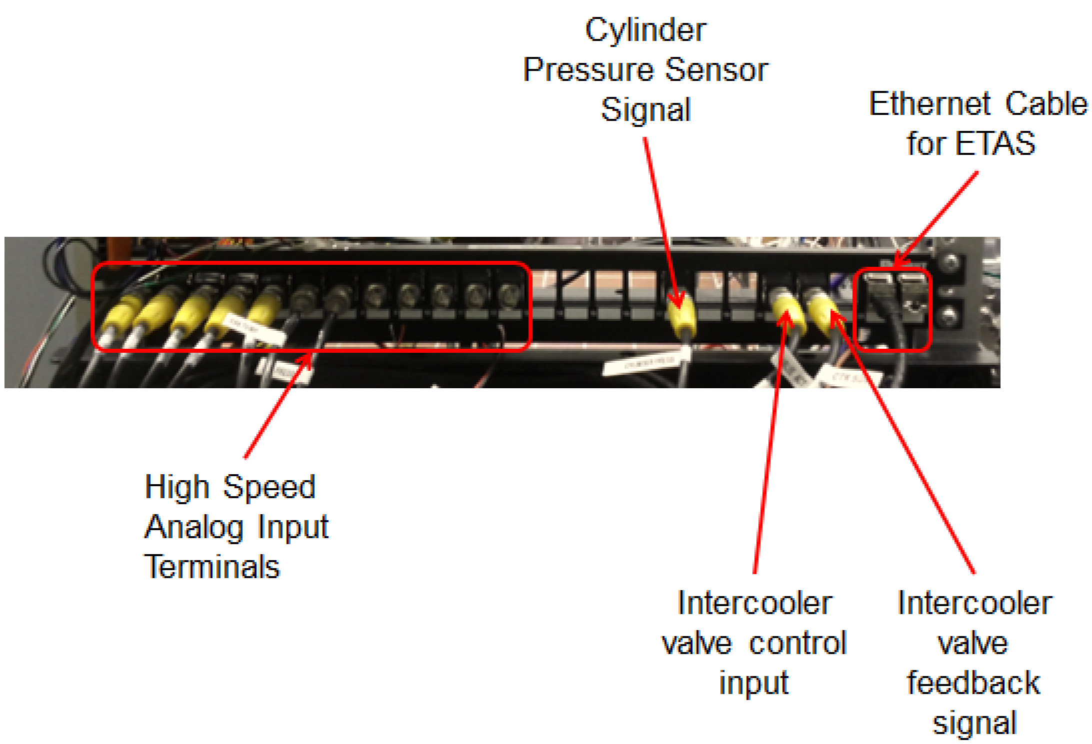
4.14.3. DC Circuit 2 (High Power 12 VDC)



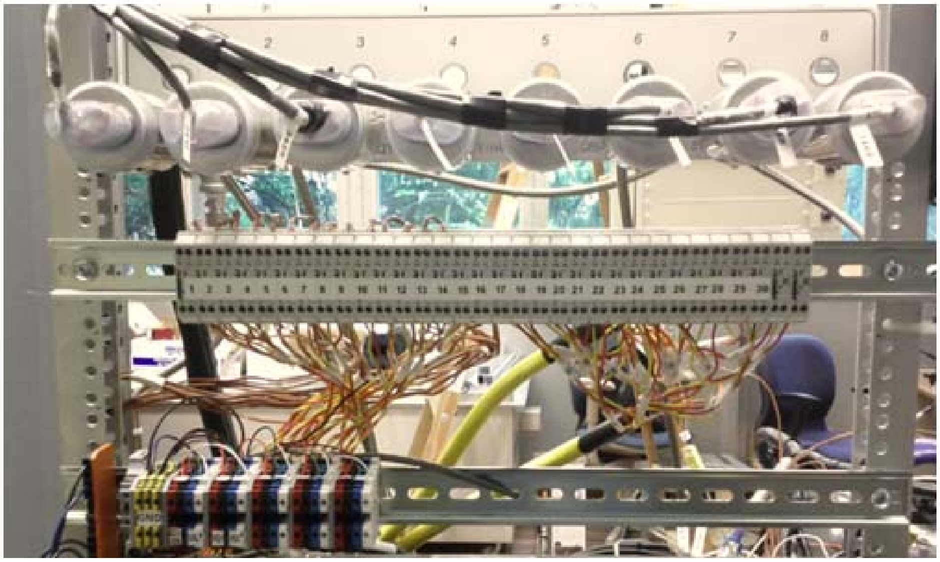
4.14.4. Power Distribution Panel



4.14.5. Signal Panel



4.14.6. Other Panels



Pressure Transducers

Thermocouple Terminals

Analog Output Terminals

5. Software

5.1. iTest[23]

see AND documents

[23] More details on “iTest_Instructor.ppt”

5.2 INCA

see ETAS document

Model Def/VCDesigner[24]

see AND documents

[24] See more details on pp. 57-108 of "AD 5445 Instruction Manual.pdf"

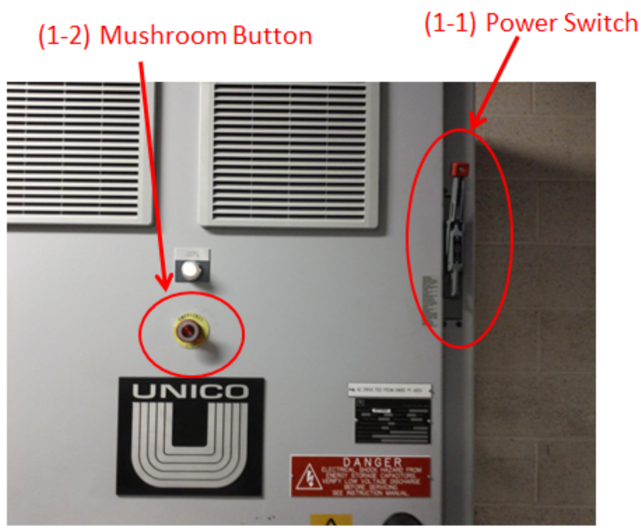
Running the Test Cell

5.2. Motor Test

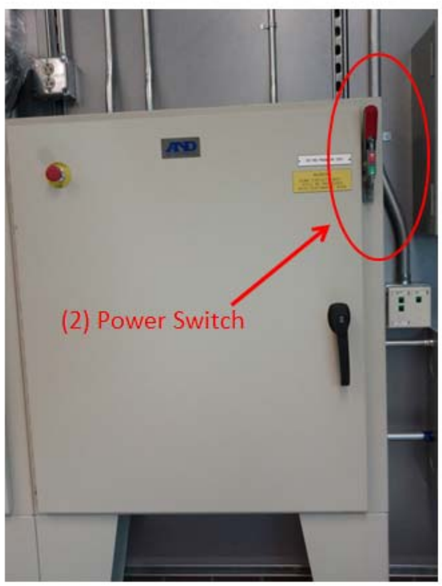
5.2.1. Starting Up Procedure for Traction Motor Test Stand

Below are the steps for starting up the test stand. Please follow the steps

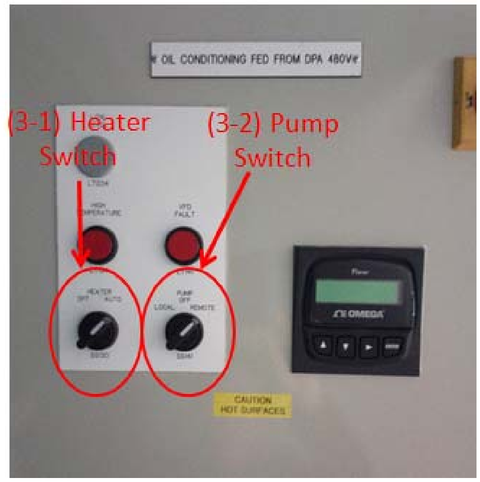
1. Turn the power to the *UNICO* Drive (in 2070 AL) on, and then pull out the red mushroom button (Emergency Stop Button) on the drive. The drive is in 2070 Auto Lab.



2. Turn on the Facility Interface Cabinet (FIC) in the test cell. This will turn the ***eGates*** and also the 24V to the *UQM* Inverter.

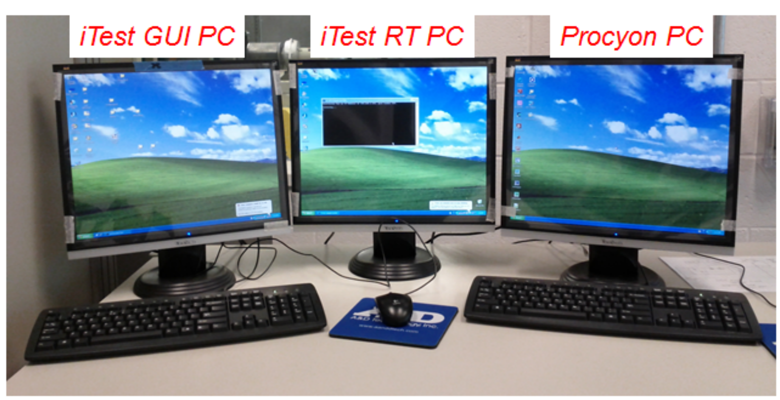


3. Turn on the Coolant Conditioner power and have the “Heater” on “Auto” and the other switch to “Remote”.



4. Start up the *iTEST* GUI PC and *iTEST* RT PC.

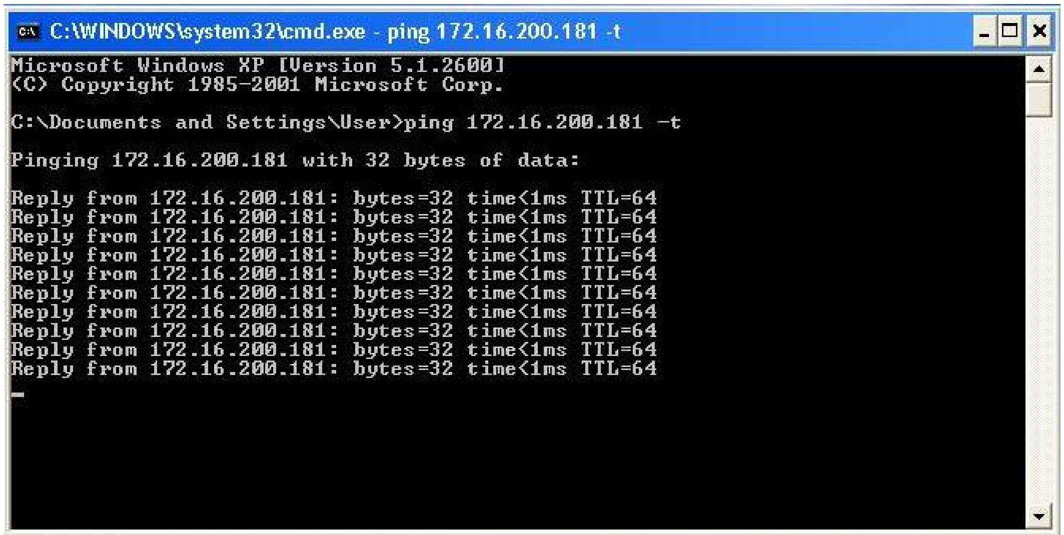
5. Start up the *Procyon* Box. The box will be booted up when you see the red LED under the “status” go off.



6. Startup the *Procyon* PC. (Make sure that the *Procyon* Box has started up first. Step number 5)

a. Make sure you can ping the Procyon PC by opening up a DOS command window and type

➢ ping 172.16.200.181 -t

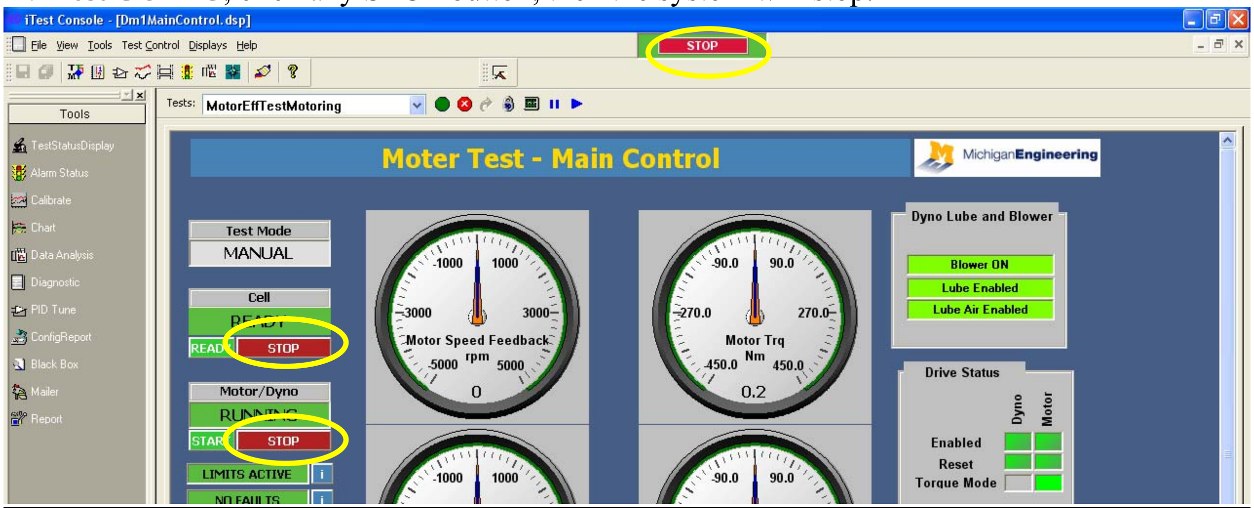


You should see a continuous ping. If not “disable” and “enable” the NIC called “ADX_VC” in “Network Connections”. Try the ping again.

7. For Lab 1, refer “Lab1 documentation.doc”. For Lab 2, refer Lab2 documentation.doc”

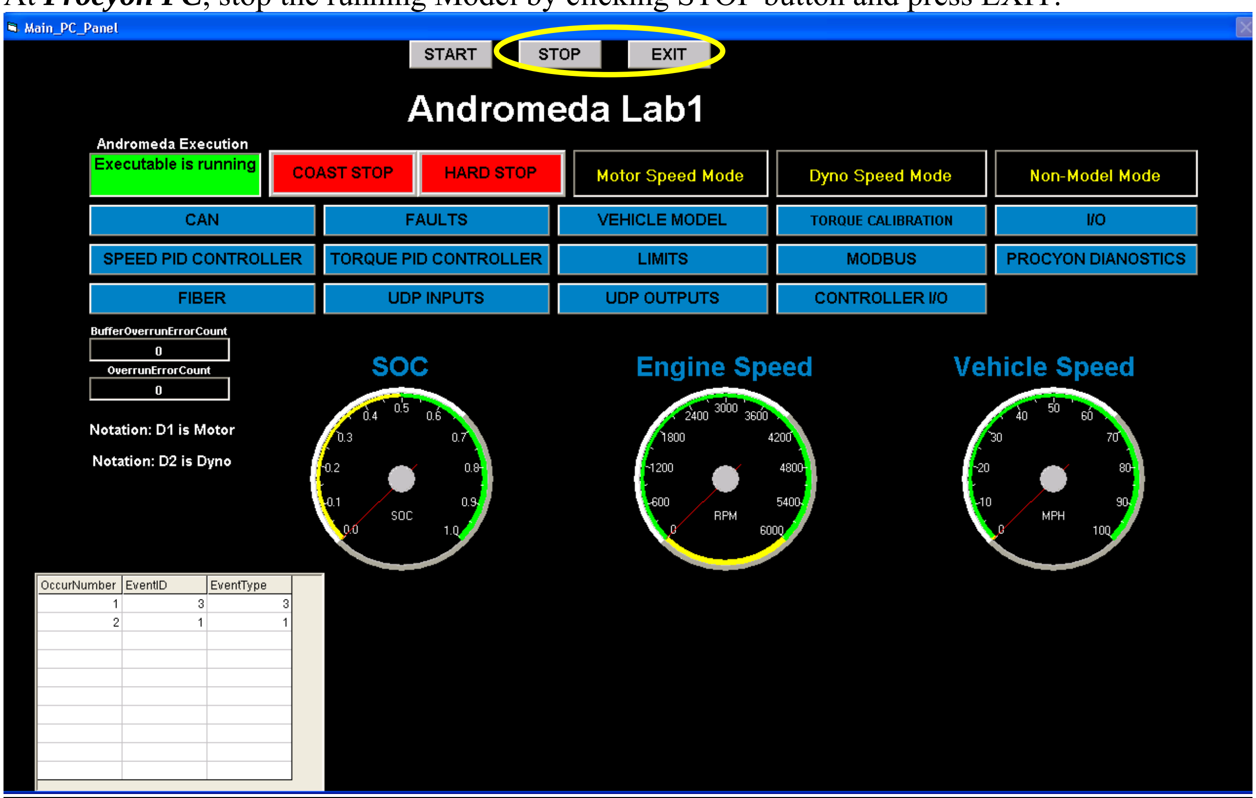
5.2.2. Shutting Down Procedure for Motor Test Stand

1. At ***iTest GUI PC***, click any STOP button, then the system will stop.

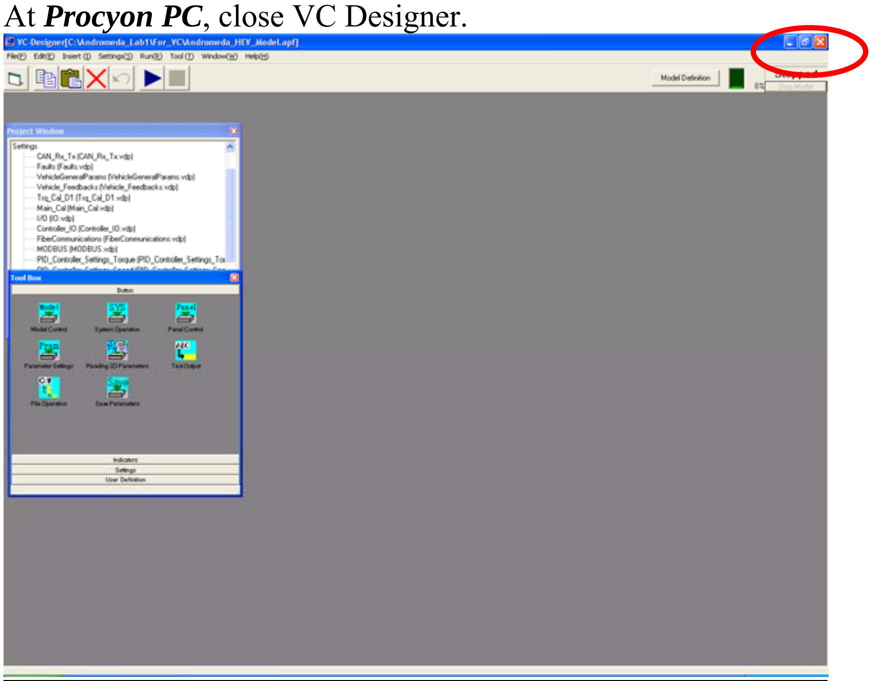


2. At ***iTest GUI PC***, close ***iTest Console 3.1*** program**.**

3. At ***Procyon PC***, stop the running Model by clicking STOP button and press EXIT.



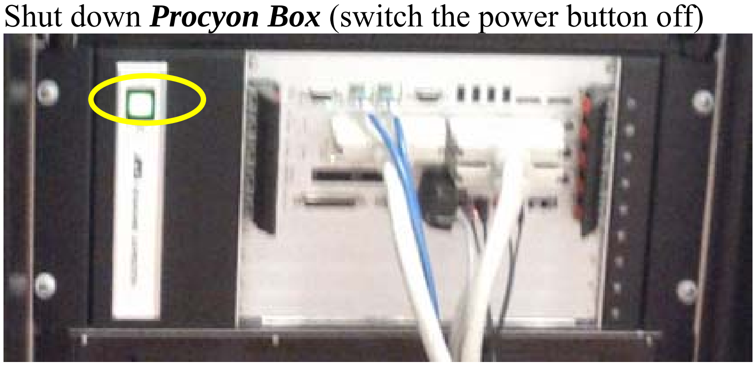
4. At ***Procyon PC***, close VC Designer.



5. Shut down ***iTest GUI PC*** and ***Procyon PC***. (regular Windows shut-down)

6. Shut down ***iTest RT PC***. There is no mouse or keyboard. To shut down the Windows, press the power switch down shortly, then Windows of the computer will start the shut-down procedure

7. Shut down ***Procyon Box*** (switch the power button off)



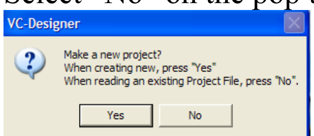
5.2.3. Procedure for Lab 1 (Motor Test)

Below are the steps for run tests of Lab 1. Please follow the steps

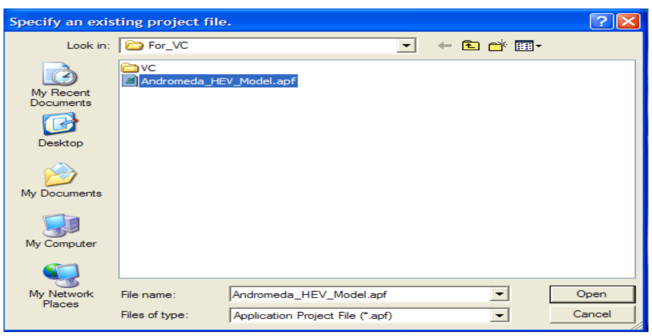
1. Make sure that all the steps listed in “Lab Startup Procedure” have been performed before getting started this procedure.

2. Load the ADx project by clicking on the VCDesigner icon on the desktop of the ***Procyon PC***.

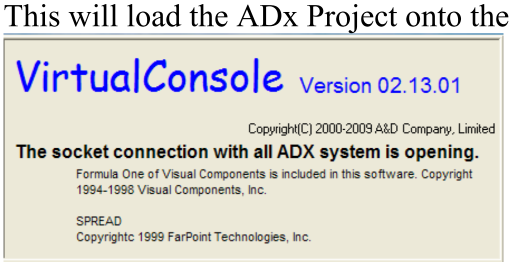
3. Select “No” on the pop that opens up

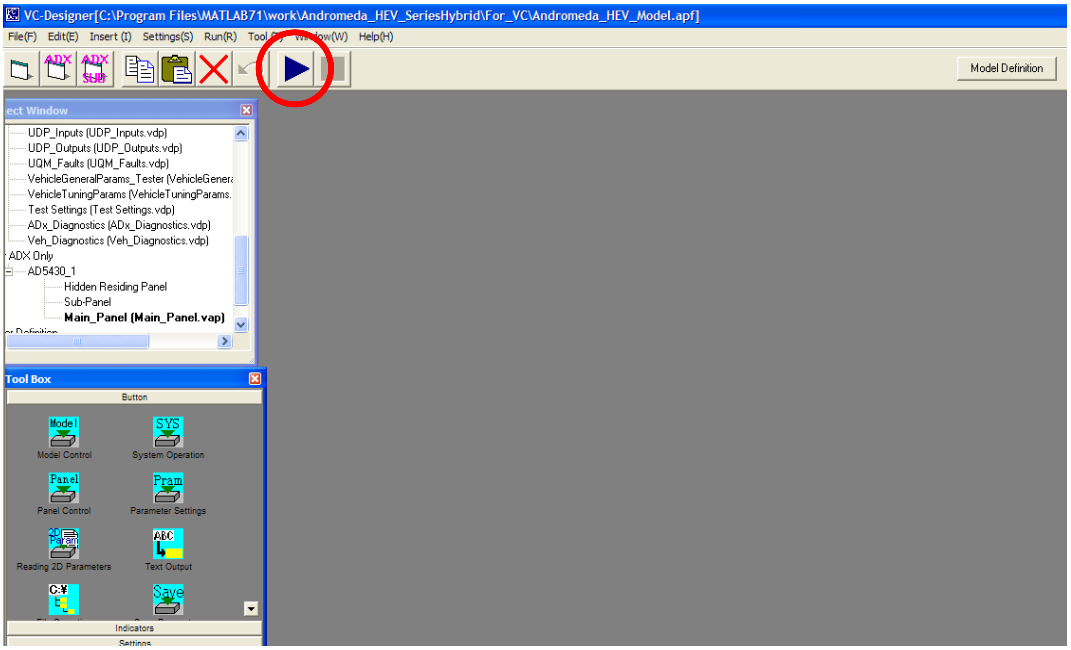


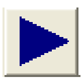
3-b. Go to the folder “**C:\Andromeda_Lab1\For_VC**” and select “**Andromeda_HEV_Model.apf** “ Project file and then “Open”.



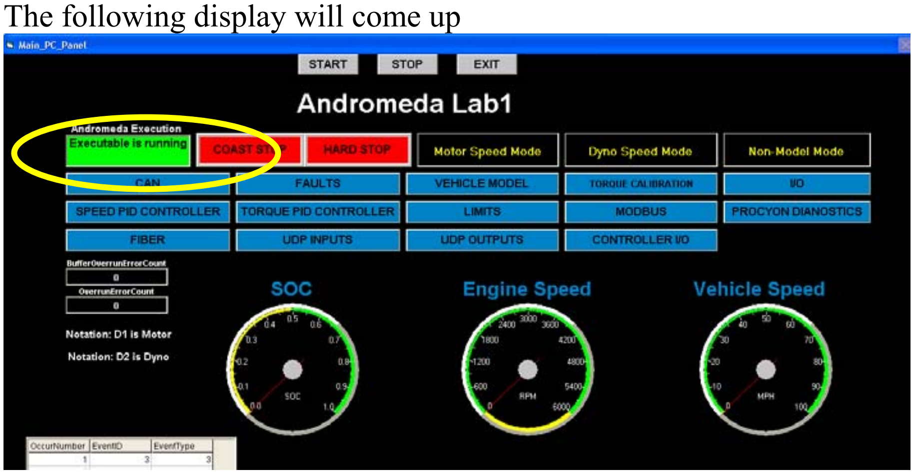
This will load the ADx Project onto the ADx.





4. Click the  to run the project.

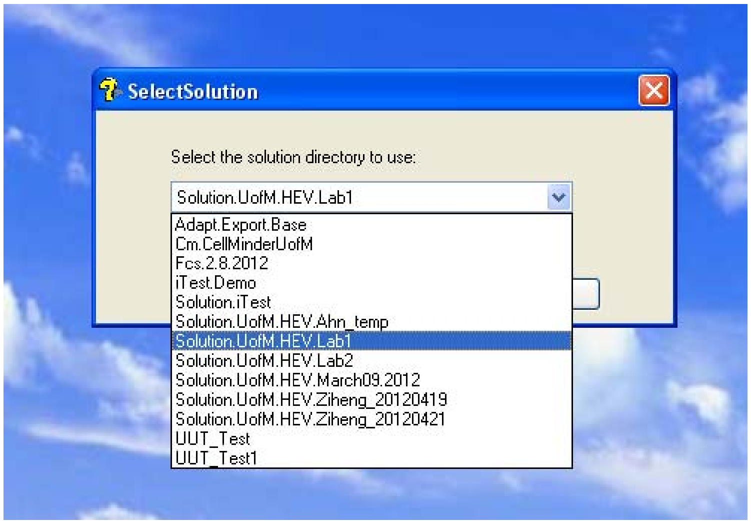
5. The following display will come up



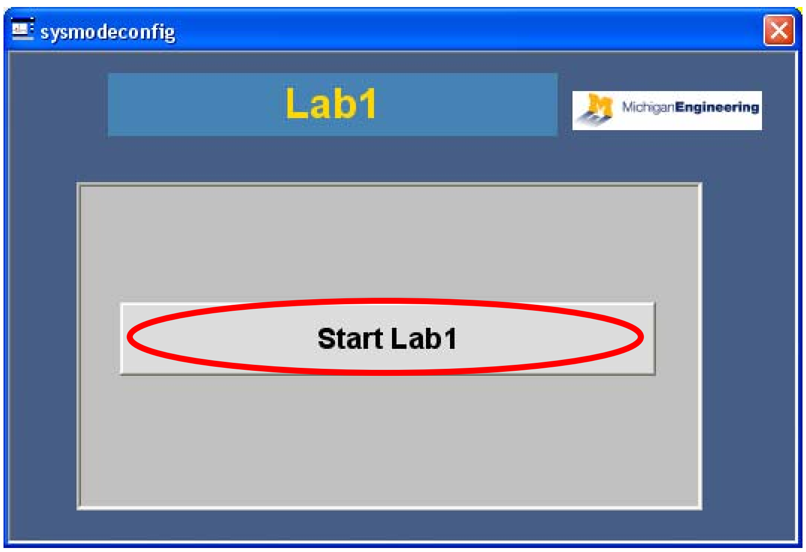
The "Model Execution Status" display on the upper left corner should say "Model is running" and it should be green.

6. The ADx is now ready to run the system.

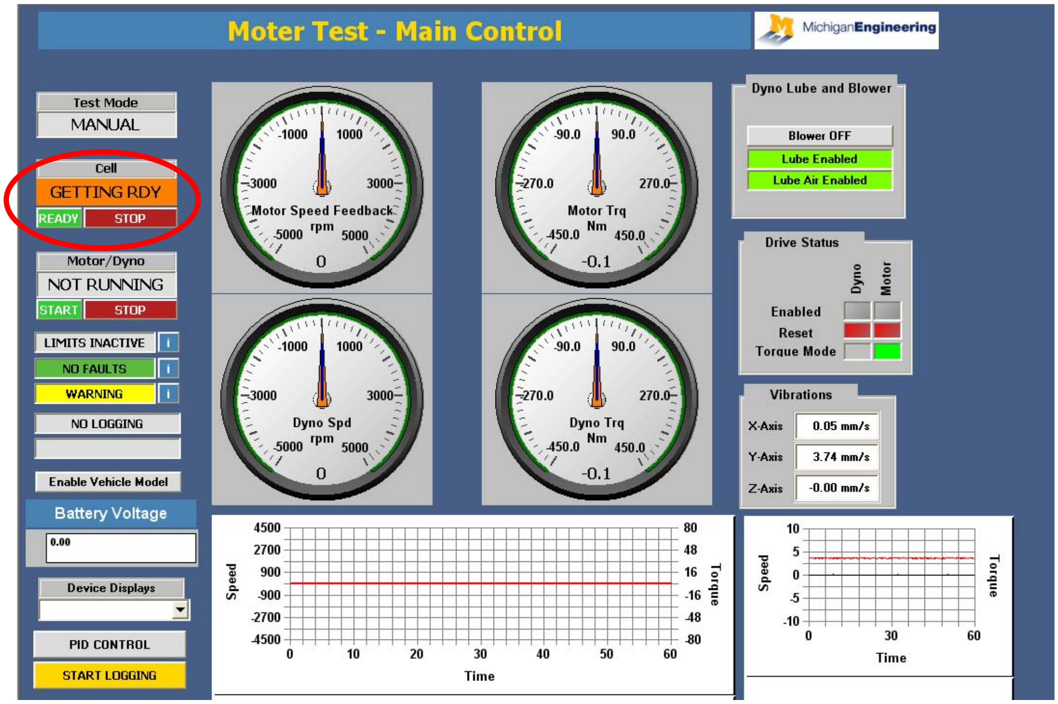
7. To start the iTest solution, double click on the ***iTest Console 3.1*** logo ![iTest Console 3.0] - located on the desktop of the *iTEST* GUI PC, this will open the commissioned solution (***Solution.UofM.HEV.Lab1***)



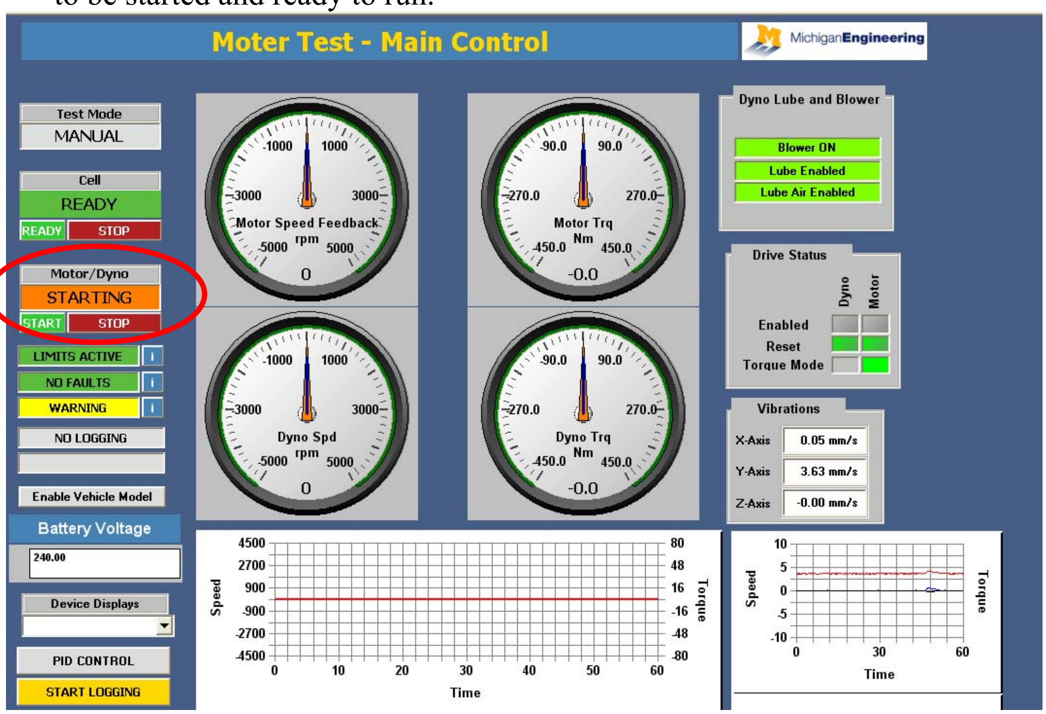
8. After opening the solution, the user will see a pop-up screen on the main screen. Click "***Start Lab 1***".



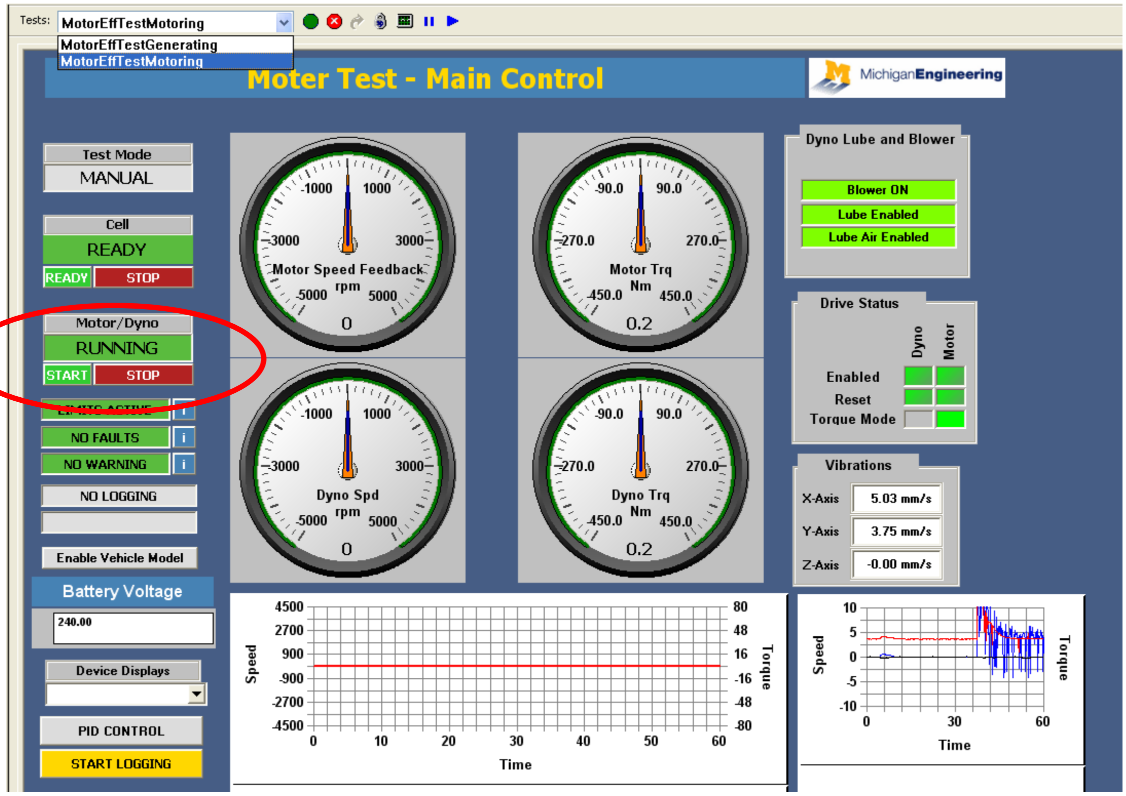
9. Before running or sending commands make sure the system is up and has voltage. Click on READY and wait for the system to be ready



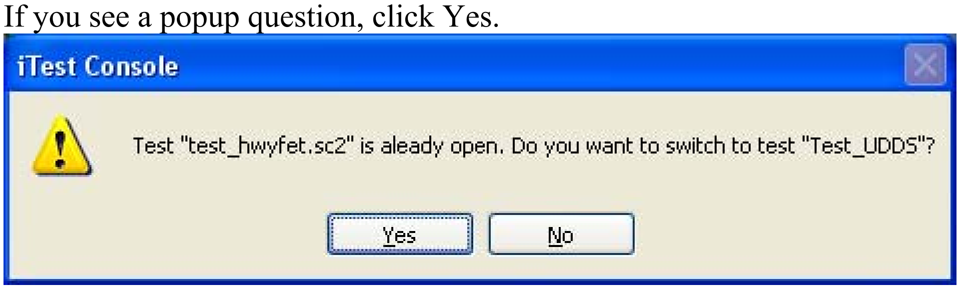
10. Next step is to provide voltage to the system, clicking on START and wait for the system to be started and ready to run.



11. To run any test, first the user needs to select the test and then run it.



If you see a popup question, click Yes.



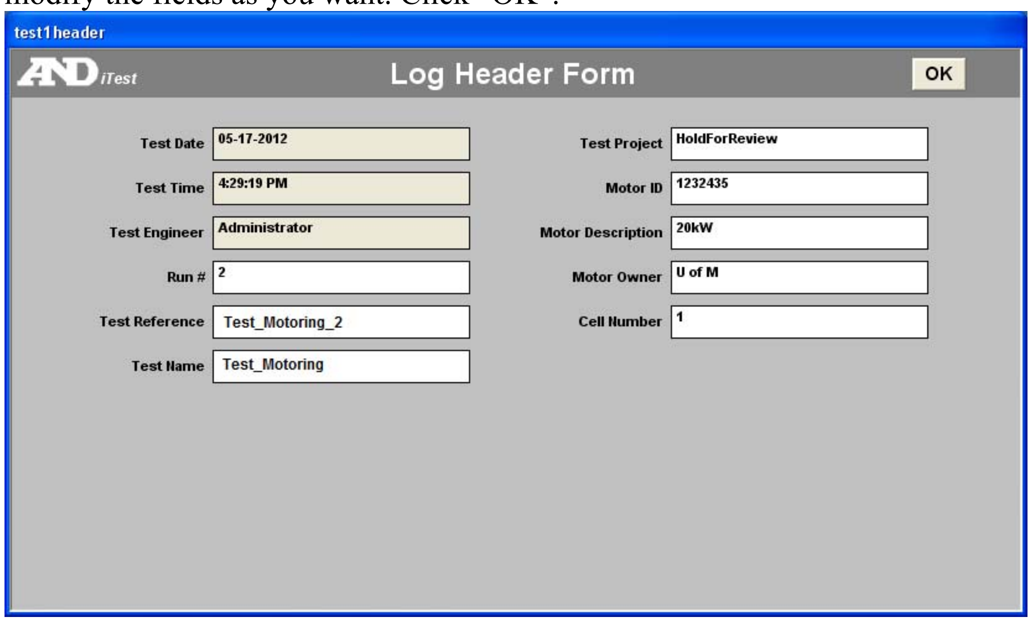
Then click the green button.

If nothing happens, stop the test by clicking the red button and re-click the green button.

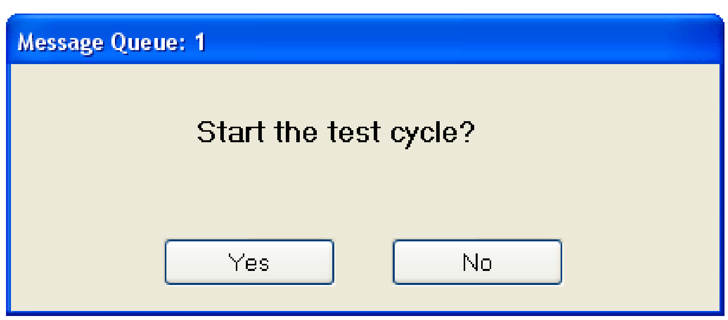
You will see following pop-up screens.

Click “***Restart***” for the question asking restart.

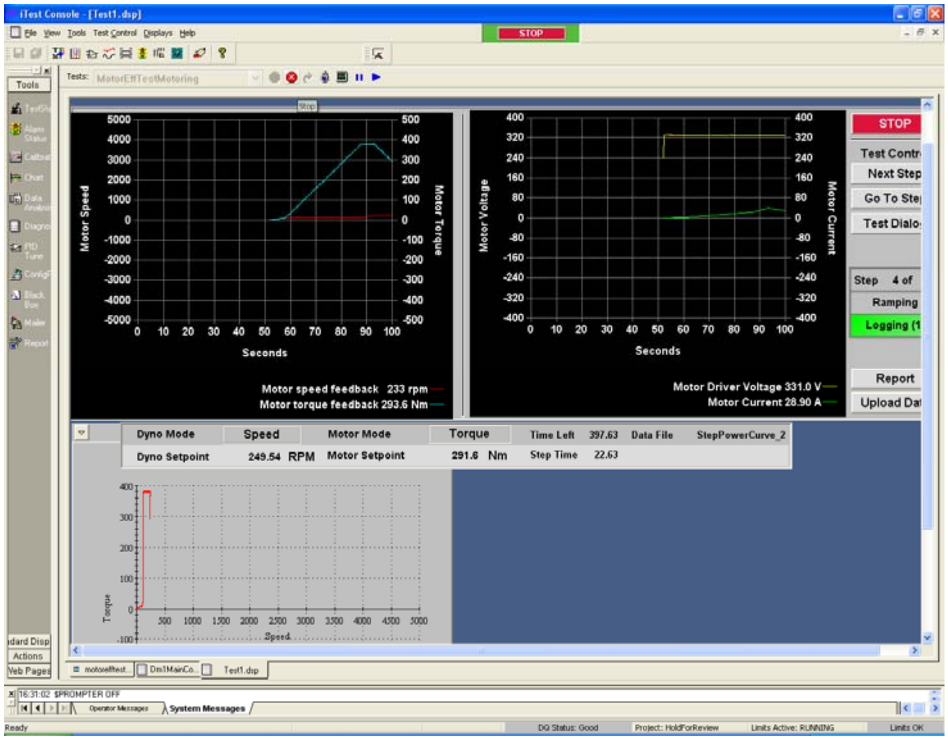
Information screen of the log data file will be popped up. You can use default values or modify the fields as you want. Click “OK”.



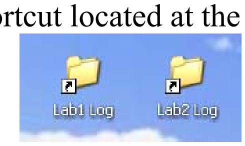
Click “Yes” for the question asking “Start the test cycle?”



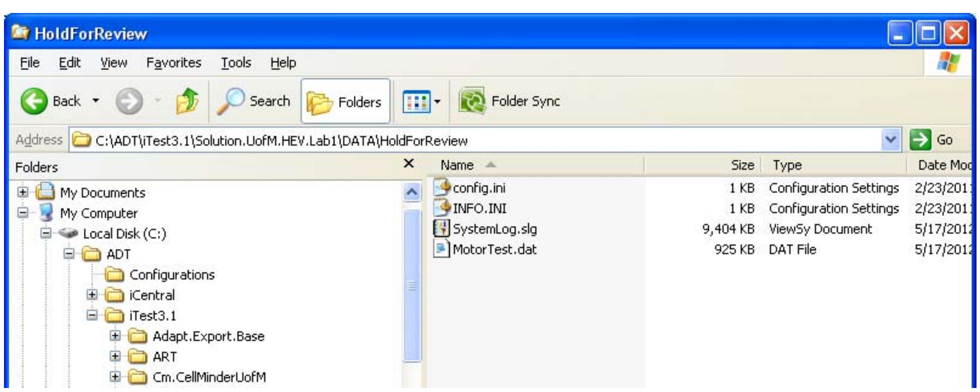
Finally, you will see the following screen.



12. The test log file is saved in "**C:\ADT\iTest3.1\Solution.UofM.HEV.Lab1\DATA\HoldForReview**" and can be accessed by clicking Lab1 Log shortcut located at the desktop of ***iTest GUI PC***.



The file names for the test named "MotorEffTestMotoring" will be "Test_motoring_1.dat", "Test_motoring_2.dat"…etc.
The file names for the test named "MotorEffTestGenerating"will be "Test_generating_1.dat", "Test_generating_2.dat"…etc.



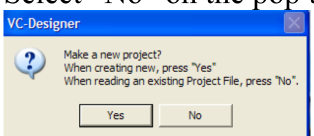
5.2.4. Procedure for Lab 2 (EV Test)

Below are the steps for run tests of Lab 2. Please follow the steps

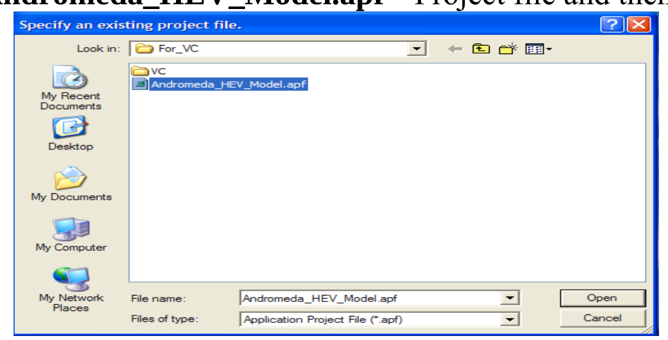
Make sure that all the steps listed in "Lab Startup Procedure" have been performed before getting started this procedure.

1. Load the ADx project by clicking on the VCDesigner icon on the desktop of the *Procyon* PC.

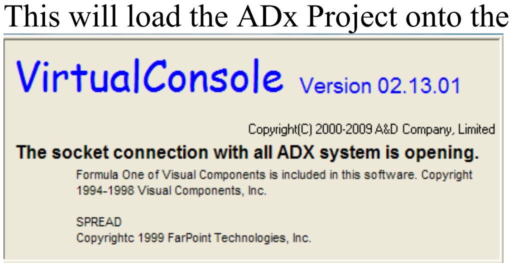
2. Select "No" on the pop that opens up

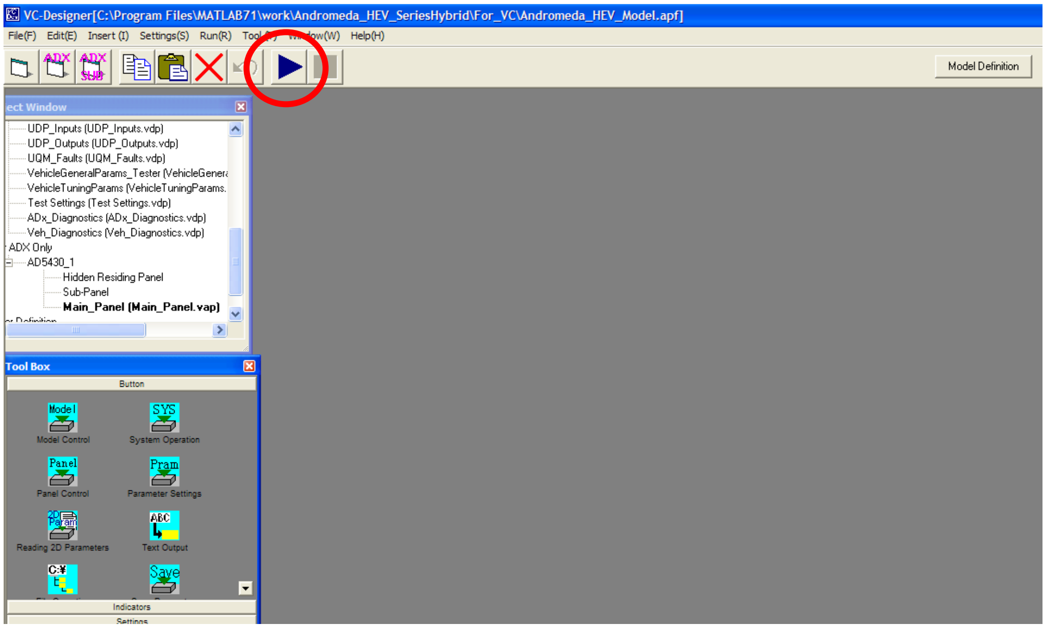


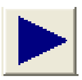
3-b. Go to the folder "**C:\Andromeda_Lab2\For_VC**" and select "**Andromeda_HEV_Model.apf** " Project file and then "Open".



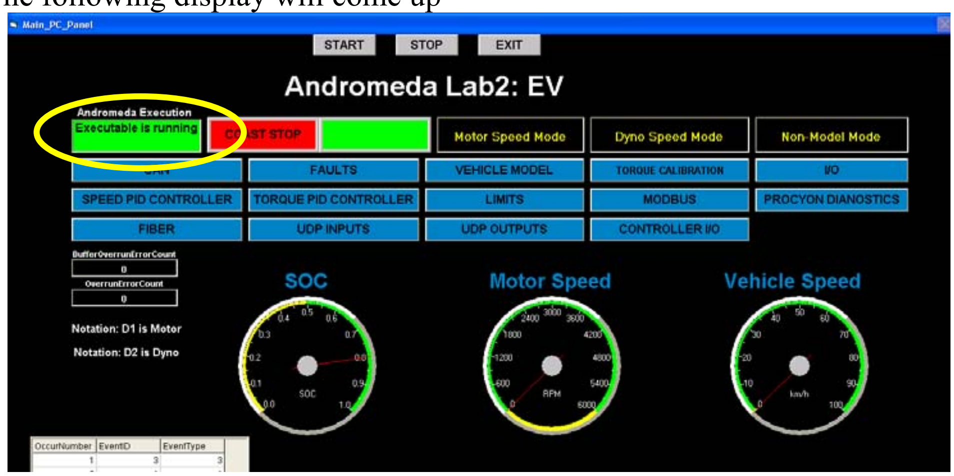
This will load the ADx Project onto the ADx.





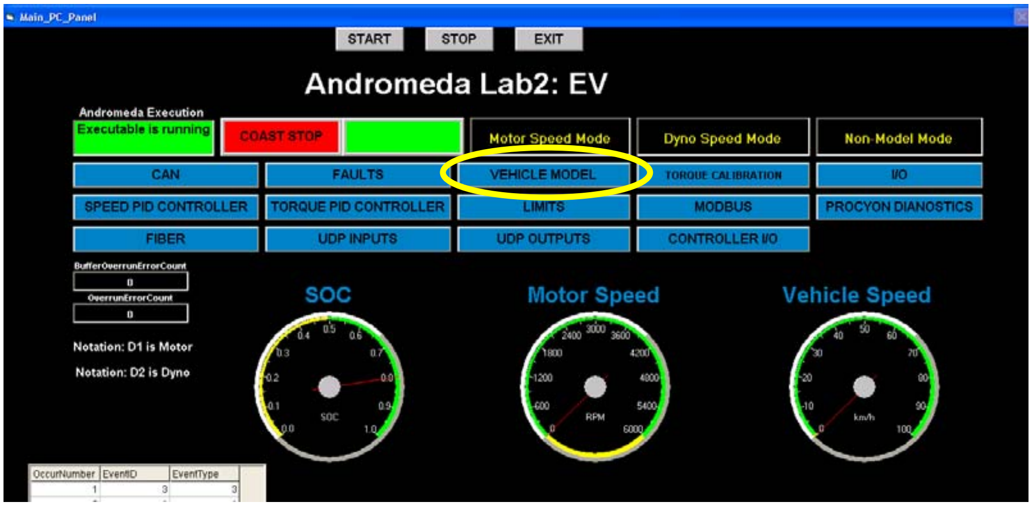
3. Click the  to run the project.

4. The following display will come up

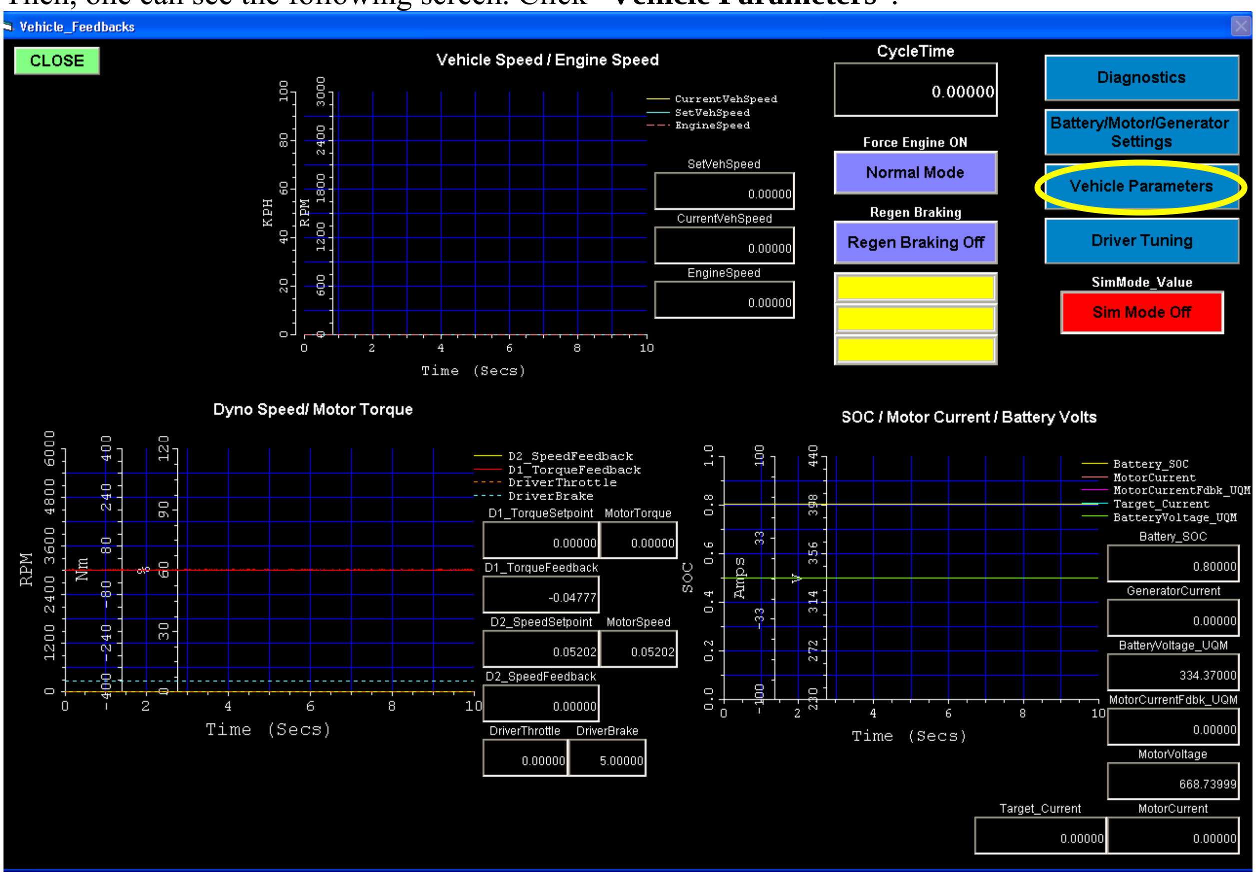


The “Model Execution Status” display on the upper left corner should say “Model is running” and it should be green.

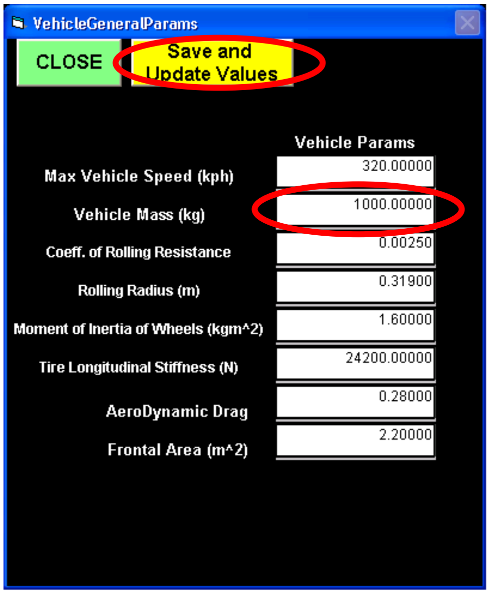
5. To see or change the vehicle mass, click “**VEHICLE MODEL**”.



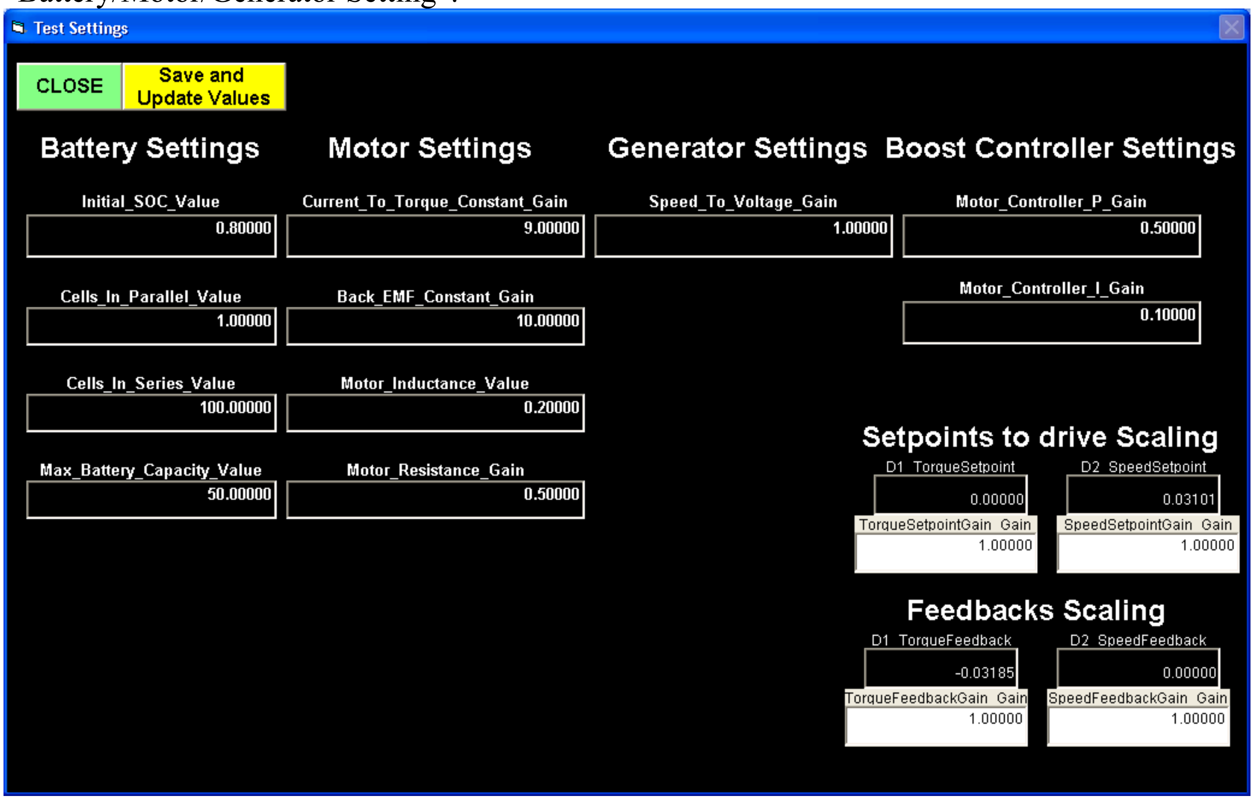
Then, one can see the following screen. Click "**Vehicle Parameters**".



If you want to change the vehicle mass, enter a new number and click "**Save and Update Values**".



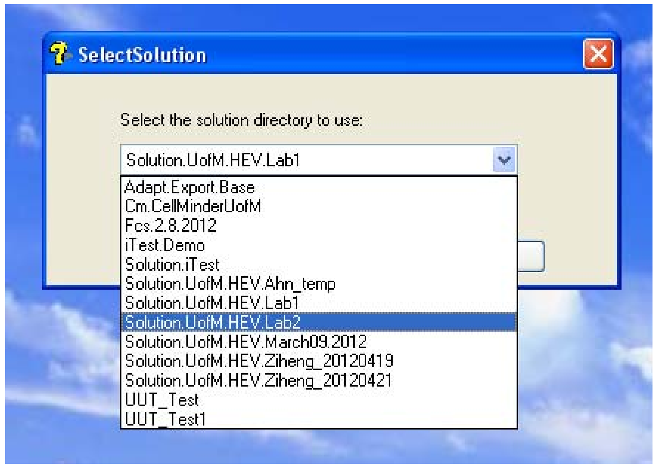
6. If you want to change the initial SOC or the capacity of the battery, click "Battery/Motor/Generator Setting".



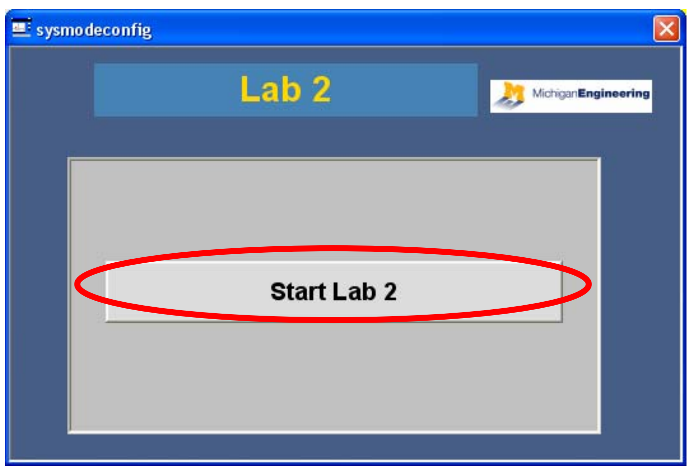
If you change parameters, make sure click "**Save and Update Values**" before closing the screen.

7. The ADx is now ready to run the system.

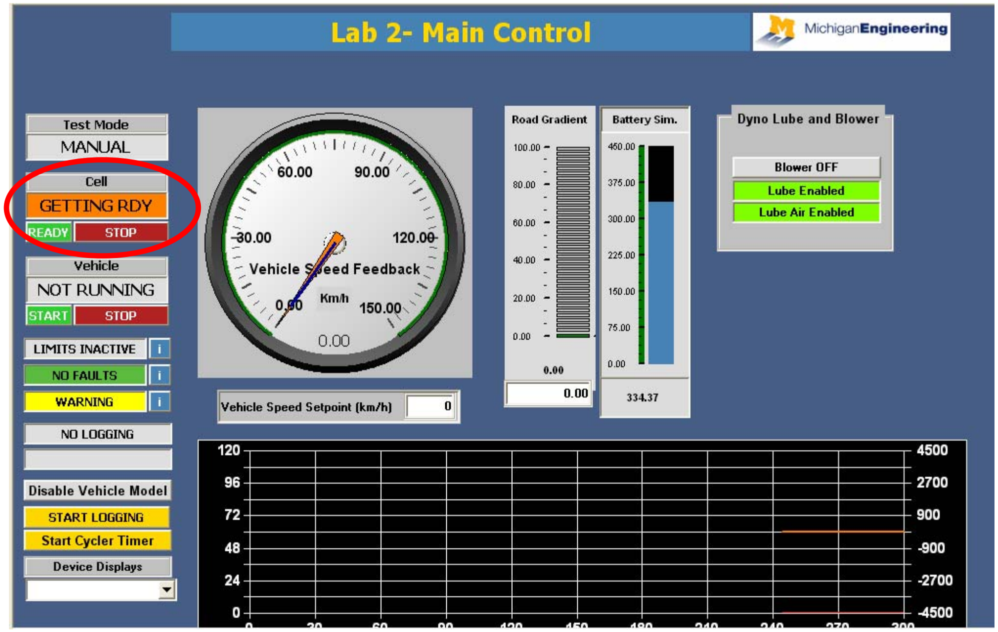
8. To start the ***iTest*** solution, double click on the ***iTest Console 3.1*** logo - located at the desktop of the ***iTest GUI PC***, this will open the commissioned solution. (***Solution.UofM.HEV.Lab2***)



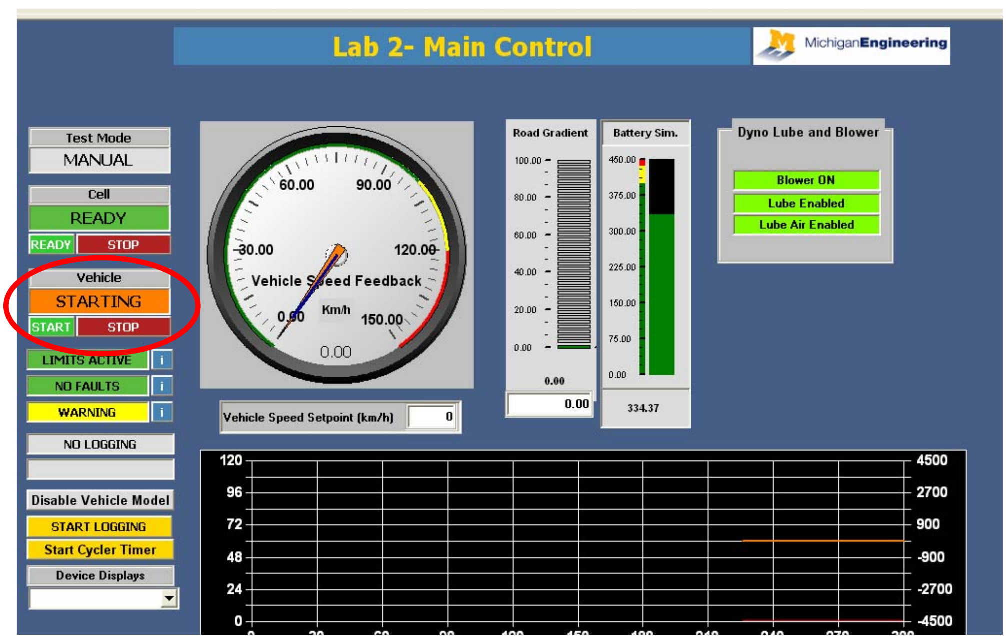
9. After opening the solution, the user will see a pop-up screen on the main screen. Click "***Start Lab 2***"



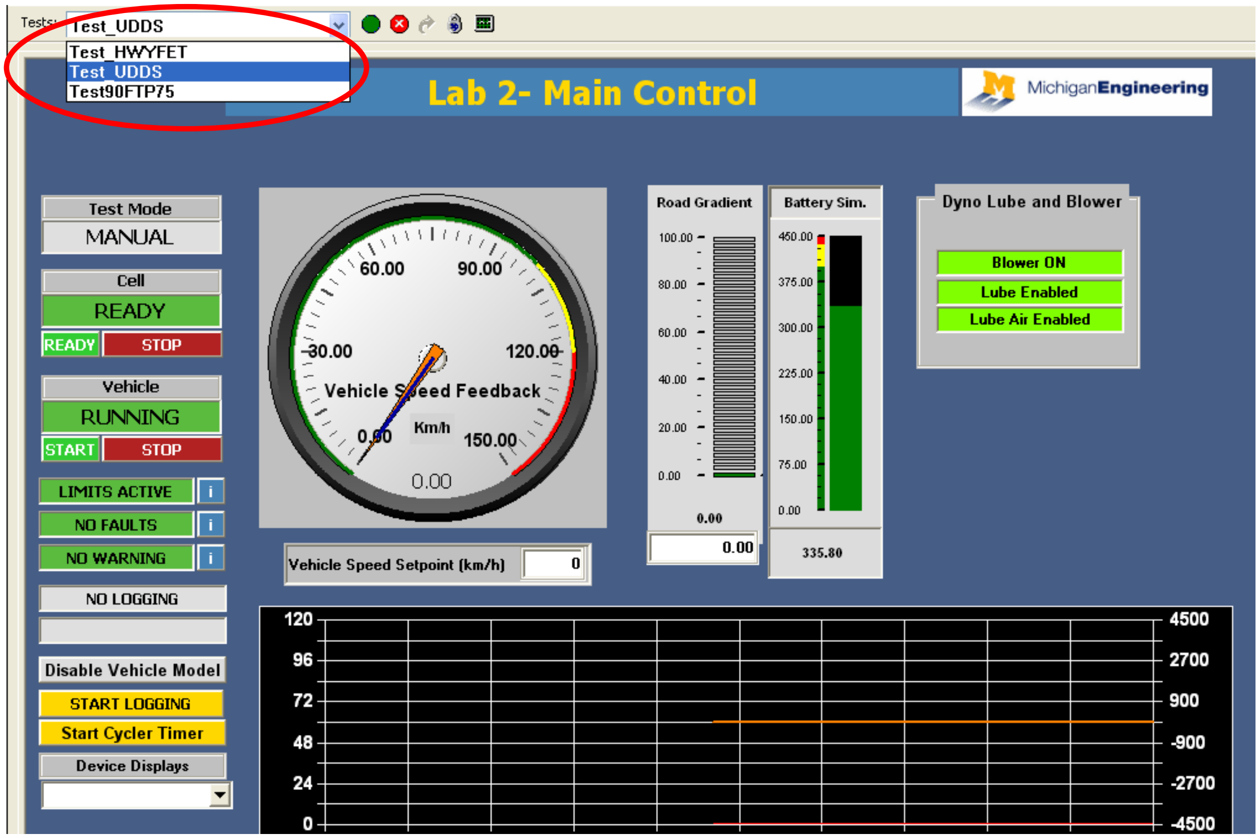
10. Before running or sending commands make sure the system is up and has voltage. Click on READY, wait for the system to be ready



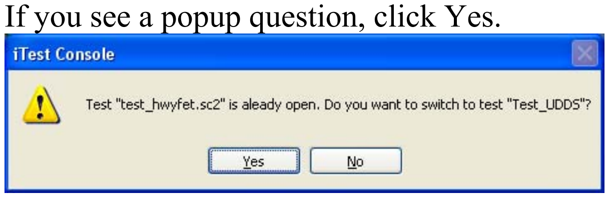
11. Next step is to provide voltage to the system, clicking on START and wait for the system to be started and ready to run.

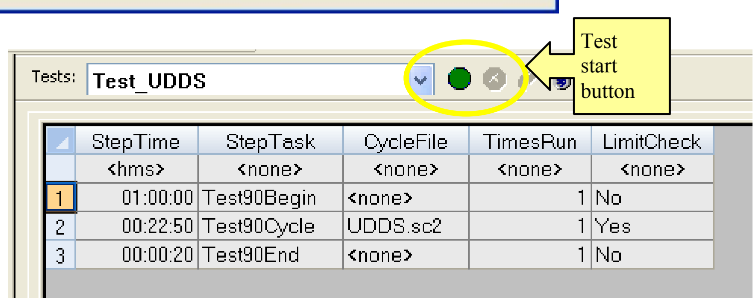


12. To run the driving cycle, first the user needs to select the test and then run it.

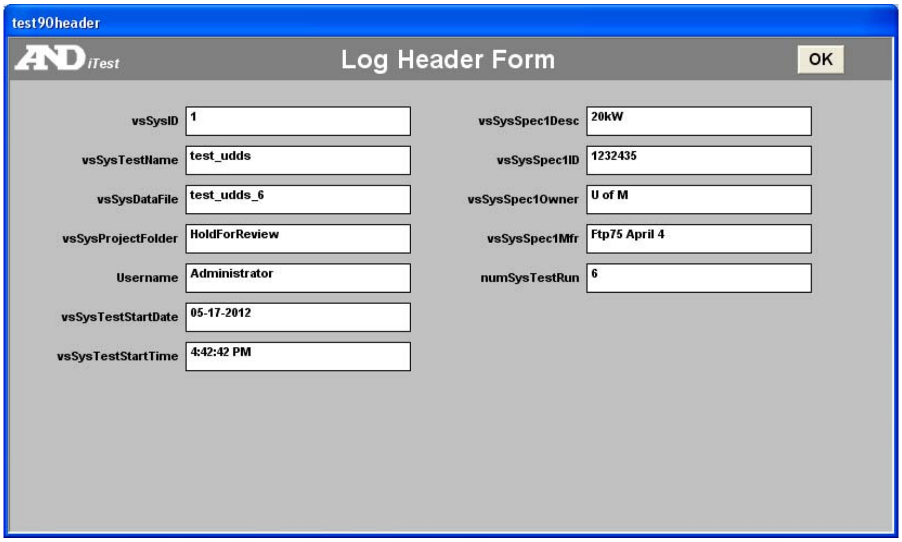


If you see a popup question, click Yes.

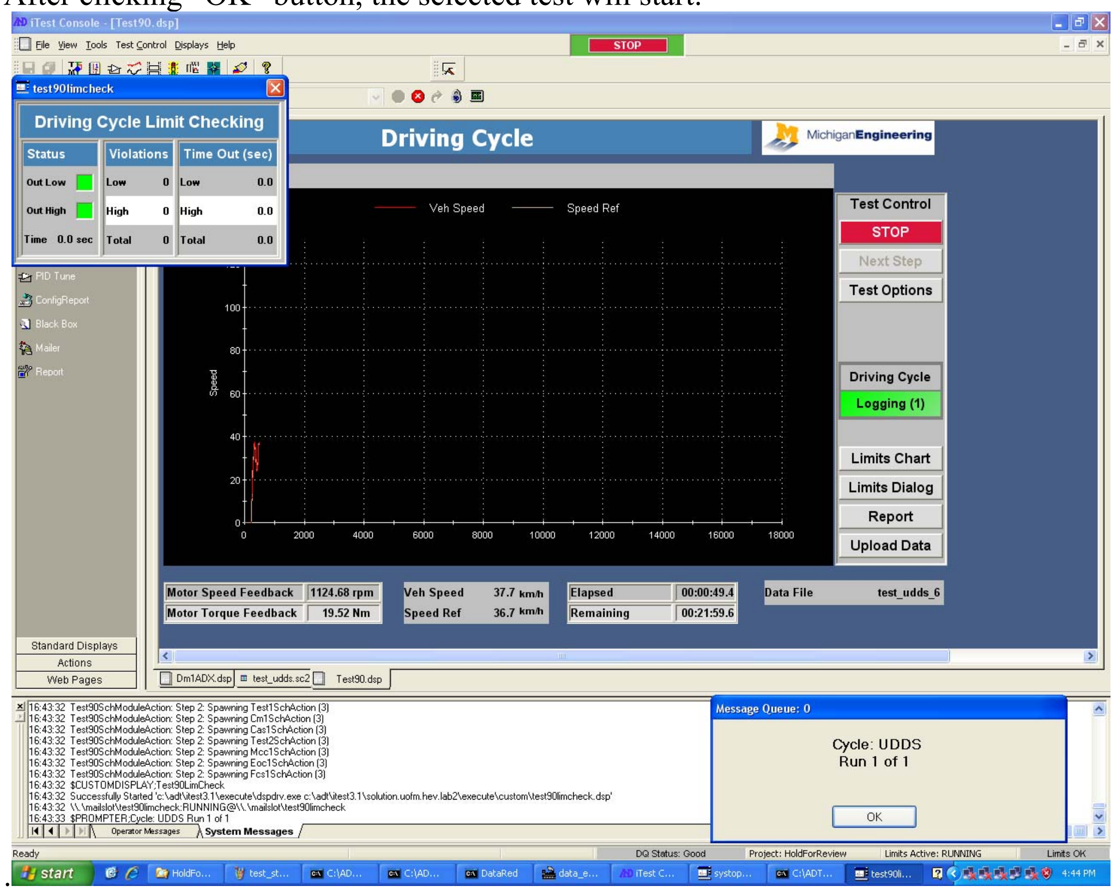




After clicking on the START button (green button)
Information screen of the log data file will be popped up. You can use default values or modify the fields as you want.



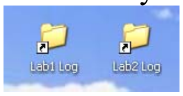
After clicking "OK" button, the selected test will start.

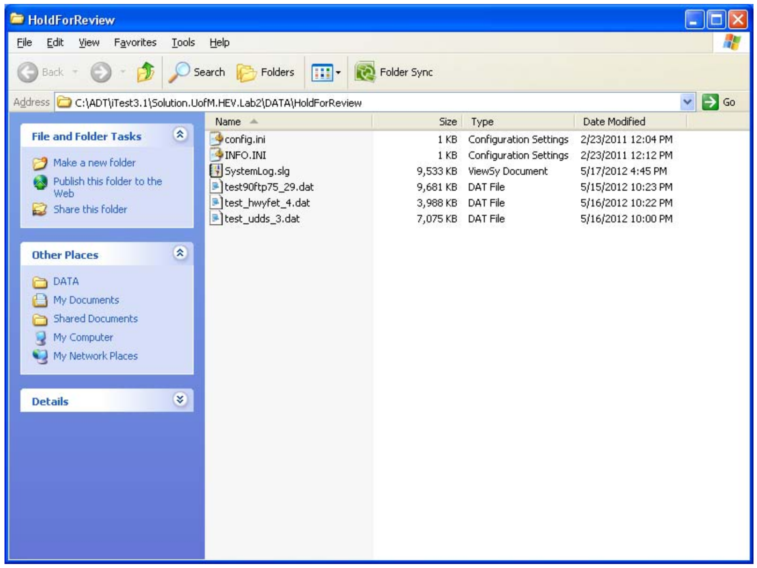


.

13. The test log file will be saved in "**C:\ADT\iTest3.1\Solution.UofM.HEV.Lab2\DATA\HoldForReview**" and can be

accessed by clicking Lab1 Log shortcut located at the desktop of ***iTest GUI PC***.





The file names for the test named “Test_UDDS” will be “test_udds_1.dat”, “test_udds_2.dat”…etc.

The file names for the test named “Test_HWYFET” will be “test_hwyfet_1.dat”, “test_hwyfet _2.dat”…etc.

5.3. Engine Test

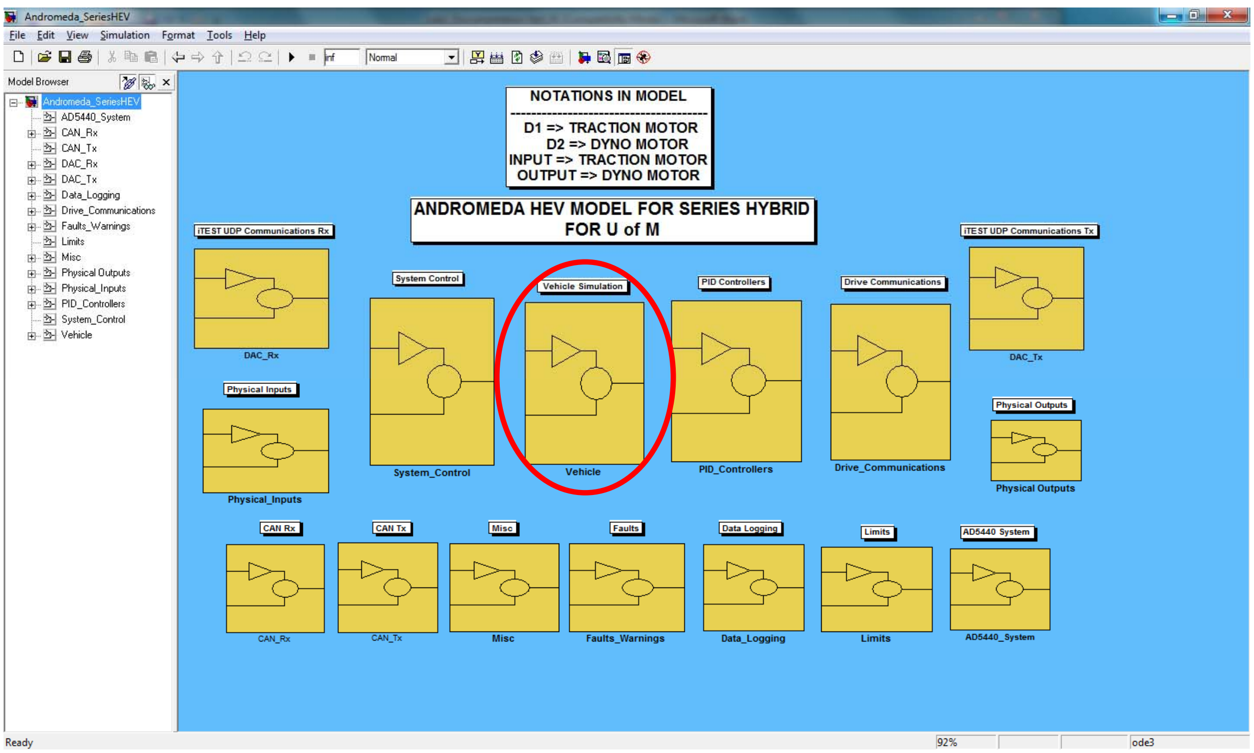
See engine manual and Lab 3 manual

Editing Simulink File in Procyon PC

If one needs change the vehicle model (In case that you need change only parameters in the vehicle, follow the previous instruction of VCDesigner in Chapter 5.2.4), refer the following instruction.

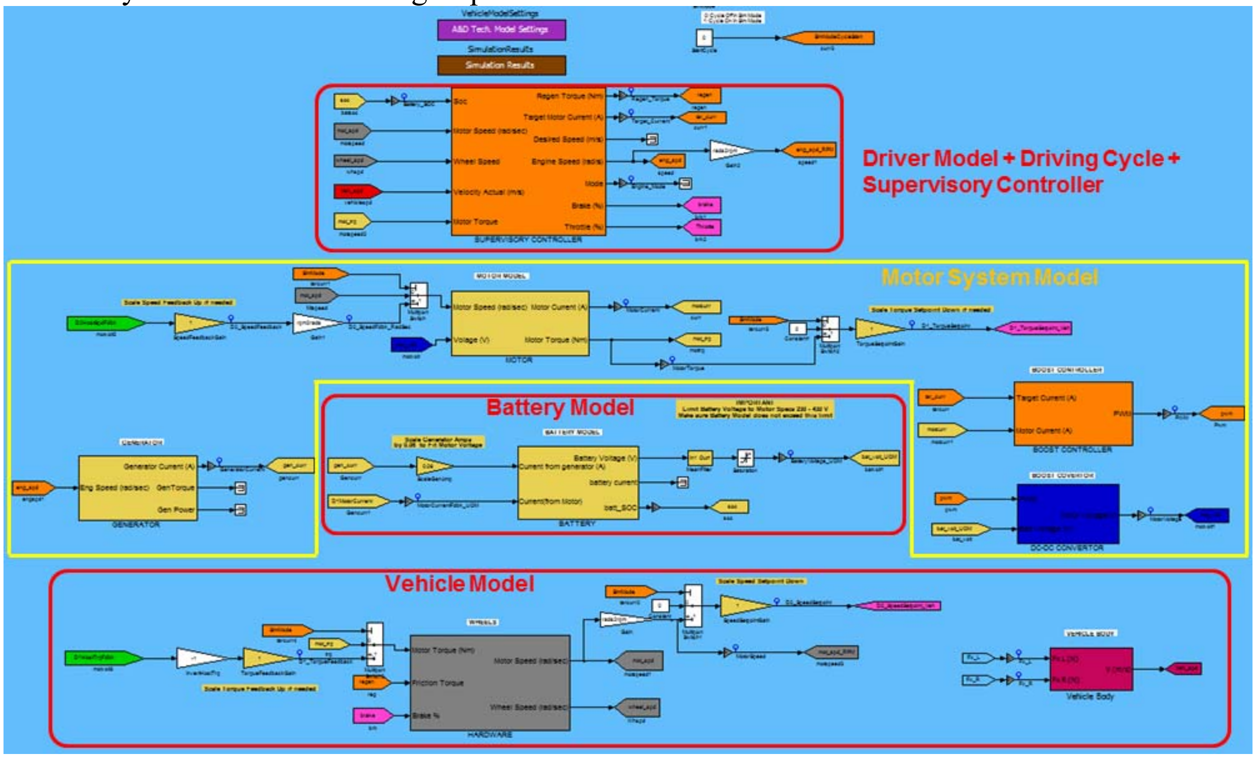
Before modifying any Simulink blocks, please copy the whole folder and rename the copied folder.

1. Open the Simulink file. Go to the folder "**C:\Your Folder**" and double click "Andromeda_SeriesHEV.mdl ", then you will see the following window.

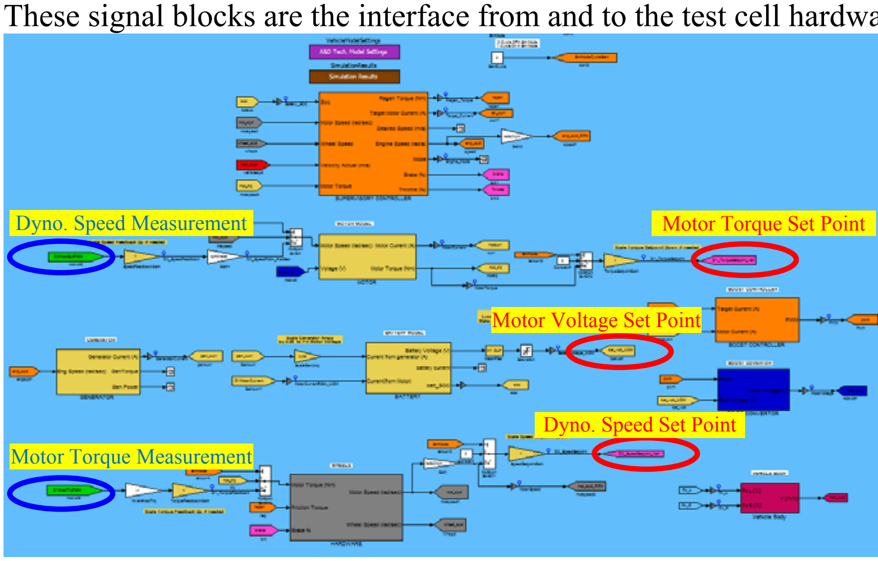


The basic vehicle parameters are in "load_parameter_seriesHEV.m".

2. To edit the 'Vehicle' block, double click the block, then following window will pop up. The system consists of four groups of functional blocks.

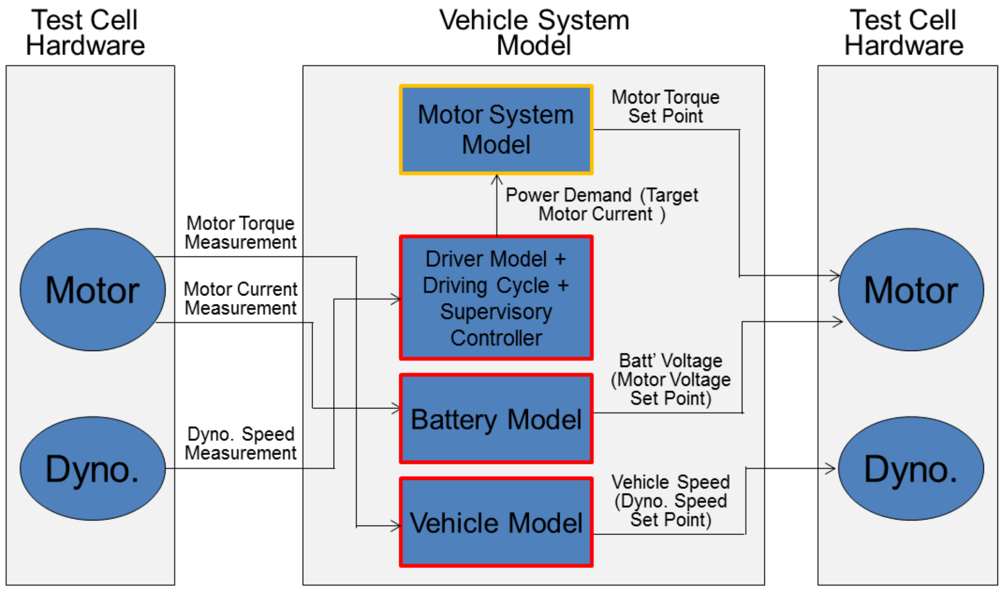


Most of Simulink blocks can be modified but the following 5 From/Goto blocks should exist. These signal blocks are the interface from and to the test cell hardware.

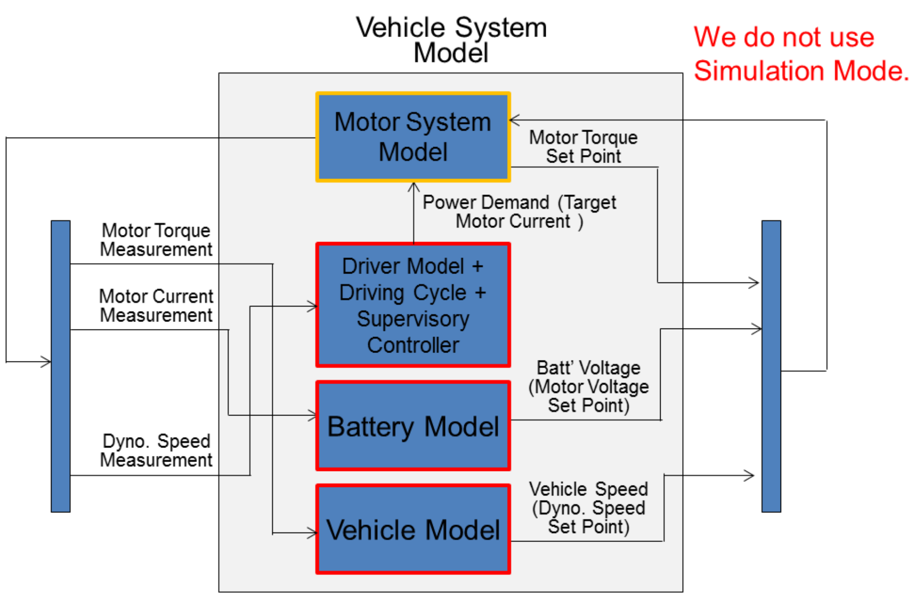


This ‘Vehicle’ block supports 2 mode: ‘Test Cell Mode’ and ‘Simulation Mode’.
In ‘Test Cell Mode’, we use the signals from the physical motor and the physical dynanometer. In ‘Simulation Mode’, we use the signals from the ‘Motor system Model’ in the Simulink file. (We do not use simulaiton mode for Lab 2).

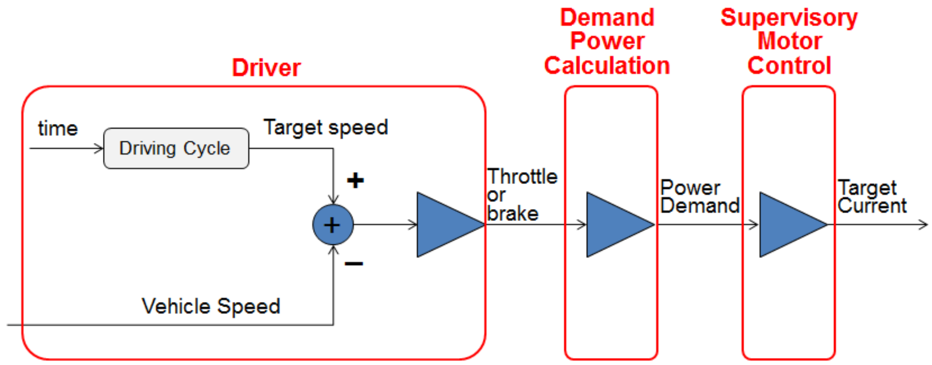
The conceptual functional diagram of ‘Test Cell Mode’ is:



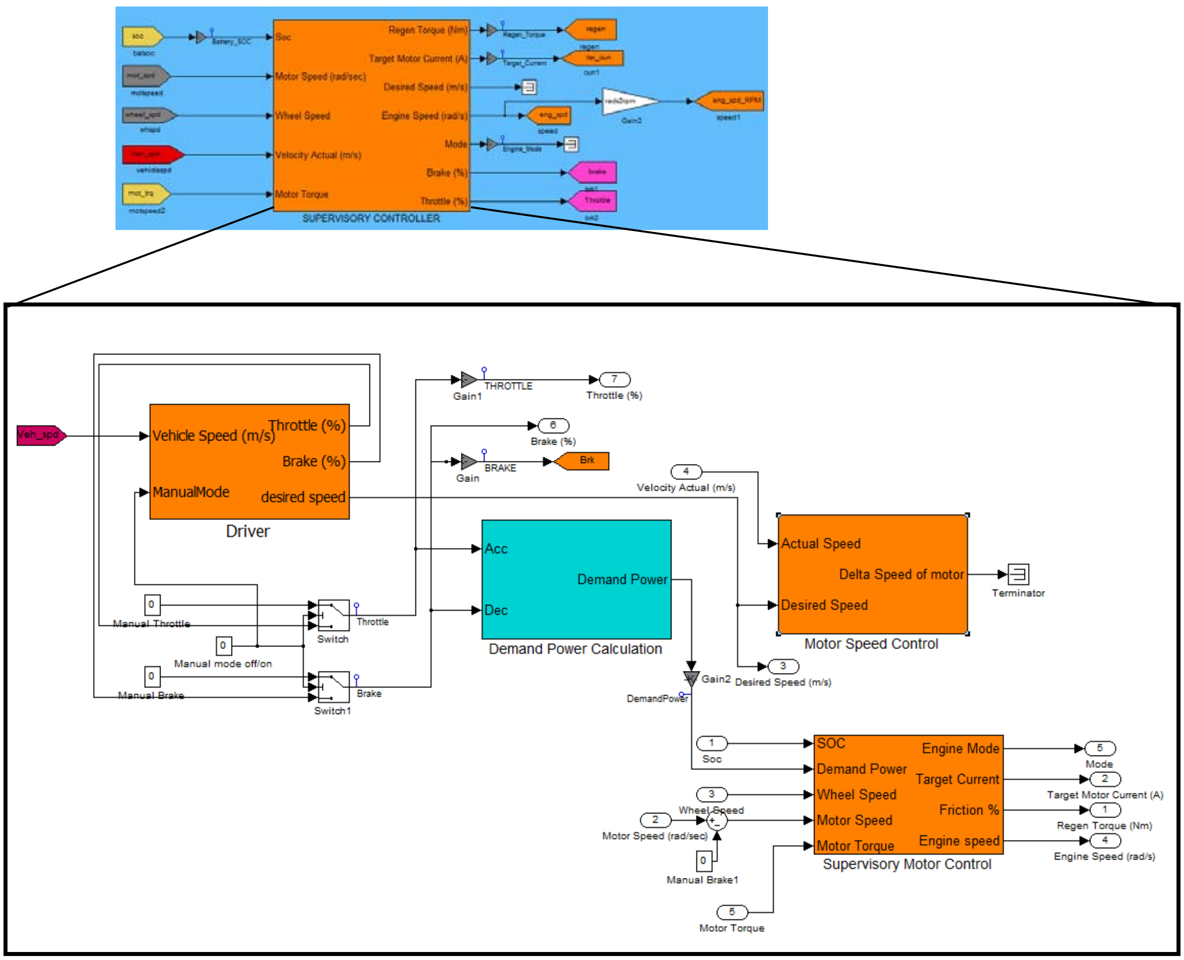
The conceptual functional diagram of ‘Simulation Mode’ is:



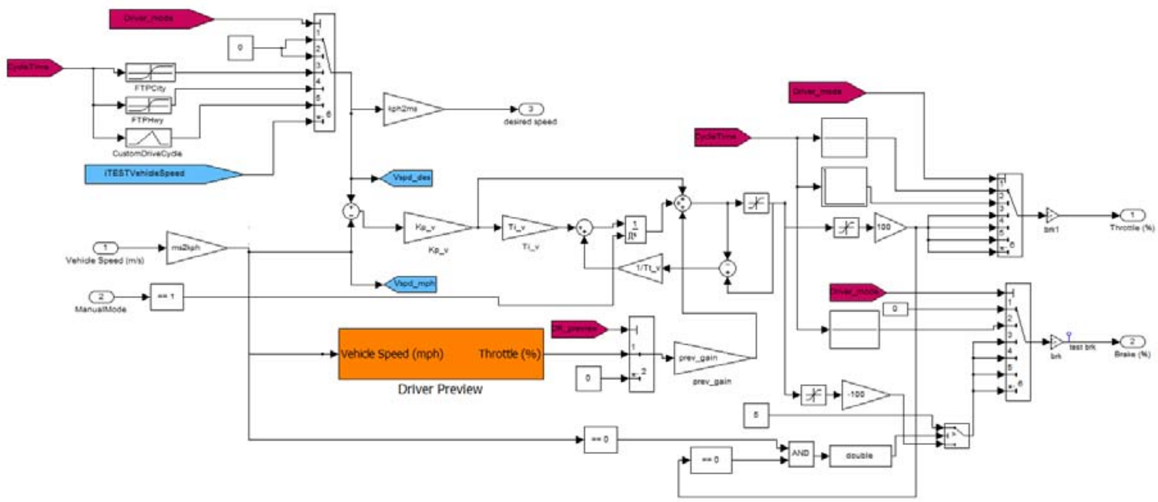
3. Editing ‘Driver Model + Driving Cycle + Supervisory Controller’:
3-1. Conceptual diagram:



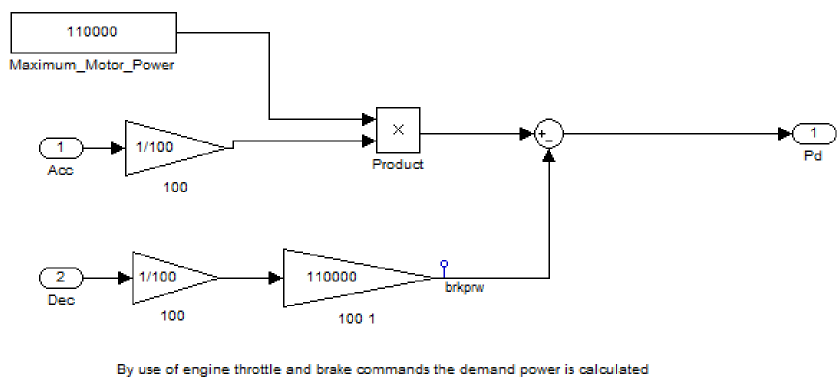
3-2. Simulink



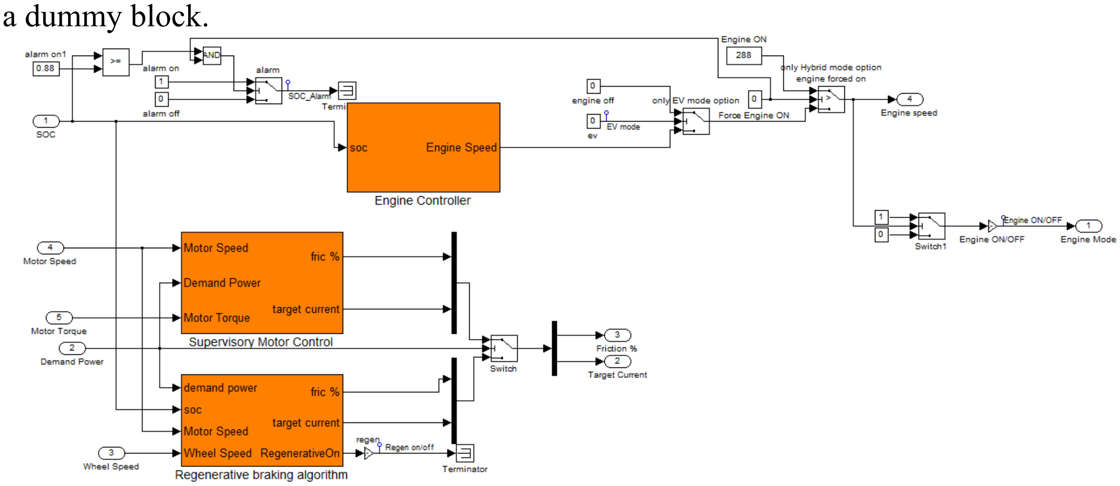
3-3 Driver Block: driver model consists of prview and feedback parts.



3-3 Demand Power Calculation Block: Power demand is proportional to the acceleration and deceleration demand.

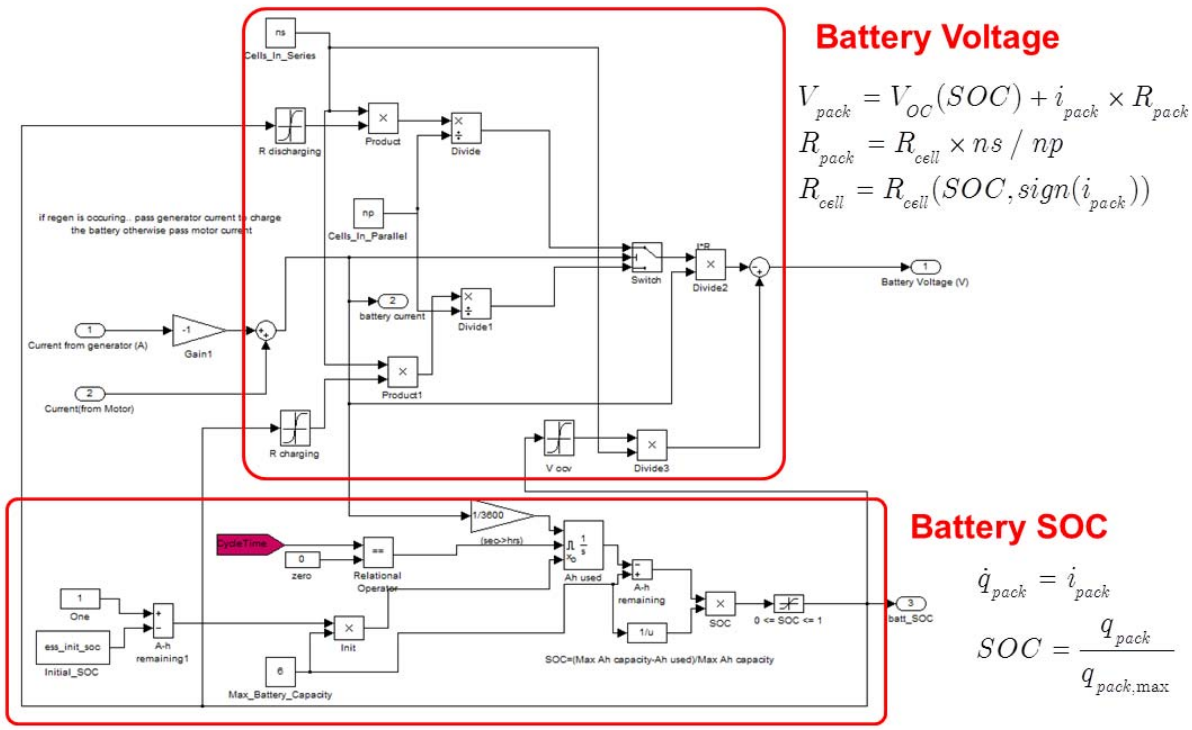


3-4 Supervisory Motor Control Block: Three blocks exist. Among them, 'Engine Controller' is a dummy block.



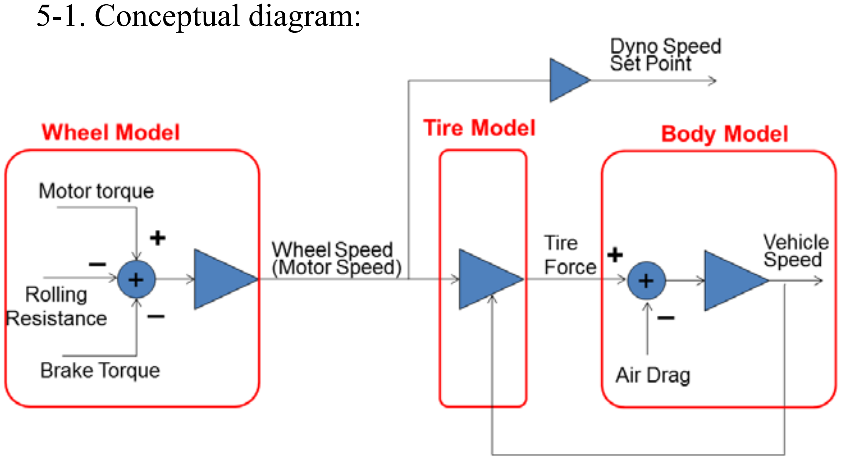
3-5 Motor Speed Control: This is a dummy block.

4. Editing 'Battery' block: Battery block consist of the voltage computation part and the SOC computation part.



5. Editing 'Vehicle Model'

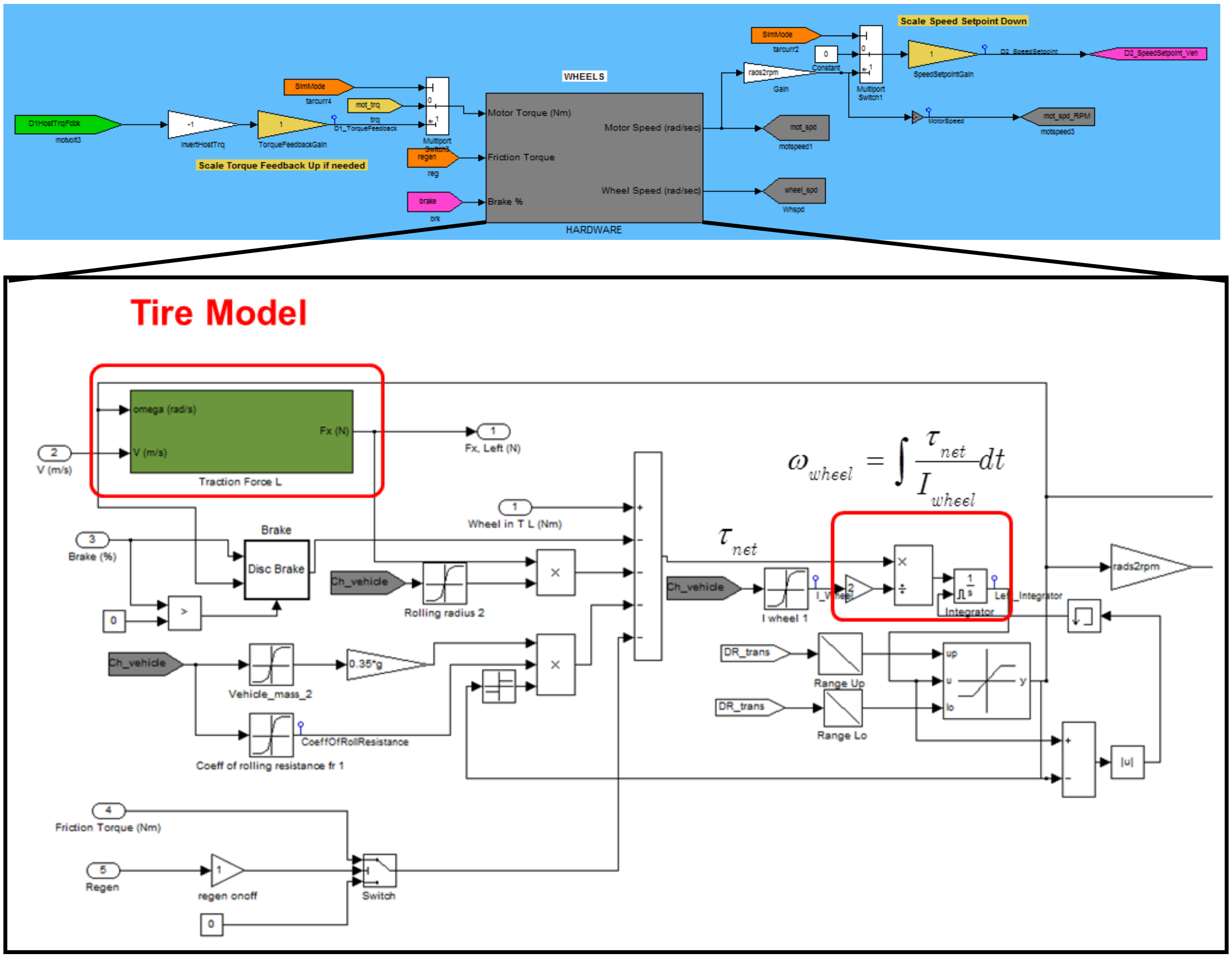
5-1. Conceptual diagram:



5-2. Wheel Model:

$$\omega_{wheel} = \int \frac{\tau_{net}}{I_{wheel}} dt,$$

$$\tau_{net} = \tau_{motor} - \tau_{brake} - \tau_{body\ inertia} - \tau_{rolling\ resistaance}$$



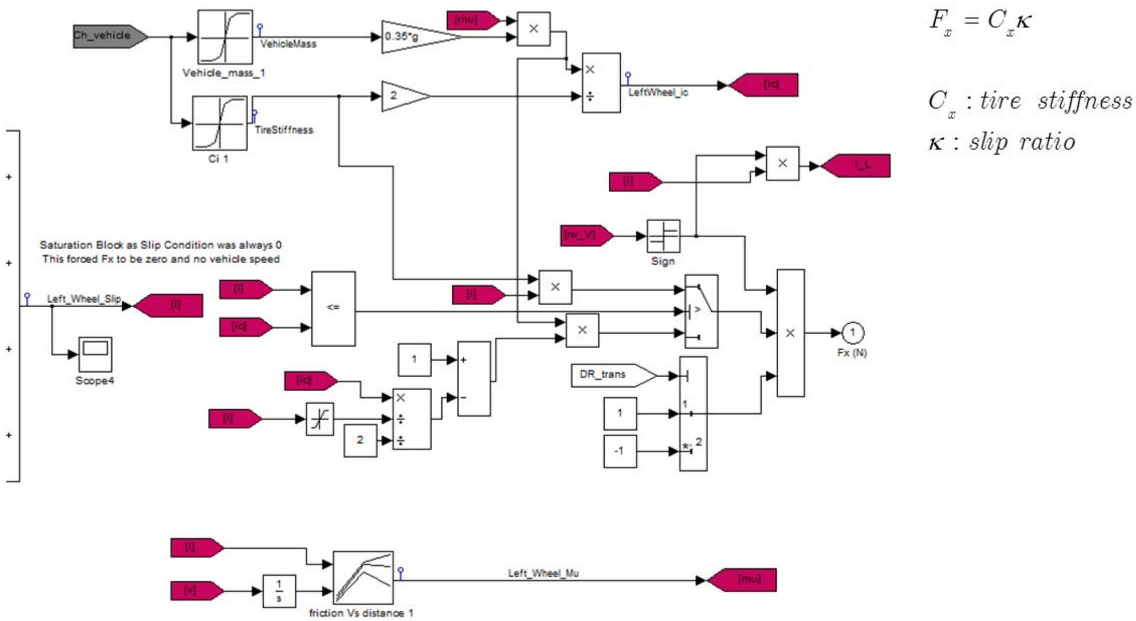
5-3. Tire Model: Simple linear tire model.

$$F_x = C_x \kappa$$

$$\kappa = \frac{R\omega_{wheel} - V_x}{V_x}$$

C_x : *tire stiffness*

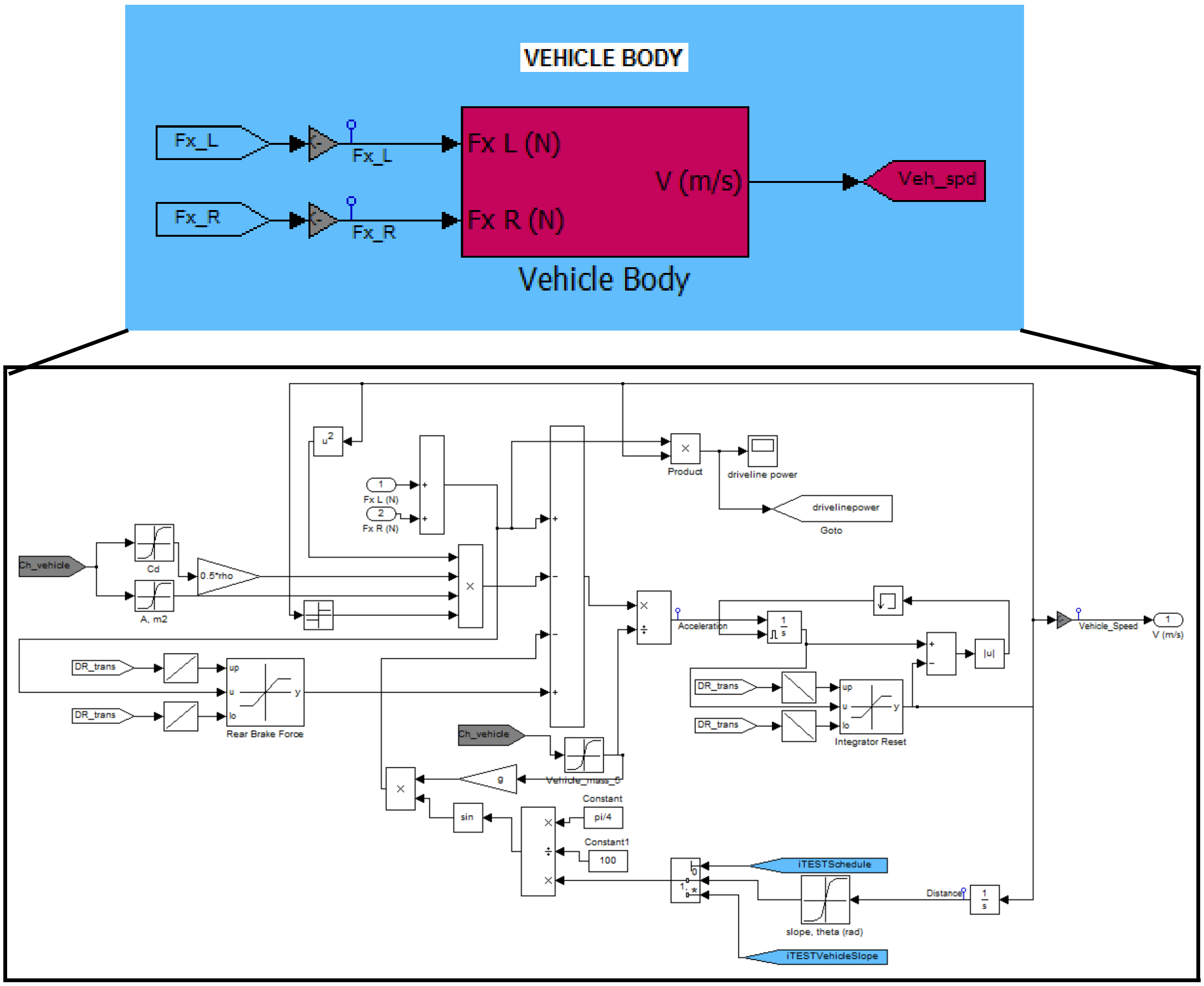
κ : *slip ratio*



5-4. Vehicle Body Model: Simple linear tire model.

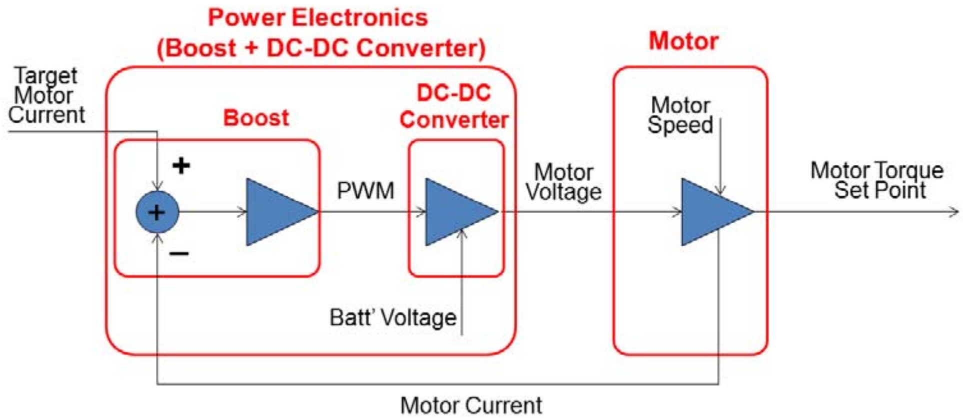
$$V_{vehicle} = \int \frac{F_{net}}{M_{wheel}} dt,$$

$$F_{net} = F_{x,\ tire} - F_{air\ drag} - F_{road\ grade}$$

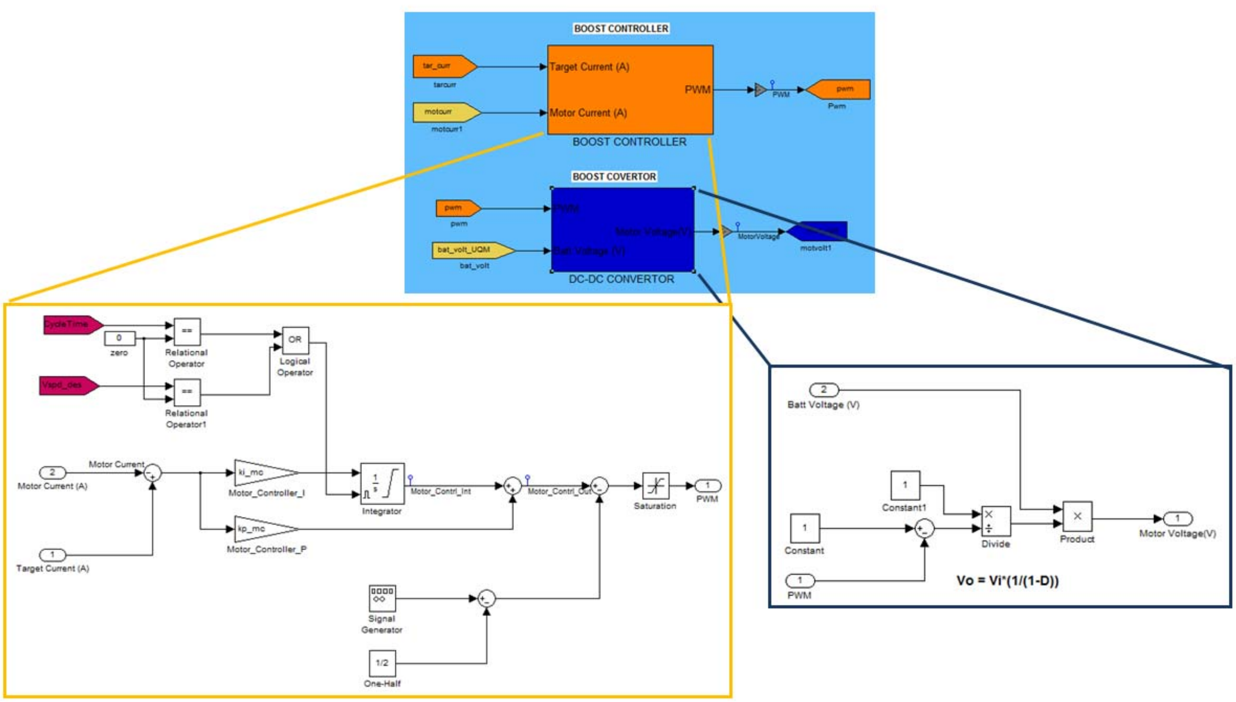


6. Editing 'Motor System'

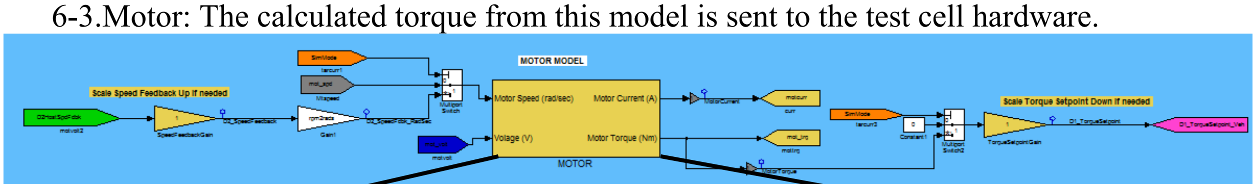
6-1. Conceptual diagram:

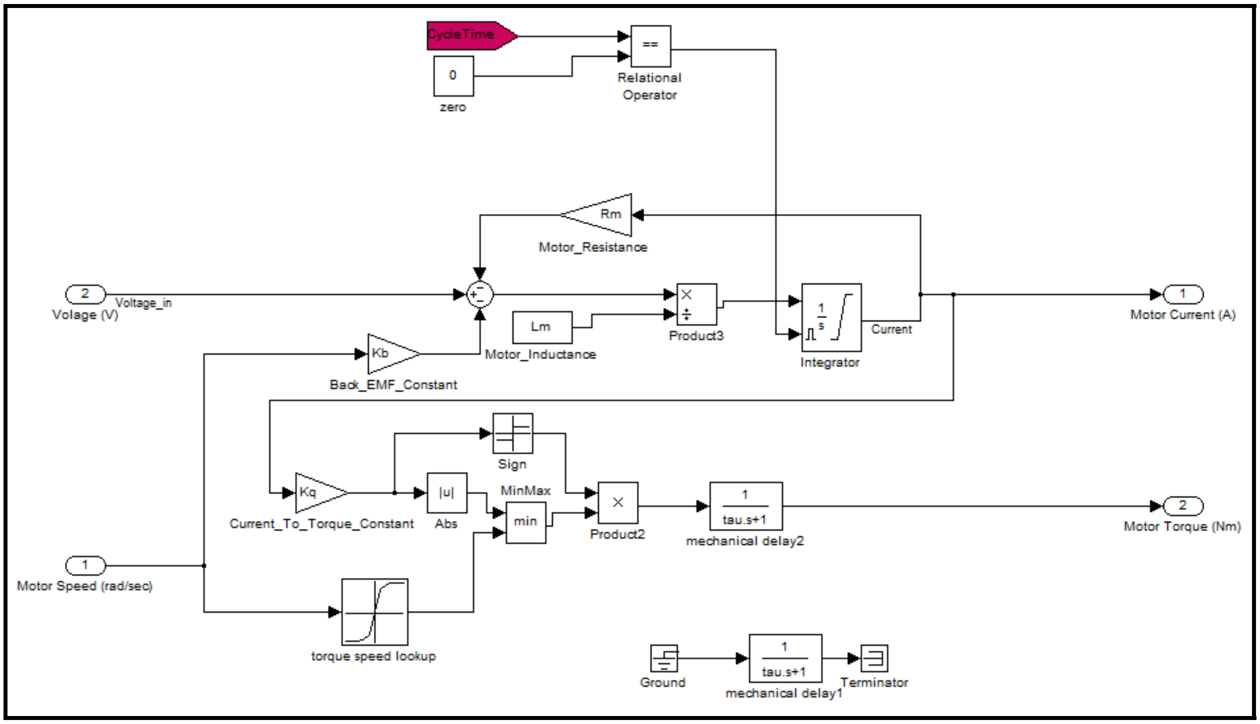


6-2. Power Electronics: It consists of 'Boost Controller' and 'DC-DC Converter'



6-3.Motor: The calculated torque from this model is sent to the test cell hardware.





7. Save the Simulink file.

8. Compiling: To use the modified Simulink file for the Lab 2, the file has to be compiled.

   To compile the file, click Tools>Real-Time Workshop>Build Model, or, alternatively, press Ctrl + B in the Simulink file window.
   Then, there will be newly created **Andromeda_HEV_Model.apf** fiile**.**

Appendix G. Syllabus of “Course 402” Automotive Power Electronics Laboratory

EECS 419 Power Electronics
Fall 2011

1. **Prerequisites**: EECS 215 and EECS 216, and preceded or accompanied by EECS 320, or graduate standing.

2. **Lecture, Lab Times:**
   Lecture: MW 3-4:30
   Lab: Thursday or Friday 3-6

3. **Purpose:** Meeting the future’s energy and environmental challenges will require the efficient conversion of electrical energy from one form to another. This course will discuss the circuits used to efficiently convert AC power to DC power, DC power from one voltage level to another, and DC power to AC power. The components used in these circuits (e.g., diodes, transistors, capacitors, inductors) will also be covered in detail. A key aspect of power electronic circuits is the control algorithms used to achieve the desired behavior (e.g., output voltage regulation), and so control theory as it applies to these circuits will be discussed. A lab will be held with the class where the students will obtain hands-on experience with power electronic circuits.

4. **Objectives:** Upon successful completion of this course, the student should:
   1. Understand how fundamental power electronic circuit topologies operate.
   2. Quantitatively determine the power quality impact of AC-connected power electronic circuits.
   3. Be able to design control algorithms for DC-DC converter circuits.
   4. Be familiar with the properties of power semiconductor devices (i.e., diodes, transistors, …) as they are used in power electronic circuits.
   5. Understand how to calculate the efficiency of power electronic circuits.
   6. Be able to analyze and design magnetic inductors and transformers for power electronic circuits.
   7. Possess a basic understanding of the cooling of power electronic circuits
   8. Have hands-on experience with many power electronic circuit topologies in the laboratory.
   9. Have designed a power electronic circuit as part of a course project.

5. **Topics**

AC-DC Conversion
DC-DC Conversion
- Fundamental converter topologies
- Isolated converter topologies

Control of DC-DC Converters
Power Semiconductor Devices
- Diodes
- Thyristors
- BJTs
- MOSFETs
- IGBTs

Power Electronic Components
- Capacitors

Inductors, Transformers
Auxiliary Circuitry
Gate and Base Drive Circuits
"Snubber" Circuits
Thermal Analysis

6. Texts:

Required:
Mohan, Undeland, and Robbins. *Power Electronics*, 3rd edition. John Wiley & Sons, Inc. New York, 2003.
Suggested:
Kassakian, Schlecht, and Verghese. *Principles of Power Electronics.* Addison-Wesley. Reading, Mass., 1991.
Krein. *Elements of Power Electronics*. Oxford University Press. New York, 1998
Erickson and Maksimovic. *Fundamentals of Power Electronics,* 2nd edition. Springer. New York, 1999.

7. Instructors:

Prof. Heath Hofmann	Office hours:
4116 EECS	Tuesdays and Wednesdays 10:30-12
(734) 647-1107	Other times by appointment
hofmann@eecs.umich.edu	
Prof. G.R. Lahiji	Office hours:
3115 EECS	Monday and Thursday 1:30-3:00
(734)763-1156	Other times by appointment
roientan@umich.edu	

8. Exams: The class will have one in-class midterm (whose time has yet to be determined) and a fina.l If you have a valid reason for missing the midterm, you must notify the instructor at least two weeks in advance so that a conflict exam can be prepared. Students from all sections will take identical exams. Exams are closed-book, but each student is allowed a single 8.5" by 11" note sheet. Exams are returned during lecture sessions. Any student caught cheating on an exam will receive a grade of 0 for the exam. Additional sanctions may also be pursued, following university guidelines.

9. Homeworks: Homeworks will be assigned on Mondays, and, unless otherwise noted, will be collected during lecture on the Wednesday of the following week. Students are encouraged to discuss homework problems in groups. **However, each student must submit their own work.** Students submitting identical work will receive a grade of zero for the homework set. Problem set solutions will be posted on the CTOOLs web site. Graded homework sets will be returned in class. **Late homework will not be accepted.** However, the lowest homework score will be dropped in calculating your overall homework grade. In order to perform well on the exams, it is important that you work each problem assigned. Although your final homework grade may be unaffected if you do not turn in one of the problem sets, your exam grades, which play a much larger role in determining your final grade, will be adversely affected.

10. Labs: In addition to the lectures, a lab will be held every week where the students will obtain hands-on experience with electric machines and drives. Students will work with a partner in the labs, and submit a joint lab report. In addition to including the data obtained during the lab, lab reports must be well-written and clearly explain the concepts presented during the lab. It is **not** acceptable to use data collected by other lab teams in your lab report; you must use your own. If there are problems with your lab data, contact the lab assistant. Measured results will be compared to expected values, with any discrepancies clearly discussed. Further information on the preparation of lab reports will be handed out during the first lab section.

Lab times will be established during the first week of classes, after student's schedules have been submitted, to determine times that will work best.

11. Project: At the end of the semester, students will complete a project involving the design, construction, testing, and demonstration of a power electronic circuit. Students will work on the project during lab times with their lab partner.

12. Grading: The following weighting factors determine your total course score:

Project	**10%**
Homework	**20%**
Lab Reports	**20%**
Midterm	**25%**
Final	**25%**

The class average does not determine the cutoff points for letter grades. Instead, the cutoff points reflect the technical competencies required of an electrical engineer. The following scale determines your final course grade:

A+	95%-100%
A	90%-95%
A-	85%-90%
B+	80%-85%
B	75%-80%
B-	70%-75%
C+	65%-70%
C	60%-65%
C-	55%-60%
D+	50%-55%
D	45%-50%
D-	40%-45%
E	<40%

At the discretion of the instructor, the minimum score needed to earn a certain letter grade may be lowered, but it will not be raised.

13. Web Page: Problems sets and other important files and announcements will be posted on the EECS 498 CTOOLS site.

14. Attendance: Although attendance will not be taken, you are expected to attend lecture. It is a student's responsibility to acquire handouts and information disseminated in class.

MECHENG 499-007/599-007 Special Topics Course

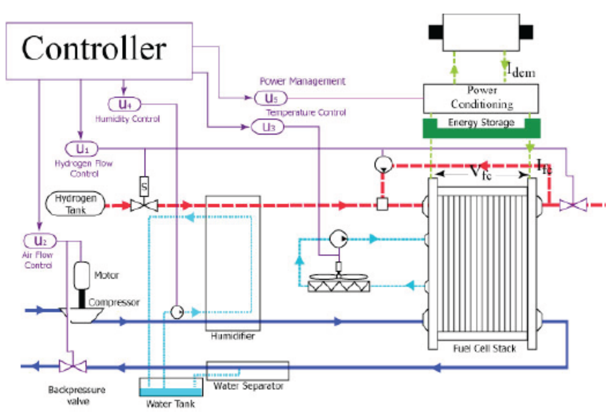
Hydrogen and Fuel Cell Systems

Instructors: Don Siegel and Anna Stefanopoulou
djsiege@umich.edu annastef@umich.edu

Fall 2011 **MW 9:30AM-11:00AM**
Room **104 EWRE** – 3 Credits

Course statement: This course covers essential aspects of fuel cell vehicle technology, hydrogen fueling infrastructure, and potential benefits & barriers to the use of hydrogen as a vehicular fuel. Emphasis is placed upon system-level modeling and control issues of polymer electrolyte membrane fuel cells and on the principles and design of on-board hydrogen storage systems. Hydrogen generation and distribution technologies are introduced, and life-cycle (well-to-wheels) analyses of petroleum consumption, efficiency, and CO_2 reduction are presented. Lectures will be supplemented with fuel cell vehicle demonstrations conducted by local automotive OEMs, and site visits to hydrogen fueling stations.

Requires a basic background (undergraduate level) in signals and systems or controls (Laplace transforms, time/frequency analysis and control design tools), and basic chemistry and thermodynamics of materials. Mathworks/Matlab will be used.



Text: Lecture notes will be distributed in class or through Ctools.

Optional sources:

1. Fuel Cell Fundamentals by Ryan O'Hayre, Suk-Won Cha, Whitney Colella, Fritz B. Prinz
2. Fuel Cell Systems Explained, Larminie, and Dirks, Wiley
3. The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs (National Academies Press)
4. Transitions to Alternative Transportation Technologies – A Focus on Hydrogen (Na. Academies Press)
5. Hydrogen Fuel: Production, Transport, and Storage (R. Gupta, CRC Press)
6. Mobility 2030: Meeting the Challenges to Sustainability (World Business Council for Sustainable Development)

Grading: 2 Quizzes: 20% each, Term Presentations: 30%, Homework: 30% (approximately 6)
Graduate students (599) and undergraduates (499) will be graded separately.

Quizzes (2): Take-home with fixed "test-time window" and on-line submission via ctools.
Dates: Quiz 1 Wed. October 12
Quiz 2 Wed. Nov. 23

HW policy: Assigned and due as indicated on course calendar.
Late HW will be marked down 25% per day late.
After two days late submissions will not be accepted.

Term presentations: Students will work in small teams to develop an annotated presentation on a topic drawn from the recent fuel cell/hydrogen literature. The instructors will provide a list of several potential topics; however, students can propose their own topic if so desired. The presentations will be conducted during the last 3 lectures of the semester, and should be approximately 20 minutes in duration. An annotated copy of the slides is due on November 30th. The selection of topics and submission of an outline will take place by Oct 31st.

Office hours: **Anna Stefanopoulou –** Tues and Wed 12-1 Autolab room 2044
Don Siegel – Monday and Wed 4-5, Autolab room G050

Tentative Course Topics:

Chapter 1: Overview: Fuel Cell Vehicles (FCV) and Hydrogen as a vehicular fuel
Benefits of a transition to FCV
(Reduced petroleum consumption, energy independence, lower CO_2 emissions…)
Types of fuel cells and their Chemistries
Barriers to the commercialization of FCV
(Infrastructure, H_2 production & storage, FC durability, DOE Performance and cost Targets)

Chapter 2: Modeling and Control of Polymer Electrolyte Membrane Fuel Cells
Voltage regulation (Pressure boost & Voltage buck/boost)
Air Flow Loop (sizing, pressure selection, stoichiometry, autonomy)
Cooling Loop
Hydrogen Loop (high pressure pure H2, Backpressure & Recirculation loop, Dead-ended)
Water management
Startup and Mal-distribution
Impedance diagnostics
Degradation

Chapter 3: Fuel Cell Vehicle
Basic architecture of a FCV ("a FCV is a HEV")
Power electronics, Hybridization strategies
Power Management, Battery and FC Sizing

Chapter 4: Hydrogen production technologies
DOE Targets for cost and efficiency
Technologies: Coal, natural gas (steam reforming), nuclear energy, electrolysis, wind and solar energy, biomass and photobiological processes

Chapter 5: Infrastructure for Hydrogen Distribution and Refueling
Scenarios for the introduction of FCVs and their supporting infrastructure
Distributed hydrogen production vs. production at central stations

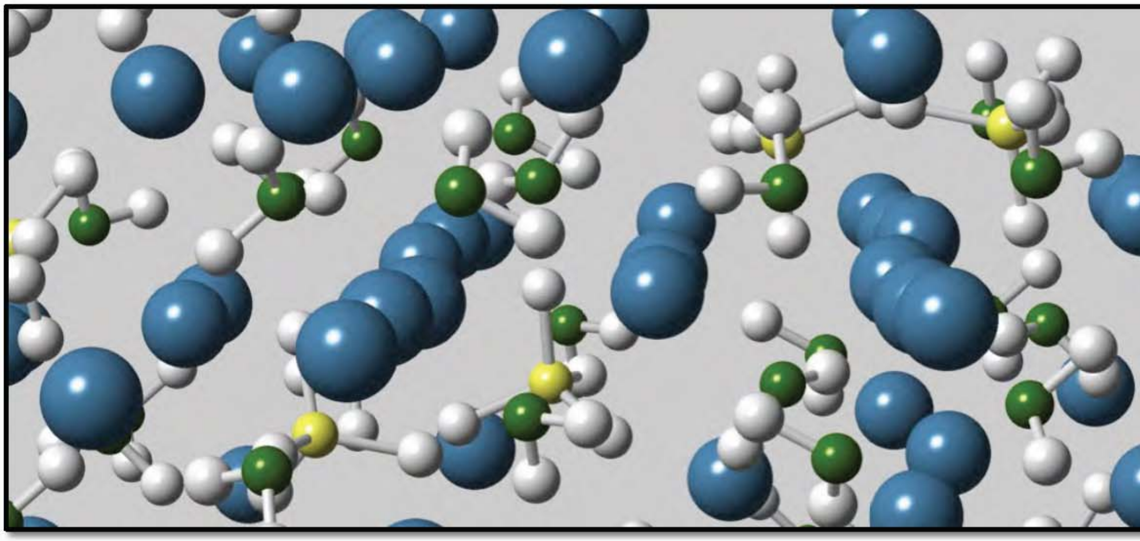
Maximum practicable number of vehicles that can be fueled by hydrogen by 2020
Funding and policy actions needed to achieve that goal

Chapter 6: Hydrogen Storage I: Fundamentals
DOE System-level targets, Types of storage: physical vs. chemical
Chemical storage methods: conventional metal hydrides, complex hydrides, chemical hydrides, sorbents, Capacity, Thermodynamics, Kinetics

Chapter 7: Hydrogen Storage II: Engineering considerations
Thermal conductivity, Effective media density
Heat management during refill
Control and interface with the FC powerplant

Chapter 8: Life-cycle and Well-to-Wheels Analyses of FCV
Introduction to the Argonne H2A Model, Petroleum consumption
Greenhouse gas emissions (CO2 reduction), Energy efficiency/energy use
Cost of ownership, Comparisons with: conventional ICE vehicles, HEV, PHEV, EV

Appendix I. Syllabus of an extended course to complement “Course 403”



MECHENG 499/599-001 Special Topics Course:

Atomistic Computer Modeling of Materials

Monday and Wednesday 1:30 – 3:00PM, Fall 2012
EWRE 185

Computational hardware and algorithms have evolved to the point where they present a compelling alternative to the traditional experiment-based approach to materials research and development. This course will cover the core methods used to simulate matter at the atomic scale, and will offer hands-on experience with a number of research-caliber simulation codes on multi-processor clusters. Several applications will be highlighted, ranging from the mechanical properties of solids to the discovery of new materials for energy storage.

Topics:

1. Preliminaries: Structure of matter and Inter-atomic potentials
2. Molecular dynamics
3. Monte Carlo methods
4. Electronic structure methods: Hartree-Fock & Density Functional Theory
5. Transition state theory
6. Accelerated dynamics and multi-scale modeling

Instructor: Prof. Don Siegel, Mechanical Engineering and Applied Physics

djsiege@umich.edu

ECE 436 – "Electric Machines and Hybrid Drives"

Prerequisites: ECE 311 as a pre-requisite.
This is an introductory course on electric machines and drive systems and their applications in EV, HEV, PHEV and FCV powertrains. The objectives are to familiarize the students with the basic concepts of electromechanical energy conversion and electric drive systems. Students are expected to be able to analyze and design electric drive systems for automotive powertrain applications. The topics covered in this course include DC machines, induction machines, permanent magnet AC machines, and switched reluctant motors and drives. Case studies in automotive applications such as electric and hybrid drivetrains will be discussed.

TOPICS:
1. Characteristics of Vehicle Loads
2. DC Motor Drives
3. Permanent Magnet AC Machine Drives
4. Induction Motor Drives
5. Switched-Reluctance Machine Drives
6. Case Studies: EV, HEV, Plug-In Hybrid, Fuel Cell Vehicles
7. Projects
8. Exams

INSTRUCTOR: Prof. Taehyung Kim, Office: 140 CIS, Phone: 313-583-6736.
Email: taehyung@umich.edu

Office hours: Tuesday: 2:00 - 4:00 PM, Wednesday: 2:00 - 4:00 PM.

Course website: http://vlt.engin.umd.umich.edu/dashboard/ (Course: ECE436-2011, key: 43611). You must register yourself at the course website, using your real name and working email address. All course material, including but not limited to, HW, exam, projects, and announcements will be posted on the course websites.

TEXTBOOK: Ned Mohan, "Electric Drives: An Integrative Approach," MNPERE, 2003

Reference: Mohan, Undeland, and Robbins, ***Power Electronics,*** John Wiley and Sons, Third Edition

PROJECTS:
There will be two design projects.

GRADING: Exams (60%), Projects and Assignments (40%).
Grades are assigned approximately as follows: A (90-100), B (80-89), C (70-79), D (60-69), and E (0-59).

Appendix K. Syllabus of “Curse 405” Vehicular Power System and Loads

ECE 4431 - Vehicluar Power System and Loads

Fall 2011

N. Natarajan and C. Mi

216 ELB
nnarasim@umd.umich.edu; chrismi@umich.edu

Catalog Description

This is an introductory course on power systems and load analysis with focus on automotive applications. The objectives are to familiarize the students with the basic principles and concepts of vehicular power systems and loads. Students are expected to be able to analyze and design basic vehicular power systems. The topics covered in this course include an overview of power systems, vehicular power system architecture, DC and AC power grid in vehicular systems, power system stability, reliability, reactive power control, load flow analysis, short circuit analysis, and vehicular power system protection. Four lecture hours per week.

Prerequisite material

- Circuit analysis
- Physics: Electricity and Magnetism
- Calculus and differential equations
- Complex numbers

Grading

Homework: 20%
Midterm Exam: 30%
Final Exam: 30%
Final Report/Presention: 20%

Academic Code of Conduct (Make sure you read this!)

campus statement

The University of Michigan - Dearborn values academic honesty and integrity. Each student has a responsibility to understand, accept, and comply with the university's standards of academic conduct as set forth by the Code of Academic Conduct, as well as policies established by the schools and colleges. Cheating, collusion, misconduct, fabrication, and plagiarism are considered serious offenses. Violations will not be tolerated and may result in penalties up to and including expulsion from the University.

College of Engineering statement

The Academic Code of Conduct (ACC) of the College of Engineering and Computer Science is based on the premise that all students in the college will perform honestly and ethically in all graded tests, projects and assignments. The CECS Academic Disciplinary Committee is a group consisting of dedicated faculty members and students.
Academic Code of Conduct and procedures for handling cases involving violations

Lesson Plan

Date	Topic	Comments
L1	Introduction to the course. Review of prerequisite materials	
L2	DC circuits, concept of power, power calculations, AC circuits	
L3	Sinusoidal signals, complex exponentials, phasors, real and reactive power, power factor, complex impendance, impedance of resisors, capacitors and inductors, AC circuits	
L4	three phase system, three phase relationships, phase and line-to-line quantities, WYE and DELTA balanced sources/loads, WYE-DELTA transformations	Last day to drop w/o penalty
L5	Completion of power system devices: Transformers, AC generators, Loads, per-unit system, sample calculations with and without per unit system	

L6	Overview of Hybrid Electric vehicles (HEV) and Fuel cell vehicles (FCV): Series HEV, Parallel HEV, Series-Parallel HEV, Fuel Cell vehicles, power management and control of HEV and FCV	
L7	== Continued ===	
L8	Power flow Analysis	Last day to drop with 50% penalty
L9	Power flow Analysis	
L1	Economic dispatch	
L11	Economic dispatch	
L12	Slack	
October 25, 2011	**Midterm Exam**	
L13	Stability - Small signal	
L14	Stability - Large Signal	
L15	Stability - Large Signal	Last day to drop with 75% penalty
L16	Protection / short circuit studies	
L17	Slack	
L18	Power electronics and electric vehicles	
L19	Power electronics continued	
L20	Battery technologies	
L21	Battery technologies	
L22	Thanksgiving Holdiday	
L23	Case Study: Prius Hybrid	
L24	Case Study: Prius Hybrid	
L25	Student presentations	
L26	Student presentations	
December 13, 2011	Student presentations	Classes end. Last day to drop ALL courses with 100% penalty

Appendix L: Agenda of the 2010 and 2011 Summer Camp for High School Students

Electrified Transportation Summer Camp Day 1 Schedule
Wednesday August 11th 2010

8:30	**Report to Camp (1303 EECS)**
9:00	**Welcome & Introductions (1303 EECS)** Professor Huei Peng
9:10	**Lecture 1 Overview and Introduction to Electrified Vehicles (1303 EECS)** Professor Huei Peng
10:00	**Break**
10:10	**Lecture 2 Hybrid Vehicles (1303 EECS)** Professor Zoran Filipi
11:00	**Break**
11:10	**Lecture 3 Electric Grid (1303 EECS)** Professor Ian Hiskens
12:00	**Lunch at Commons**
13:30	**Lecture 4 Batteries (1303 EECS)** Professor Anna Stefanopoulou **Levi's Battery lab tour and hands-on experience**
15:00	**Break**
15:20	**Lecture 5 Electric Motors (2052 AL)** Professor Chris Mi
16:10	**Break**
16:20	**Lab 1 Electric Motors (2052 AL)** Professor Huei Peng, Jean Chu, Sei Jin Park, Daniel Yang
17:30	**End of day 1**

Electrified Transportation Summer Camp Day 2 Schedule
Thursday August 12th 2010

8:30	**Board Bus (in front of GGB)**
8:45	**Arrive at site 1 (UM Solar Car team,** 574 S. Mansfield, Ypsilanti**)** Rachel Kramer, Project Manager, 248.231.1234
9:30	**Leave site 1**
10:30	**Arrive at site 2 (Volt, Milford Proving Ground)** Tim Grewe, Chief Engineer and Director, GM (248) 840-2423
12:00	**Leave site 2 and lunch**
13:30	**Arrive at site 3 (ITC Transco,** 27175 Energy Way, Novi, MI 48377**)** Archisman (Archie) Gupta (734) 660-1402
14:30	**Leave site 3**
15:00	**Arrive at site 4 (Ford,** Research Innovation Center (RIC) at 2101 Village Road, Dearborn**)** Tony Phillips, 313-594-4717
16:30	**Leave site 4**
17:30	**Return to campus**

Electrified Transportation Summer Camp Day 3 Schedule
Friday August 13th 2010

8:30	**Lecture 6 Fuel Cells (1303 EECS)** Professor Anna Stefanopoulou
9:20	**Break**
9:30	**Lecture 7 Hydrogen (1303 EECS)**

Professor Don Siegel

10:20 **Break**

10:30 **Tour of COE labs** in two small groups

	Group 1	Group 2
10:50-11:10	**Anna's fuel cell lab**	**Ian's electric lab**
11:15-11:35	**Zoran's HEV lab**	**Anna's fuel cell lab**
11:40-12:00	**Ian's electric lab**	**Zoran's HEV lab**

12:00 **Lunch at Commons**

13:30 **Lecture 8 Wind power (1303 EECS)**
Professor Ian Hiskens

14:20 **Break**

14:30-17:00 **Lab 2 and Electric car kit competition (2052 AL)** Professor Huei Peng, Jean Chu, Sei Jin Park, Daniel Yang

17:00 - 17:30 **Awards and close of camp** Professor Huei Peng

Electrified Transportation Summer Camp Day 1 Schedule
Wednesday August 3rd 2011

8:30 **Report to Camp (1500 EECS)**

9:00 **Welcome & Introductions (1500 EECS)**
Professor Huei Peng

9:10 **Lecture 1 Overview and Introduction to Electrified Vehicles (1500 EECS)**
Professor Huei Peng

10:00 **Break**

10:10 **Lecture 2 Key components of electrified vehicles (1500 EECS)**
Mike Rothenberger (PSU, education kit designer)

11:00 **Break**

11:10 **Lecture 3 Recharging the Auto Industry: The Story of the Chevy Volt (1500 EECS)**
John Ferris (General Motors)

12:00 **Lunch at Commons**

13:30 **Lecture 4 Batteries (1500 EECS)**
Professor Don Siegel

15:00 **Break**

15:20 **Lecture 5 Electric Motors (3437 EECS)**
Professor Heath Hoffman

16:10 **Break**

16:20 **Lab 1 Electric Motors (2052 AL)** Professor Huei Peng, Mike Rothenberger

17:30 **End of day 1**

Electrified Transportation Summer Camp Day 2 Schedule Thursday August 4th 2011

8:30	**Meet at site 1 (UM Solar Car team, Wilson Center, North Campus)**
9:30	**Board bus, leave site 1**
10:30	**Arrive at site 2 (Ford,** Research Innovation Center (RIC)
12:30	**Leave site 2 and lunch**
12:50	**Arrive at site 3 (Ford Rouge Plant Tour)** 3001 Miller Rd, Dearborn MI, 48120
14:45	**Leave site 3**
15:15	**Arrive at site 4 (CNG station, Ann Arbor)** 117 West Summit Street, Ann Arbor, 48104
15:50	**Leave site 4**
16:00	**Return to campus—Chevy Volt Demo and Drive and UM Formula Hybrid work**
17:00	**End of day 2**

Electrified Transportation Summer Camp Day 3 Schedule Friday August 5th 2011

8:30	**Lecture 6 Ann Arbor Clean City (1500 EECS)** Lisa Warshaw (Clean City Ann Arbor)
9:20	**Break**
9:30	**Lecture 7 Sustainable Transportation (1500 EECS)** Eli Cooper (City of Ann Arbor, Transportation Program Manager)
10:30	**Break**
10:40	**Lecture 8 Wind Energy (1500EECS)** Professor Peretz P. Friedmann
12:00	**Lunch at Commons**
13:30	**Lecture 9 Solar Energy (1500 EECS)** Professor Akram Boukai
14:20	**Break**
14:30	**Lab 2 and Electric car kit competition (2052 AL)** Professor Huei Peng, Mike Rothenberger
17:00 - 17:30	**Awards and close of camp** Professor Huei Peng

Appendix M: Summary of the Development of an Integrated Kit For K-12 Education And Outreach In Vehicle Electrification

SYNOPSIS

This document summarizes progress to date on the development of an integrated video/videogame/toy kit for K-12 education and outreach in the vehicle electrification and hybridization area. The document begins by presenting the structure of this integrated kit. The document then summarizes the graduate and undergraduate student employment and education opportunities made possible by this kit. The document then proceeds to its main focus, namely, the progress on each of the kit's three main components. Finally, the document concludes with a summary of ongoing progress towards the kit's completion and dissemination.

STRUCTURE OF INTEGRATED KIT

The integrated K-12 education and outreach kit consists of three main components, as shown in Figure 1. The first component is a set of high-quality **educational videos** intended to introduce K-12 students to the components, configurations, and functionality of hybrid electric vehicles. The second component is an **educational videogame** intended to give K-12 students an interactive introduction to the design and functionality of hybrid electric vehicles. The third component of the kit is a **hands-on hybrid vehicle toy kit** intended to give K-12 students an opportunity to build their own scaled-down toy versions of different hybrid powertrain configurations. These three components of the kit are intended to work together synergistically to provide a holistic introduction to hybridization for K-12 students. By deliberately designing the kit to incorporate educational videos, an educational videogame, and a hybrid vehicle toy kit, we hope to achieve success in targeting different K-12 students with different learning styles and preferences. The remainder of this report describes each of the above three components of the integrated hybrid vehicle education and outreach kit in more detail.

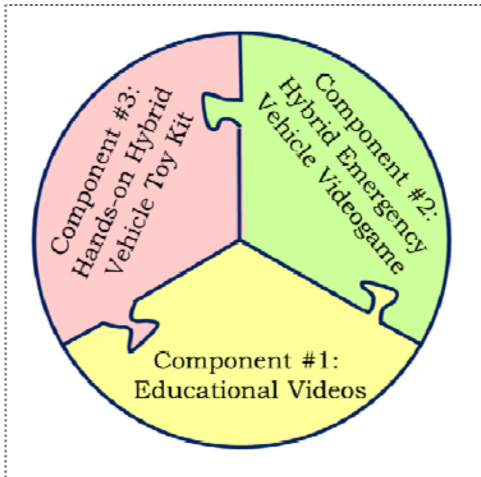


Figure 1: Components of Integrated Education Kit

STUDENT EDUCATION AND EMPLOYMENT

Five graduate and undergraduate students have participated in the development of the integrated education and outreach kit:

1. **Mr. Kaushik Krishnamurthy** (University of Michigan) was employed through DOE-ARRA funds as an hourly graduate student assistant to provide the initial design of the educational videogame and educational videos.

2. **Mr. Michael Rothenberger** (Penn State University) enhanced the above initial design of the videogame, and also built both the videogame and educational videos, as part of his M.S. thesis. He also participated in the 2011 Huron High School summer camp, where an initial draft of the educational videos was shown to students as a preamble to the camp. Finally, he is currently employed through DOE-ARRA funds over the course of the summer of 2012 to finalize the videogame and educational videos.
3. **Mr. Nathaniel Michaluk** (Penn State University) designed the series hybrid toy car component of the educational toy kit. This design effort served as his Schreyer Honors Thesis at Penn State University. He was also employed through DOE-ARRA funds to implement an initial hardware prototype of this design.
4. **Ms. Lindsay Johannes** (Penn State University) designed the parallel hybrid toy car component of the educational kit. This design effort served as her Schreyer Honors Thesis at Penn State University. She was also employed through DOE-ARRA funds to implement an initial hardware prototype of this design.
5. **Mr. Randall Schur** (Penn State University) is currently employed on DOE-ARRA funds to improve the design of the educational toy kit's power electronics, implement this design, and build multiple replicas of the kit.

EDUCATIONAL VIDEOS: PROGRESS AND NEXT STEPS

Twelve videos were created as part of the integrated education and outreach kit. These videos introduce their viewers to: *(i)* the motivation for vehicle electrification, *(ii)* the high-level design tradeoffs involved in vehicle electrification, *(iii)* the different components of hybrid vehicle powertrains, *(iv)* the different configurations into which hybrid vehicle powertrains can be arranged, and the *(v)* advantages and limitations of each configuration. All in all, twelve educational videos were created, designed to get the viewers to think about the following questions:

1. **Motivation:** *What is vehicle electrification? What are the factors driving it? What benefits can society expect from electrification? What societal, environmental, and economic tradeoffs must electrification attempt to mitigate?*
2. **Introduction to HEVs:** *What makes a vehicle "hybrid"? What is the definition of hybridization? What are the main components of a hybrid vehicle, and what are their purposes? What goals must one seek to optimize in designing a hybrid electric powertrain?*
3. **Internal Combustion Engine:** *What is an IC engine? How does it operate? What are the factors affecting its fuel consumption and efficiency? How can one incorporate engine efficiency maximization into powertrain design and control?*
4. **Electric Motor/Generator:** *What is an electric motor/generator? How does it operate? What are the factors affecting its efficiency and performance? What are the potential benefits of combining electric motor/generators with internal combustion engines?*
5. **ICE Efficiency:** *What is the definition of "brake specific fuel economy"? How does it vary with engine torque and speed, and why? What is the "bsfc sweet spot"? How can one achieve minimal engine bsfc?*

6. **Introduction to Configurations:** *What are the different basic configurations of hybrid electric vehicles? What are the differences in operating principles and power flow between these configurations? Why is it important to think about hybrid configurations?*
7. **Parallel Configuration:** *What does it mean to build a "parallel" hybrid electric powertrain? What does a parallel HEV powertrain look like, physically? How does power flow in a parallel HEV powertrain?*
8. **Parallel Operation:** *How does a parallel HEV operate? What are the advantages and disadvantages of a parallel HEV? What types of vehicles and duty cycles is the parallel configuration ideal for?*
9. **Series Configuration:** *What does it mean to build a "series" hybrid electric powertrain? What does a series HEV powertrain look like, physically? How does power flow in a series HEV powertrain?*
10. **Series Operation:** *How does a series HEV operate? What are the advantages and disadvantages of a series HEV? What types of vehicles and duty cycles is the series configuration ideal for?*
11. **Power Split Configuration:** *What does it mean to build a "power split" hybrid electric powertrain? What does a power split HEV powertrain look like, physically? How does power flow in a power split HEV powertrain?*
12. **Power Split Operation:** *How does a power split HEV operate? What are the advantages and disadvantages of a power split HEV? What types of vehicles and duty cycles is the power split configuration ideal for?*

In building the above videogames, we placed substantial emphasis on visual quality. Three-dimensional models and animations were built of both the components of hybrid powertrains (e.g., Figure 2) and the configurations into which these components can be assembled (e.g., Figure 3). These models and animations were built in SolidWorks® and combined with scripted audio explanations using Camtasia Studio®. The overall end product is a set of high-quality multimedia videos explaining the benefits, components, configurations, and design tradeoffs for hybrid electric vehicles.

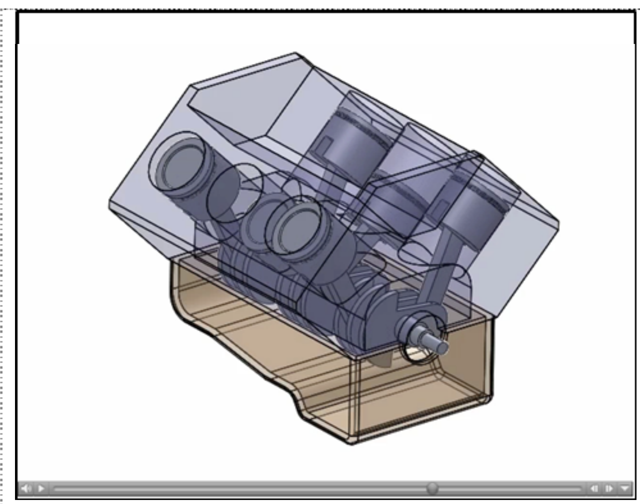


Figure 2: Screenshot of ICE Educational Video

The creation of the educational videos is now complete, and only two tasks remain to be completed with regards to these videos: *(i)* their integration within the educational videogame and *(ii)* their dissemination to a broad K-12 audience. These two outstanding tasks are discussed further under the sections titled "Educational Videogame: Progress and Next Steps" and "Integrated Kit Dissemination: Progress and Next Steps".

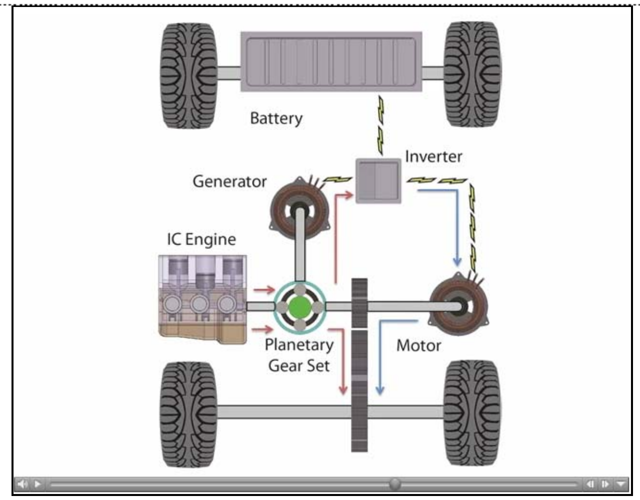


Figure 3: Screenshot of Power Split HEV Video

EDUCATIONAL VIDEOGAME: PROGRESS AND NEXT STEPS

The purpose of the educational videogame is to provide K-12 students with a collaborative and interactive environment within which they can design different hybrid vehicle powertrains, simulate them, and compare them in terms of performance, fuel economy, and emissions. The target vehicle in the game is a **Hybrid Emergency Vehicle (HEV)**: an ambulance whose powertrain is to be configured and designed by the game's player. The choice of an ambulance for hybridization serves two purposes. First, it is intended to help K-12 students appreciate the societal value of engineering in general, and vehicle hybridization in particular. Second, emergency vehicles experience a broad range of different driving conditions (e.g., stop-and-go traffic, aggressive acceleration, highway cruising, etc.), which makes it possible for the game to emulate those driving conditions. Figure 4 shows the videogame's logo.

Figure 4: Videogame Logo

The process of developing this videogame has consisted of six main steps. The **first step** focused on developing the **terrain, environment, and race courses** for the game. We began this step by developing a tool in Matlab that makes it possible to quickly assemble fictitious "hilly terrains", as shown in Figure 5. One particular hilly terrain was generated using this tool and exported to OpenGL. This particular hilly terrain is shown in Figure 6. A road was then analytically superimposed on this hilly terrain in Matlab and exported to OpenGL, as shown in Figures 7 and 8. Finally, buildings were added to this terrain as shown in Figure 9. The process of creating the terrain, road, and overall race course uses Matlab code extensively, and it is therefore very easy to create new terrains, roads, and courses. Furthermore, all the source code created throughout the entirety of this project is freely available to the public, and listed directly within an appendix to Mr. Mike Rotheberger's M.S. thesis.

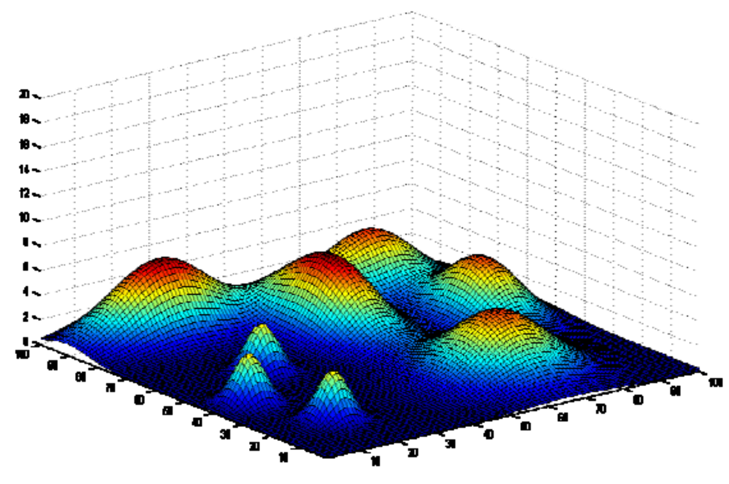


Figure 5: Hilly Terrain in Matlab

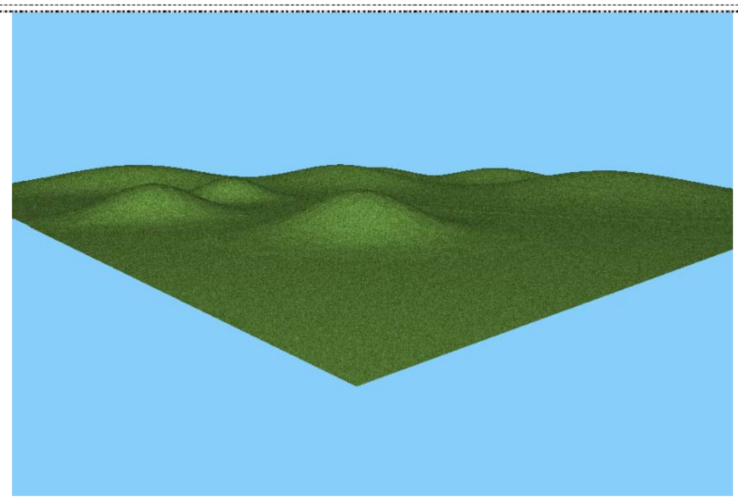


Figure 6: Hilly Terrain in OpenGL

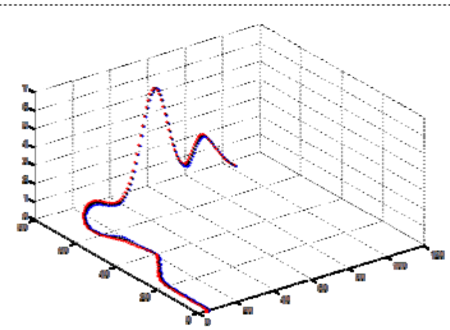


Figure 7: Road in Matlab

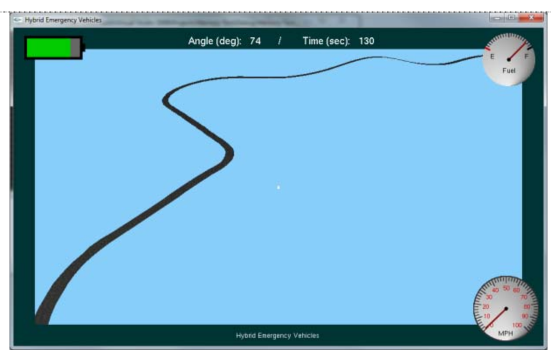


Figure 8: Road in OpenGL

The **second step** of the videogame development process focused on creating a visual model of the hybrid emergency vehicle, as well as a **head-up display** allowing the players to monitor the vehicle's battery state of charge, fuel consumption, and speed. Figure 10 shows a picture of the hybrid emergency vehicle, incorporated within the head-up display.

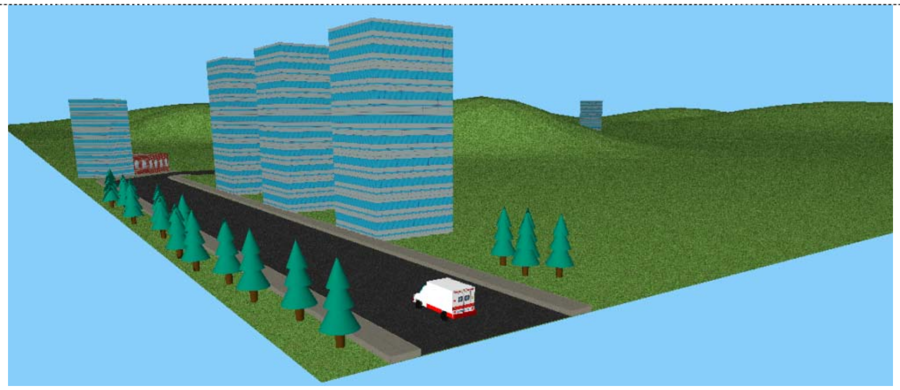


Figure 9: Videogame Race Course

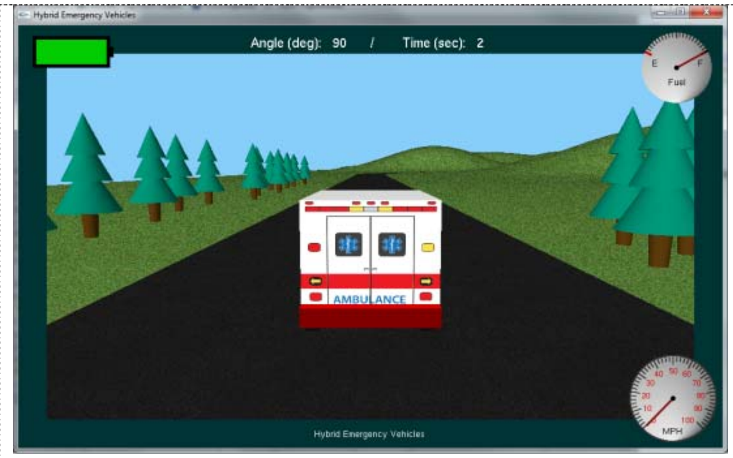


Figure 10: HEV and Head-up Display

The **third step** of the videogame development process was the creation of the game's **design menu**. The design menu is perhaps the most important element of the videogame. An initial version of the menu was created early on in the game's development process, and is shown in Figure 11. As the game is finalized, the design menu is being actively rebuilt to incorporate changes to the game's structure. The menu serves four different purposes. First, it allows game players to **select the HEV's powertrain configuration**. Available choices include a conventional automatic transmission, a series HEV configuration, and a parallel HEV configuration. Other configurations (e.g., power split) can be easily added to the game's publically-available source code. Second, the design menu allows game players to **size the HEV's components**, especially the internal combustion engine, battery pack, and motor/generators. Third, the design menu provides **structure**

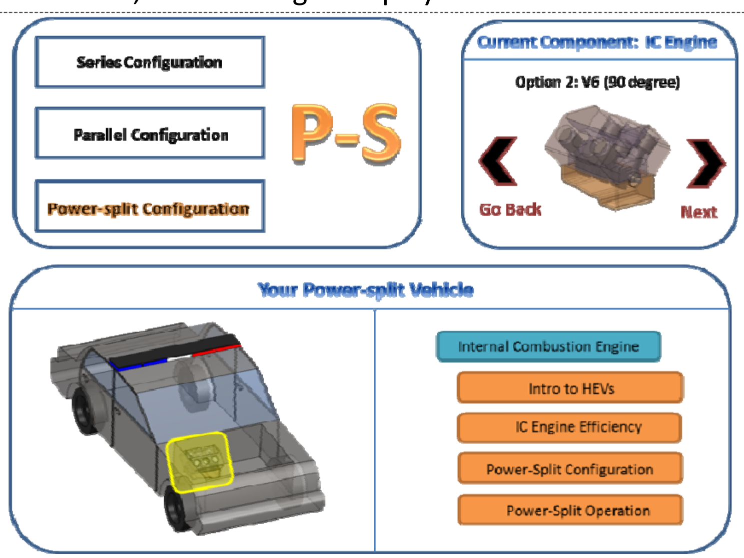


Figure 11: Design Menu (Earlier Version)

and scaffolding to the videogame. It only allows players to "unlock" more advanced configuration and component sizing options once they have played the game with the more basic ones. This is very important, because it introduces players to the various concepts associated with vehicle electrification and hybridization one at a time. Finally, the design menu **links the videogame to the educational videos,** allowing players to browse seamlessly between these two components of the overall education and outreach kit.

The **fourth step** of the videogame development process was the development of a **feedback menu** providing players with information on how well their vehicle designs did over a given race in terms of fuel consumption, performance, emissions, etc. Figure 12 shows the current feedback menu.

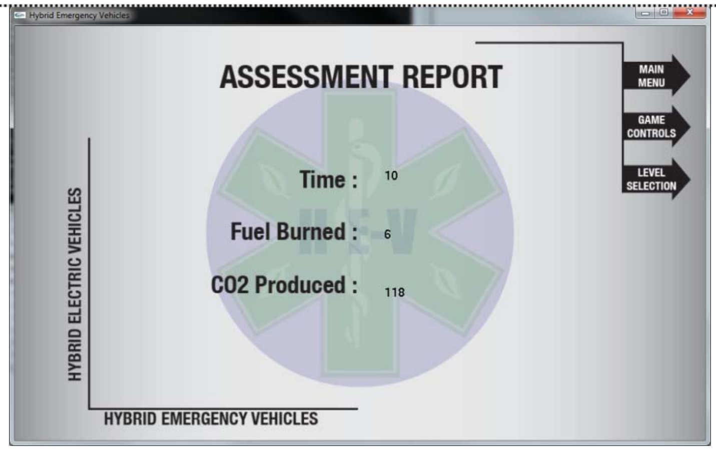


Figure 12: Feedback Menu

The **fifth step** of the videogame development process was the development of **physics-based models of the HEV's longitudinal and lateral dynamics**. These models make the videogame quite realistic by incorporating phenomena such as tire cornering stiffness, rolling resistance, aerodynamic drag, etc. Details of the physics-based models are discussed in Mr. Rothenberger's M.S. thesis, and omitted here for brevity.

The **sixth and final step** of the videogame development process was the development of **physics-based models and elementary control designs for two HEV configurations (series and parallel)**. These models were first build in Matlab/Simulink based on the scientific literature, one example being the Simulink model of a series HEV in Figure 13. The models were then tested extensively, then re-implemented in C++, and finally incorporated into the videogame.

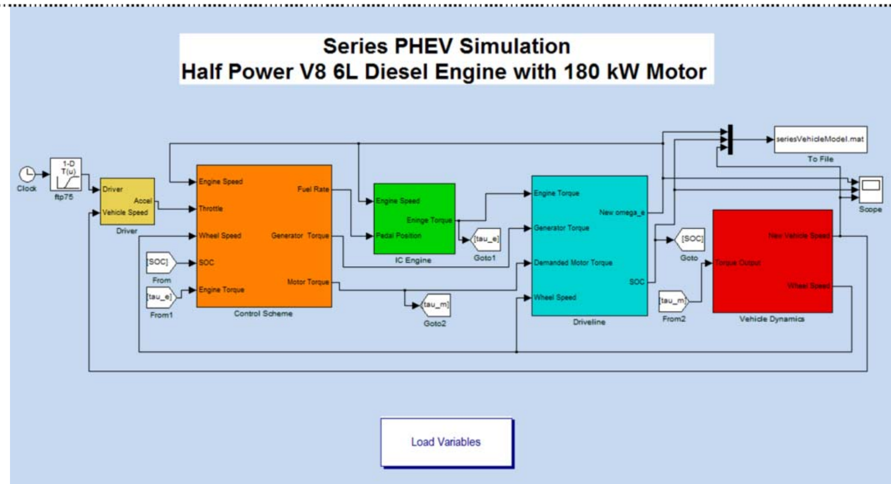


Figure 13: Series HEV Model in Simulink

With the completion of the above 6 steps, the educational videogame development process has now reached its concluding phase. All what remains is the re-implementation of the design menu to incorporate the final simulation models, component sizing options, educational videos, and scaffolding structure intended for public release. The videogame will then be compiled into its final form, and disseminated to the public as discussed below (see "Integrated Kit Dissemination: Progress and Next Steps").

HANDS-ON HYBRID VEHICLE TOY KIT: PROGRESS AND NEXT STEPS

The purpose of the hands-on hybrid vehicle toy kit is to allow K-12 students to build their own hybrid toy cars by converting a combustion-powered radio-controlled race car to different hybrid configurations. The process of developing this kit can be divided into 12 steps, 8 of which have been completed while the remaining 4 are ongoing. These 12 steps are described in depth below.

Figure 14: Commercial RC Toy Car

The **first step** was the selection of a commercial radio-controlled combustion-powered vehicle as a baseline vehicle for the kit. Figure 14 shows this baseline vehicle as purchased, and Figure 15 shows the vehicle with the cover removed. The vehicle has a self-starting internal combustion engine, which is particularly valuable for hybridization. The vehicle also achieves all-wheel driving using front, rear, and front-to-rear differentials. This is particularly valuable because the front-to-rear differential can be used as a power split device if one wishes to develop a **power split** version of the toy car (a **stretch goal** for this project: our main goal is to develop **series and parallel** versions of the toy car).

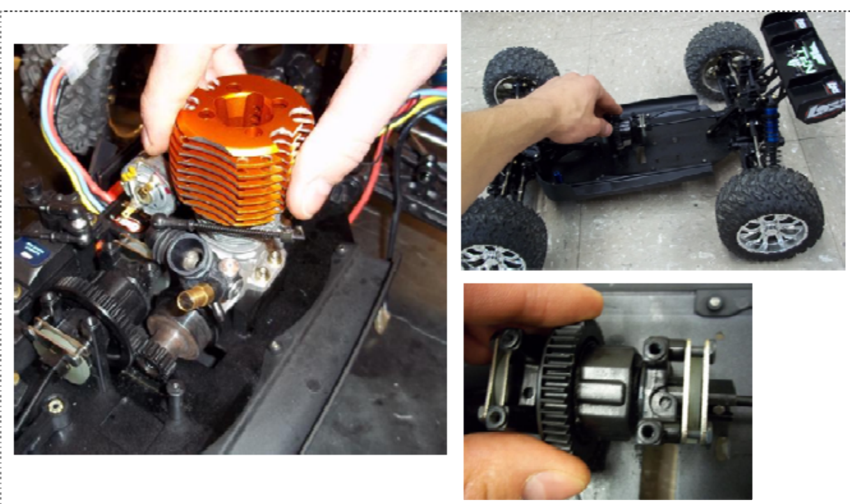


Figure 15: Dissecting the Commercial RC Vehicle

The **second step** was the **dissection** of the above vehicle by Ms. Lindsay Johannes and Mr. Nate Michaluk to understand both its mechanical and electronic functionality. This involved taking the vehicle apart, as shown in Figure 15. More importantly, this also involved measuring and monitoring all the communication signals flowing between the vehicle's components to understand the vehicle's control logic.

The **third and fourth steps** of the toy kit development process involved modifying the design of the above commercial vehicle to convert it to a **series hybrid vehicle** and a **parallel hybrid vehicle,** respectively. The third step constituted Ms. Lindsay Johannes' Schreyer Honors Thesis at Penn State University, and has been completed successfully. The fourth step constituted Mr. Nate Michaluk's Schreyer Honors Thesis at Penn State University, and has also been completed successfully. Both theses are available for download to the public through Penn State's Schreyer Honors College, and contain detailed descriptions of the new series and parallel vehicle designs.

The **fifth step** of the toy kit development process involved the implementation of the series hybrid vehicle redesign by Ms. Lindsay Johannes. Ms. Johannes has completed this step successfully, and Figure 16 shows the completely-rebuilt series hybrid vehicle.

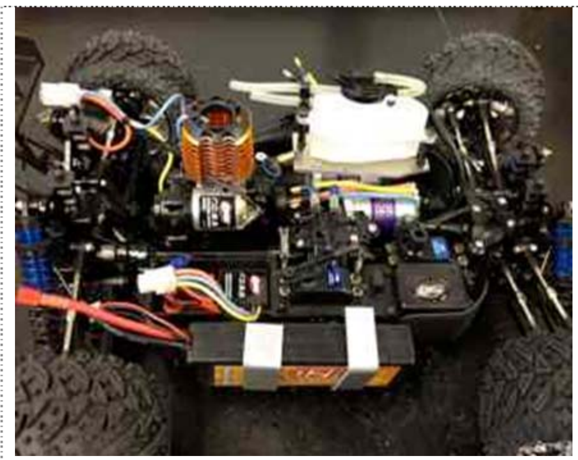


Figure 16: Series Hybrid Toy Car

The **sixth step** of the toy kit development process involved the implementation of the parallel hybrid vehicle redesign by Mr. Nate Michaluk. Mr. Michaluk has completed this step successfully, and Figure 17 shows the completely-rebuilt parallel hybrid vehicle.

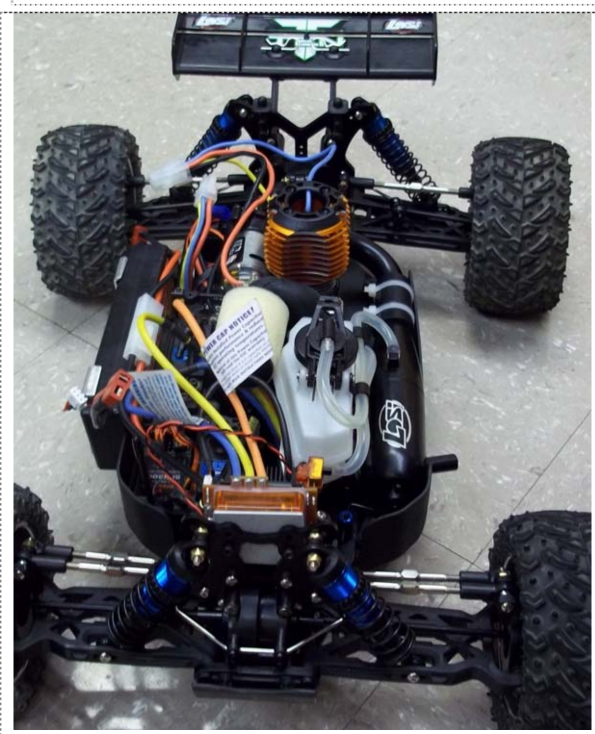


Figure 17: Parallel Hybrid Toy Car

Throughout Steps 1-6 above, we have focused predominantly (but not entirely) on the **mechanical redesign** of the commercial RC toy car to enable it to function as a series or parallel hybrid. Equally important is the **electronic redesign** of this toy car to allow it to run as a hybrid vehicle. Electronic reconfigurability is the focus of Steps 7-12, discussed briefly below. Our focus in **step 7** was on developing an electronic speed control system for the hybrid vehicles' electric motors. We began by implementing a commercial speed controller, and were successful in doing so. Unfortunately, the commercial motor speed controller we used did not enable regenerative braking: a feature we believe is important for the toy kit to be realistic. This led to **step 8**, namely, the development of our own motor speed controller from scratch. Mr. Nate Michaluk and Ms. Lindsay Johannes completed this step successfully using a BASIC STAMP microprocessor board. Due to the limitations of the BASIC STAMP board, Mr. Randy Schur has re-implemented our motor speed controller from scratch using an Arduino MEGA board. Both the implementation on the BASIC STAMP and Arduino re-implementation have been successful. Therefore, **steps 1-8 of the 12-step hands-on toy kit development process are complete**. This leaves steps 9-12 as ongoing work:

Step 9: Incorporate regenerative braking within the Arduino-based motor speed controller (the speed controller currently only allows one-way power flow to the electric motor).

Step 10: Add a simple battery management system that incorporates battery state-of-charge (SOC) estimation to avoid overcharging and over-discharging.

Step 11: Ass rudimentary supervisory controllers to the series and parallel hybrid vehicles. These supervisory controllers will translate driver/player commands to motor and engine power commands.

Step 12: Build the kit, and disseminate it to the public.

At this point, Steps 8-12 are still in progress, and Mr. Randy Schur is employed on DOE-ARRA funds to complete them. We anticipate all 12 steps of this toy kit development effort to be completed in the late summer or early fall of 2012.

INTEGRATED KIT DISSEMINATION: PROGRESS AND NEXT STEPS

The integrated kit described in this report will only succeed in meeting its education and outreach potential and goals if it is disseminated aggressively. We have not yet begun the kit's dissemination efforts in earnest. We do intend, however, to ramp up the kit's dissemination efforts dramatically as soon as the kit's construction is finalized. We are exploring seven different venues for kit dissemination:

1. **Summer camps at the University of Michigan:** The University of Michigan has played a leading role in K-12 education and outreach throughout this DOE-ARRA project, mostly through its summer camp program. The educational videos developed as part of this kit have already been used in a Michigan-organized summer camp. We will explore the possibility of disseminating the entire kit as part of future Michigan summer camps.
2. **Summer camps at Penn State University:** Penn State University runs several mechatronics-focused summer camps for K-12 education and outreach, including a highly successful summer camp titled "**robots, rockets, and race cars**" led by PSU's Professor Sean Brennan. We will explore the possibility of disseminating the integrated kit through that summer camp.
3. **Penn State Engineering Ambassadors Program:** Penn State's *Engineering Ambassadors* are a group of more than 50 undergraduate Penn State Engineering students. Their organization's main focus is on education and outreach to K-12 students, especially women and underrepresented minorities (the *Ambassadors* themselves are more than 60% female/minority students). They travel to K-12 schools around the State of Pennsylvania to educate students and parents about the field of engineering, its impact on society, and the exciting intellectual/research challenges and career opportunities it provides. They act as role models to

these prospective students, and guide them on visits to Penn State's campus and research labs. The *Engineering Ambassadors* program has quickly become a pivotal component of Penn State's engineering education and outreach efforts to K-12 students and their parents, and a key tool for the recruitment of women and underrepresented minorities to PSU engineering. One exciting possibility involves using the program to distribute the above integrated kit to K-12 students who can take it home after an *Ambassador* visit, play with it, learn from it, and then return it to the *Ambassador* program for distribution to other students and schools. We have contacted the *Engineering Ambassadors* program's faculty advisor to explore this possibility.

4. **State College Discovery Museum:** State College, PA, has a newly-built "discovery museum" intended to provide hands-on experience in the sciences to K-12 children. We have contacted this discovery museum to explore whether they would like this kit to be part of their exhibit and/or one of the kits they allow children and their families to check out and play with at home.
5. **Vehicle Design Competitions (e.g., EcoCar):** Penn State is involved in several vehicle design competitions, such as EcoCar. We have contacted the faculty leaders of these competitions to see if they would be interested in using the above kit to introduce their teams to hybrid vehicle design on a small videogame/toy car scale as a way of easing them into these competitions.
6. **Penn State University School of Education:** Penn State University's School of Education teaches courses to both undergraduate and graduate students interested in becoming future science teachers. We have had preliminary discussions with these courses' instructors on the possibility of using the above kit in these courses to both explore the science behind hybrid vehicles with the students taking the courses and explore the value of the kit for science education.
7. **Internet-based dissemination:** Last but not least, parts of the kit (e.g., the educational videos and educational videogame) are suitable for Internet-based dissemination, and will be placed on the web for access by broad audiences worldwide.

The choice of which of the above dissemination options to pursue most aggressively will be made in the late summer/early fall of 2012, and we are committed to pursuing the options we choose aggressively.

Appendix N. Construction cost of the "401 Lab" located in 1070 and 1080 Lay Auto Lab. The cost of the construction project alone exceeds the cost share requirement of this grant, indicating the commitment of the University of Michigan.

Project Name: **Dynamometer installation in Room 1070** PEXT #: **P100040011001**

Updated By: Jeffrey Haviland Date Updated: 02/18/2011 Version: Post Bid Budget 2/3/11

Created By: David King Date Created: 01/07/2011 Program: P2276

Budget Line	Approved Version 12/16/2010	Approved Adjustment	Current Budget	Pending Adjustments	Working Budget	Commitments	Potential Cost	Construction Contingency Available	To Be Awarded/ Adjustment Needed	OCR Required
Construction Cost	**726,400**	**77,051**	**803,451**	**0**	**803,451**	**803,451**	**45,203**			
GC Construction	726,400	77,051	803,451	0	803,451	803,451	45,203	-45,203	-45,203	
Base Bid	696,200	77,051	773,251	0	773,251	0	0			
Taxes on User Managed equipment purchase	30,200	0	30,200	0	30,200	0	0			
Related Construction Cost	**42,804**	**-42,114**	**690**	**0**	**690**	**690**	**0**			
Asbestos	1,000	-310	690	0	690	690	0		0	
Lead Abatement	1,000	-1,000	0	0	0	0	0		0	
City/Municipal Charges	0	0	0	0	0	0	0			
DDC	40,804	-40,804	0	0	0	0	0		0	
Contingencies	**49,191**	**-37,048**	**12,143**	**0**	**12,143**	**0**	**0**			
Construction Contingency	49,000	-36,857	12,143	0	12,143	0	0	12,143	12,143	
Rounding Contingency	191	-191	0	0	0	0	0		0	
Subtotal Construction & Contingencies	**818,395**	**-2,111**	**816,284**	**0**	**816,284**	**804,141**	**45,203**			
Professional Fees	**97,241**	**-1,411**	**95,830**	**0**	**95,830**	**95,830**	**0**			
External A/E Design	66,000	8,239	74,239	0	74,239	74,239	0		0	
Basic Fee	58,500	8,239	66,739	0	66,739	0	0			
Reimbursables	1,500	0	1,500	0	1,500	0	0			
Extra Services Allowance	6,000	0	6,000	0	6,000	0	0			
Internal Design	15,000	0	15,000	0	15,000	15,000	0		0	
Basic Fee	15,000	0	15,000	0	15,000	0	0			
Consultants	2,000	-2,000	0	0	0	0	0			
Testing Consultant	2,000	-2,000	0	0	0	0	0		0	
Inspections	6,591	0	6,591	0	6,591	6,591	0			
Internal Inspection	6,591	0	6,591	0	6,591	6,591	0		0	
Interior Design	0	0	0	0	0	0	0			
Commissioning	6,650	-6,650	0	0	0	0	0			
Plant Commissioning	6,650	-6,650	0	0	0	0	0		0	
State of Michigan	1,000	-1,000	0	0	0	0	0			
BFS (Plan Review)	1,000	-1,000	0	0	0	0	0		0	
Printing/Drawing Reproduction	0	0	0	0	0	0	0			
Architecture Engineering & Construction	**26,364**	**0**	**26,364**	**0**	**26,364**	**26,364**	**0**			
AEC Project Management	26,364	0	26,364	0	26,364	26,364	0			

Print Date: 02/19/2013 Working Copy Budget Type: Projected AE-IT-SERPENS03\Production\BudgetvsCostDetail.rpt Page 1 of 2

UNIVERSITY OF MICHIGAN
ARCHITECTURE, ENGINEERING AND CONSTRUCTION

COST VS. BUDGET

Building: **1000400 - Lay Walter E Automotive Lab**

Project Name: **Dynamometer installation in Room 1070**

AEC Project #: **P00004349**

PEXT #: **P100040011001**

Updated By: Jeffrey Haviland   Date Updated: 02/18/2011   Version: Post Bid Budget 2/3/11

Created By: David King   Date Created: 01/07/2011   Program: P2276

Budget Line	Approved Version 12/16/2010	Approved Adjustment	Current Budget	Pending Adjustments	Working Budget	Commitments	Potential Cost	Construction Contingency Available	To Be Awarded/ Adjustment Needed	OCR Required
Telecommunications	**13,000**	**-5,500**	**7,500**	**0**	**7,500**	**7,500**	**0**			
Cabling and Hardware	10,000	-2,500	7,500	0	7,500	7,500	0		0	
Design and Management	1,000	-1,000	0	0	0	0	0		0	
Activation	2,000	-2,000	0	0	0	0	0		0	
Other Orders	**5,000**	**9,022**	**14,022**	**0**	**14,022**	**14,186**	**0**			
Other Orders	5,000	9,016	14,016	0	14,016	14,180	0	-164	-164	
Shipping and Handling	0	7	7	0	7	7	0		0	
Furnishings and Equipment	**0**	**0**	**0**	**0**	**0**	**0**	**0**			
Moving	**0**	**0**	**0**	**0**	**0**	**0**	**0**			
AEC Managed Total	**960,000**	**0**	**960,000**	**0**	**960,000**	**948,021**	**45,203**			
Unfunded Contingency	**0**	**0**	**0**	**0**	**0**	**0**	**0**			
User Managed Items	**0**	**0**	**0**	**0**	**0**	**0**	**0**			
Owner Furnished Equipment	0	0	0	0	0	0	0			
Non-AEC Managed Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**			
Budget Total	**960,000**	**0**	**960,000**	**0**	**960,000**	**948,021**	**45,203**	**-33,224**	**-33,224**	

Note (1): Changes to Unallocated Contingency require User and/or Funding Authority notification only. Signature approval is not required.

Total To Be Awarded/OCR Required: -33,224

Budget Notes:

Budget reduced from Pre-bid to remove User Managed Items since they are not needed/required for inclusion.