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The Benchtop Hybrid - Using a Long-Term Design Project to Integrate the Mechanical Engineering Curriculum

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ABSTRACT

This paper describes the use of a large-scale, multi-semester design project as a means of integrating six courses in the mechanical engineering curriculum. The project, a bench-scale hybrid powertrain, is built up – component by component – as students advance through the curriculum. The authors used the project to test two research hypotheses: 1) that a long-term, large-scale design project would increase long-term subject matter retention and 2) that a long-term, large-scale design project would increase students' design and problem-solving skills. The authors found that the design project had no measurable effect on long-term subject matter retention, but did have an impact on design thinking and skill. The paper gives a full description of the project and assessment effort, and provides some of the insights acquired by the authors while conducting this research. A complete description of the project and videos of student designs can be found on the project website, www.benchtophybrid.com.

Key words: Project-based learning, curricular integration, design education

INTRODUCTION

Ensuring retention of critical engineering concepts can be quite challenging. Hearing a variation on “but we never learned this!” is an all-too-frequent experience for most instructors, and many students feel justified in jettisoning all knowledge of a subject once the final examination is past. The situation is well summarized by Avitabile [1]:

> *The unfortunate part is that as soon as the test is over or the course is completed, the students often just forget the material since they have no reason to retain the compartmentalized, modularized material.*

Subjects that are separate in the curriculum, such as thermodynamics and mechanical design, are integrated in practice, since thermal and mechanical systems must function cohesively in real mechanical systems (e.g. an air conditioner). With this in mind, we have implemented a novel approach to integrating coursework through five semesters of the core mechanical engineering curriculum. The work was designed to test two hypotheses:

1. A long-term design project that integrates knowledge from multiple courses strengthens student knowledge retention.
2. A large-scale design project requiring tools from many courses improves student problem-solving and design skills.

Before and after testing, using a series of concept inventories and design exercises, was conducted to assess a) change in knowledge retention between courses and b) change in student problem-solving and design skills. The project – a bench-scale hybrid powertrain – is completed by students in modules spanning six courses in the mechanical engineering curriculum. The six courses begin in the second semester of the sophomore year, and end in the second semester of the senior year: a span of three years. The control group for this project was the Rowan University Mechanical Engineering Class of 2013. These students did not complete any of the modules, but took the same assessment instruments as the test groups. The two test groups in this study were the Classes of 2014 and 2015. A fully-documented project website was created for the use of the students and instructors, and can be found at www.benchtophybrid.com.

The first part of this paper provides a brief background in the state of the art in engineering education reform and curricular integration. This is followed by a description of the “technical” aspects of this project: the six modules in the hybrid powertrain. We then describe the assessment tools used to measure the effects of the project on the students. The final section describes some of the important lessons learned in completing this project, and our plans for future work.

BACKGROUND

Many sources have made the case for reforming engineering education to reflect modern trends. Most notably, a recent National Academy of Engineering (NAE) report found that [2]

> *Engineering education must avoid the cliché of teaching more and more about less and less, until it teaches everything about nothing. Addressing this problem may involve reconsideration of the basic structure of engineering departments and the infrastructure for evaluating the performance of professors as much as it does selecting the coursework students should be taught.*

This report and others stress the importance of teaching young engineers the merits of sustainable design [3] and ecologically-friendly practices.

Benefits of Project-Based Instruction

The literature on project-based learning is quite extensive, and only a cursory treatment will be provided here. One of the crucial concepts in project-based learning (PBL) is that of *learning in context.* In other words, if students understand *why* they are learning a particularly difficult concept, their *motivation* to learn that concept will increase. An excellent overview of a type of PBL called Challenge-Based Learning (or Instruction) is given by Cordray, et al. [4], and an example of CBI as applied to a biomechanics course is illustrated by Roselli and Brophy [5]. In both cases, the use of PBL was found to increase student learning, especially in situations involving difficult concepts, and both groups implemented recommendations in *How People Learn*, by Bransford, et al. [6]. Jiusto and DiBiasio [7] suggest that immersive, project-based assignments may better prepare students for lifelong and self-directed learning. Vanasupa, et al. [8] propose a four-faceted model for use in designing experiential learning exercises for engineering students. In developing their model, they note that "increases in *understanding the broader context* lead to increases in *motivation*, which lead to increases in *engagement*, which lead to an increase in *moral/ethical development*." Of course, successful PBL activities must be carefully designed by the instructor and informed by the literature, as found by Benjamin and Keenan [9]. For a very thorough treatment of the Project-Based Learning literature, see [10].

Increasing Involvement of Underrepresented Groups

Integrated design projects of the type discussed here have the potential to increase the comfort level of traditionally underrepresented groups in mechanical engineering. As Busch-Vishniak and

Jarosz [11] note, emphasizing the links between courses, demonstrating the relevance of topics to the “real world” and increasing team-oriented activities can have a positive impact on many students who perceive the traditional engineering environment to be hostile or unwelcoming. In addition, Rosser [12] notes that a holistic, global approach to the engineering pedagogy may create a more welcoming climate for female students. Further evidence of the efficacy of design-based instruction is given by Mehalik, et al. [13], who compared traditional, scripted instruction with design-based instruction in a set of middle school STEM courses. Encouragingly, they found that design-based instruction had a significant, positive impact on the participation of traditionally underrepresented groups in STEM fields.

Curricular Integration – Prior Work

Other researchers have reported the positive effects of small-scale course integration, usually among first-year courses. Froyd and Ohland [14] provide a thorough review of efforts at integrating engineering and science coursework in the freshman and sophomore years, observing that:

> *Design projects have the potential to help students make connections among subjects, material, and applications. The process orientation of design holds promise for improving the systems thinking of engineering students*.

DeBartolo and Robinson [15] describe the integration of four freshman engineering courses. An effort at integrating engineering and communications coursework in the sophomore year was undertaken by Marchese, et al. [16]. In general, these efforts obtained positive results, but see [17] for a set of recommendations. To the best of our knowledge, integration of five semesters of high level engineering coursework has never been attempted.

Project Description - Technical Aspects

The project that we chose for our curriculum integration was the design, fabrication, and testing of a benchtop hybrid powertrain. A simplified diagram of a hybrid powertrain is shown in Figure 1. The powertrain is very similar to the one used in a first-generation Toyota Prius. In this design, power is supplied to a load using an *air motor* and *DC motor*. The contributions of the air motor and DC motor are combined using the *planetary gearset*. Power is stored for later use during light parts of the load cycle by the *generator* charging up the *battery pack*. The strategy employed by the *controller* is to keep the output shaft turning at a constant speed, despite variations in load. It does this by regulating the 1) air flow to the air motor, 2) the electrical flow to the DC motor and 3) the rate of charging in the generator. A rendering of the physical setup of the benchtop hybrid can be seen in Figure 2.

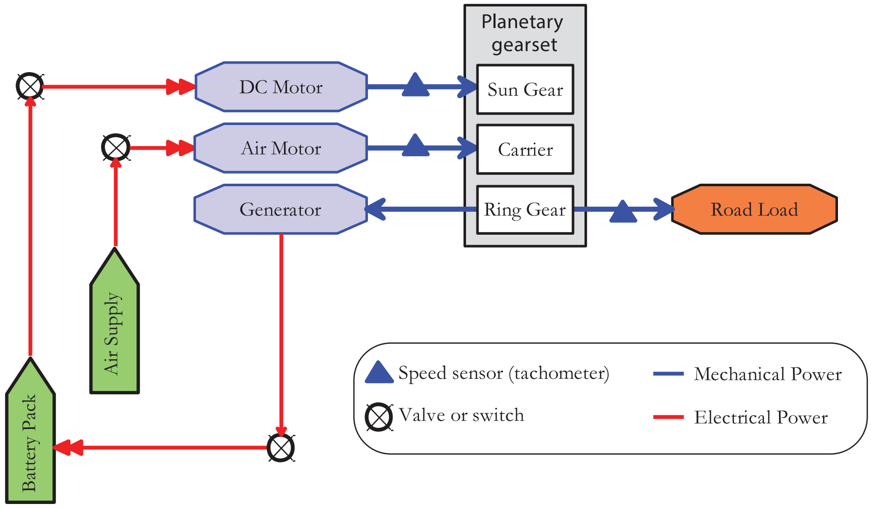

Figure 1. Schematic diagram of benchtop hybrid powertrain system. The system is modeled on the drivetrain of a Toyota Prius.

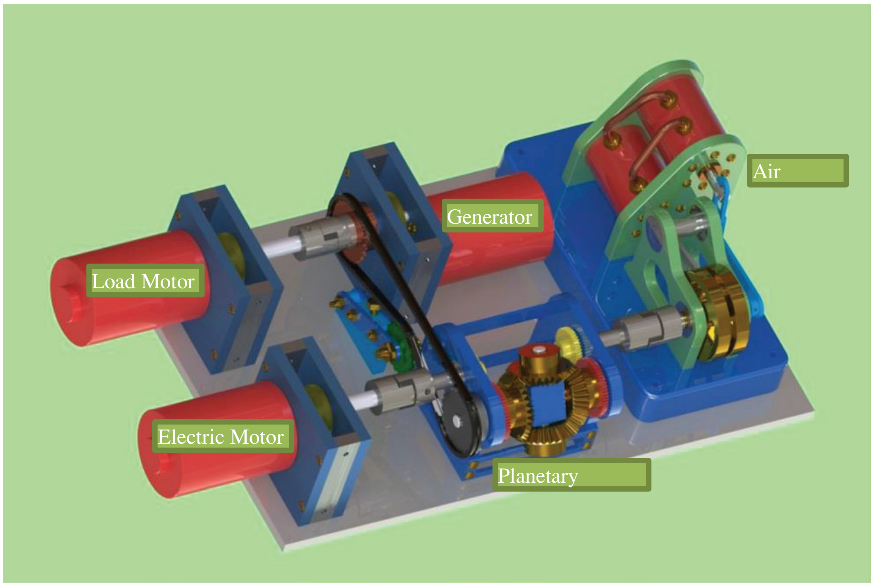

Figure 2. The Bench-Scale Hybrid Powertrain. The prime mover is the Air Engine; the Electric Motor can share the load. The Generator can be used to charge a battery pack as needed. The Load Motor is designed to supply a variable load torque, simulating uphills and downhills. Three of these workstations have been fabricated for student use.

Table 1. Implementation Schedule for hybrid powertrain project.

Semester		Course	Module
Year 1 (2011 – 2012)	Fall		
	Spring	ME Lab	Tachometer
Year 2 (2012 – 2013)	Fall	Thermal Fluid Sciences I Machine Design	Air-powered motor Planetary gearset
	Spring	Thermal Fluid Sciences II	Assessment and optimization of air motor
Year 3 (2013 – 2014)	Fall	System Dynamics and Control I	Electric and air motor speed control
	Spring	System Dynamics and Control II	Overall control system

Over the course of five semesters, the students design, fabricate and assess the components shown in Table 1. Each module was designed to be stand-alone; that is, students could implement the *Electric Motor Speed Control* module without having completed the *Planetary Gearset* module. The overall goal of the design project is to produce a hybrid powertrain that drives the "wheels" at constant speed under varying load, in a similar fashion to cruise control in many automobiles. The prime mover in the system is the air motor, and the "fuel consumption" is the amount of compressed air used by the motor in driving the system. For the final project (the *Overall Control System*) the student designs were judged upon how much compressed air is used to "drive" the system for a given number of miles under varying load conditions and how closely they achieve constant speed under varying loads. Note that in some cases the system is driven "downhill"; that is, the load motor back-drives the powertrain. In these cases, the generator provides regenerative braking, and charges the battery pack. Thus, the performance of the powertrain depends upon the efficiency of the students' air motors as well as the effectiveness of their overall control strategies.

The following sections provide details on the individual design projects, starting with the Arduino-based tachometer and concluding with the overall control system. Additional details about the overall system and control scheme can be found in [18] and [19] as well as on the project website: www.benchtophybrid.com.

The Tachometer Project

The first project completed by the students is a simple Arduino-based tachometer, shown in Figure 3. The learning goal for this module is for students to be able to effectively design and fabricate a simple mechatronic sensing device using a microcontroller programmed in the Arduino environment. The tachometer consists of two components: a sensor and a daisy wheel. The daisy wheel is a disk with slots along the periphery. The ideal number of slots is found by the students through trial

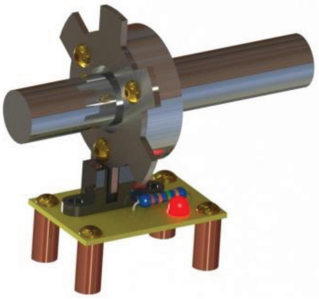

Figure 3. The Tachometer Assembly.

and error. Many varieties of sensors have been tested over the past six years, including a Reflective Object Sensor (Optek OPB704) and a Hall Effect Sensor (Optek OHB900). The reflective sensor was found to be too sensitive to variations in room lighting, so the Hall Effect Sensor was chosen in the final design. Unfortunately, this required the daisy wheels to be made from a ferrous material (instead of plastic or cardboard) but students were able to prototype them quickly and easily using Rowan's abrasive water jet cutter. Complete details about this project, including sample code, can be found on the project website at http://benchtophybrid.com/CS_Tachometer.html.

The Air Engine Project

Rowan mechanical engineering students have designed and build the air engine (see Figure 4) as part of their Thermal-Fluid Sciences course for many years [20], so it was not necessary for us to

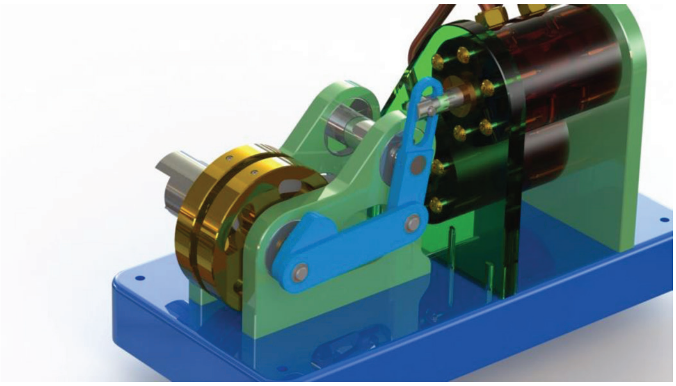

Figure 4. The Rowan "faculty model" Air Engine.

design a completely new air engine project. The engine is powered by 100psi compressed air from the shop air supply. The students' learning outcomes for the project are as follows:

1. Design and fabricate a functioning air-powered reciprocating engine.
2. Use Thermodynamic principles to maximize the efficiency of the engine. This is accomplished through optimization of cylinder bore, stroke length, valve timing and other design variables.

A thorough description of the project is the subject of a forthcoming paper, and only the broad outline will be given here. For the purposes of the benchtop hybrid, the air motors are subject to the following constraints:

- Power cylinders must be double acting and have a displacement of approximately 25cc.
- The output shaft must be ½ inch in diameter, 1 inch long, rotate counter-clockwise (when looking head-on), and have centerline 3 inches from the bottom surface of the air motor.
- Common materials such as 1.5 inch diameter Delrin rod and ¼ inch thick aluminum plate are provided, and each team is limited to a maximum budget of $100 for additonal materials.

In the fall semester the primary goal was to design a motor that met these constraints and test for free speed (no applied load) of the motor. As an example, in the Fall of 2013 the average free speed was 1710 rpm with a standard deviation of 555 rpm. The maximum free speed that semester was 2200 rpm and the minimum was 1000 rpm. At the end of the project, the students submitted a full laboratory report. A section of the report titled "Design Selection Process and Design Outcome" was critically reviewed by us. Each team was required to explain how it went about creating and selecting designs and what those designs were. We also asked for clarity regarding the idea creation process (ideation) and the team's approach to evaluating each design. A more complete description of the air engine project, along with videos of student designs, can be found on the project website http://benchtophybrid.com/AE_Intro.html.

Assessment and Optimization of the Air Engine

In the spring semester the focus was switched to refining the air-powered motors so that they could be tested for torque, power, and efficiency. To assess the performance of their air engines, the students attached the output shafts of the engines to a small, bench-scale dynamometer. Typical results from such testing are shown in Figure 5. In their design reports, the teams often echoed James Skakoon's classic text *Elements of Design*, learning a great deal about textbook subjects in the context of the project. Some of the ideas that particularly resonated included:

- "*Start simple and have a backup plan*". One student's rotating valve piston was a classic example. The team was unable to get its initial complicated design to work - but was able to build a simpler machine in 24 hours based on the lessons learned from the earlier, more complex machine.

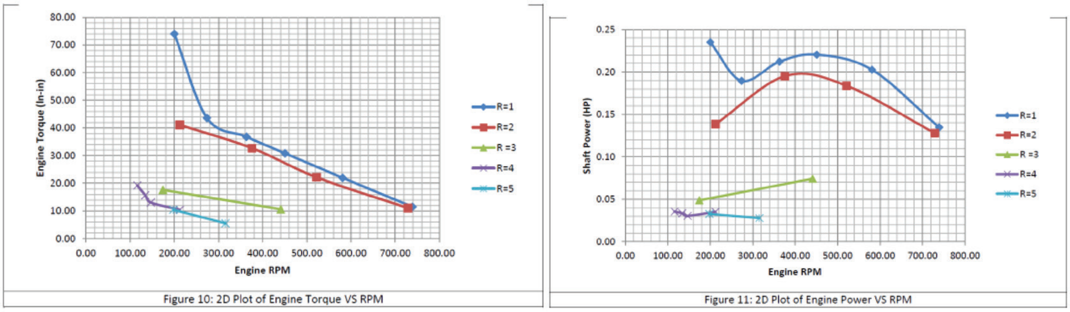

Figure 10: 2D Plot of Engine Torque VS RPM

Figure 11: 2D Plot of Engine Power VS RPM

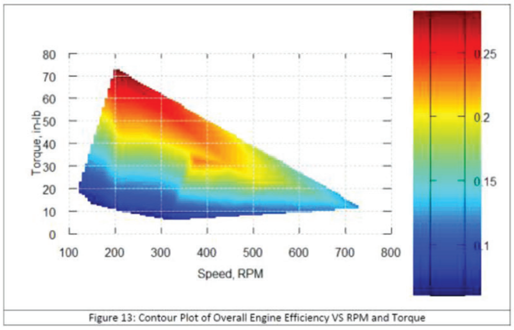

Figure 13: Contour Plot of Overall Engine Efficiency VS RPM and Torque

Figure 5. Torque/Speed Plot, Speed/Power Plot and Efficiency Map for a student engine. These charts were cut and pasted directly from a student report, and show typical behavior of a reciprocating engine.

- "*Catching all the design flaws in CAD is nonsense*". While CAD (SolidWorks) was used to successfully draw and model rotational and translational motion, continuous design iterations were required for every team.
- "*Press fits can be a bear*". While these can be drawn nicely in CAD, many students struggled with these fits and found alternative assembly means. Design for disassembly was found to be critical for success in most teams.

With a total of ten lab periods of effort (over two semesters), the teams were given sufficient time to design, model, build, and test their systems. Students had access to real-time peer evaluations, which may have helped drive them all to successful completion. In terms of speed, maximum values ranged from 700 to 2500 rpm, maximum torque values were 18-74 in-lbs, maximum power values were 120-240 Watts, and maximum mechanical efficiencies were 20 to 28%. Outcomes like these also appeared to boost student confidence in every aspect of design from conception to testing (based on informal student comments during the course of the project). In addition, students frequently commented to their instructors that they learned a lot about working as a team, setting goals, establishing responsibility and communicating to meet a deadline. Overall, it was an extremely rewarding project for both the students and the instructors.

The Planetary Gearset Project

First-semester juniors in our Machine Design course were given the task of designing and fabricating the planetary gearset that is the heart of the hybrid powertrain system. The learning outcomes of the differential gearbox project are twofold. The primary goal is for students to learn how to design a transmission for specified inputs/outputs. The secondary goal is for students to apply stress analysis techniques to make their gearboxes as small and light as possible.

In the planetary gearset project, students combined input from the electric motor (the same for every team, with a speed range of 0-1000rpm) with input from the student-constructed air motor (speed range dependent on the team's design) to produce an output speed that can be regulated to 500rpm (by varying the speeds of the electric motor and air engine). Two planetary gearset tutorials were developed, one focused on the kinematics of a planetary gearset and the other focused on its efficiency.

To begin, the students were presented with SolidWorks models of twelve possible planetary gearset configurations (not including the differential). To enable the students to visualize the sometimes-counter-intuitive behavior of planetary gearsets, three faculty prototypes were constructed, as shown in Figure 6.

Each student team was given a $20 budget to purchase gears (mostly from SDP-SI.com). A typical example of a student design is shown in Figure 7.

Students submitted their "final reports" on the planetary gearset project using YouTube videos. A complete description of the project and student videos can be seen in [21] and on the project website http://benchtophybrid.com/PG_Intro.html.

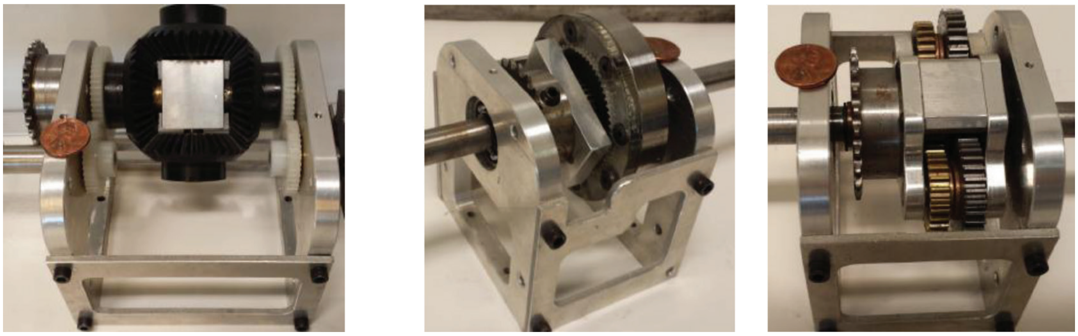

Figure 6. Faculty prototypes of three planetary gearsets. Left: differential topology. Center: traditional sun/planet/ring topology. Right: two suns/two planets topology.

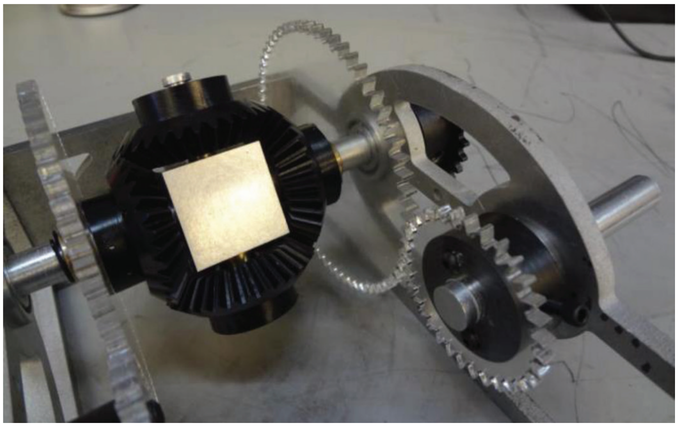

Figure 7. Student prototype of the Planetary Gearset using the differential topology. Note the use of purchased gears at the center. All other parts were fabricated by the student team.

Overall Control System

The student teams designed, modeled and implemented the overall hybrid control scheme during their senior year, as part of their System Dynamics and Control courses. System Dynamics is a two-semester course sequence where students learn system modeling (mechanical, electrical, hydraulic and pneumatic) as well as the fundamentals of control system design and implementation. During the fall semester, the students measured the dynamic properties of the DC motor and air engine, and implemented a simple PI speed control scheme for each. The overall hybrid control system was developed during the second semester. The learning outcomes for this project included:

- Using theory and measurements, develop dynamic models of the air engine and electric motor.
- Using the air engine and electric motor models developed in the previous project, implement an Arduino-based control scheme to maximize instantaneous fuel economy.

The sections below provide details on each aspect of the control system project, and further details can be found in [22].

Speed Control the DC Motor

During the first semester of their senior year, the students designed and implemented speed control systems for the air engine and DC motor. A PI control scheme (implemented in Arduino) was used to control the speed of each motor. A pulse-width modulated signal was used to drive a

MOSFET switch for the DC motor. To provide reasonable starting values for the controller gains, the students measured the dynamic parameters of the motor (electrical, inertial and damping) before testing their control systems. From these models, the students computed the required controller gains for specified maximum overshoot and settling times.

Speed Control of the Air Engine

Six solenoid valves (AutomationDirect AVS-5313-24D) were used to regulate the flow of air with the aim of controlling the speed of the air motor (see Figure 8). The air engine is powered by shop air at 120psi (8.3bar). This air is supplied to an aluminum block with six appropriately-sized orifices. These orifices limit the flow of air based on their cross-sectional areas. The exhaust of each orifice is directed into a solenoid valve. Finally, the air from the valves is combined and sent to the air engine. By opening and closing each solenoid valve, the speed of the air engine can be regulated. Each student team designed and fabricated its own orifice block.

The design of the aluminum block is determined by the cross-sectional area of each orifice such that the six valves can work together in a "binary" pattern. That is, opening the smallest orifice gives the lowest speed (speed "000001"), opening the second smallest gives the second lowest speed (speed "000010"), opening the two smallest simultaneously gives the third speed (speed "000011") and so on, for a total of 63 different "steps". Figure 9 shows an orifice block connected to the solenoid valves on the benchtop setup.

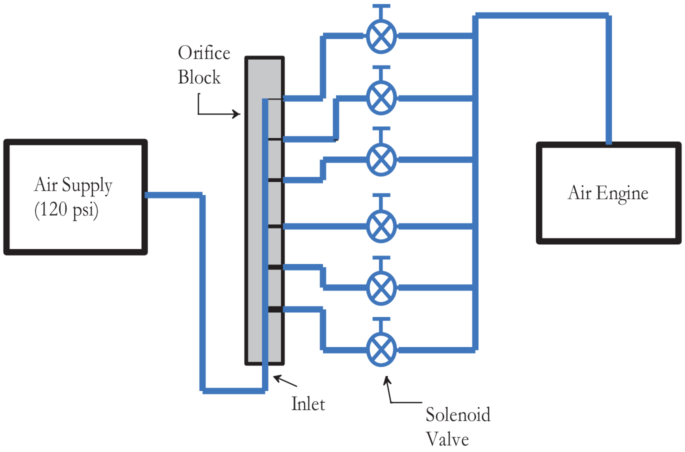

Figure 8. Air flow control system for air engine.

Figure 9. Solenoid valves and orifice block for air engine speed control.

Overall Hybrid Control System

The combination of microcontroller, sensors and actuators results in a continuously variable transmission. The microcontroller determines the desired operating condition and the existing operating condition, and then it controls the motors and generator in real time to achieve the desired output.

The Arduino has control over the speed of both the air engine and electric motor. Also, it monitors the "battery" state of charge and it can connect or disconnect the generator from the system. A second (faculty-operated) Arduino controls the load applied to the system in order to simulate uphills or downhills as on road. Finally, to achieve "cruise control", two independent PI controllers are integrated into the code: one for the air engine and the other for the DC motor.

Decision-Making Algorithm

The decision-making of the benchtop hybrid is fairly similar to the Toyota Prius with the aim of achieving maximum instantaneous fuel economy. For the prototype, the three variables that influence the decision making are the setpoint (desired wheel speed), the state of charge of the "battery" and the actual wheel speed. Based upon these values the microcontroller decides between three cases:

Case 1: Air engine works by itself and not necessarily at its most efficient speed. This occurs when the battery charge is low. The generator is connected to the system in order to charge the battery. Overall speed is regulated by modulating the rate at which the generator charges the battery.

Case 2: Electric motor works by itself. This occurs when the battery is fully charged and there is a small load on the system (e.g. during coasting). The generator is disconnected from the system.

Case 3: Both power sources work simultaneously. This occurs when the battery has sufficient charge and a heavy load is on the system (e.g. driving uphill). For this case the air engine operates at its most efficient speed and the electric motor compensates to reach the desired setpoint. The generator is connected to the system. For the faculty air engine the optimal speed is 1000 rpm, although the students must choose the most efficient operating point for their own air engines (determined in the previous year's project).

After the microcontroller decides which of the operating source(s) to activate, the "cruise control" system is effected by using a PI controller for each motor.

Figure 10 shows a typical performance curve from a student hybrid powertrain during a load cycle. The maroon curve shows the state of charge of the "battery" and the blue curve shows the output speed of the powertrain. The setpoint is a constant 250rpm (shown in green). Note the jagged nature of the blue curve between 0 and 120 seconds. This is the portion of the load

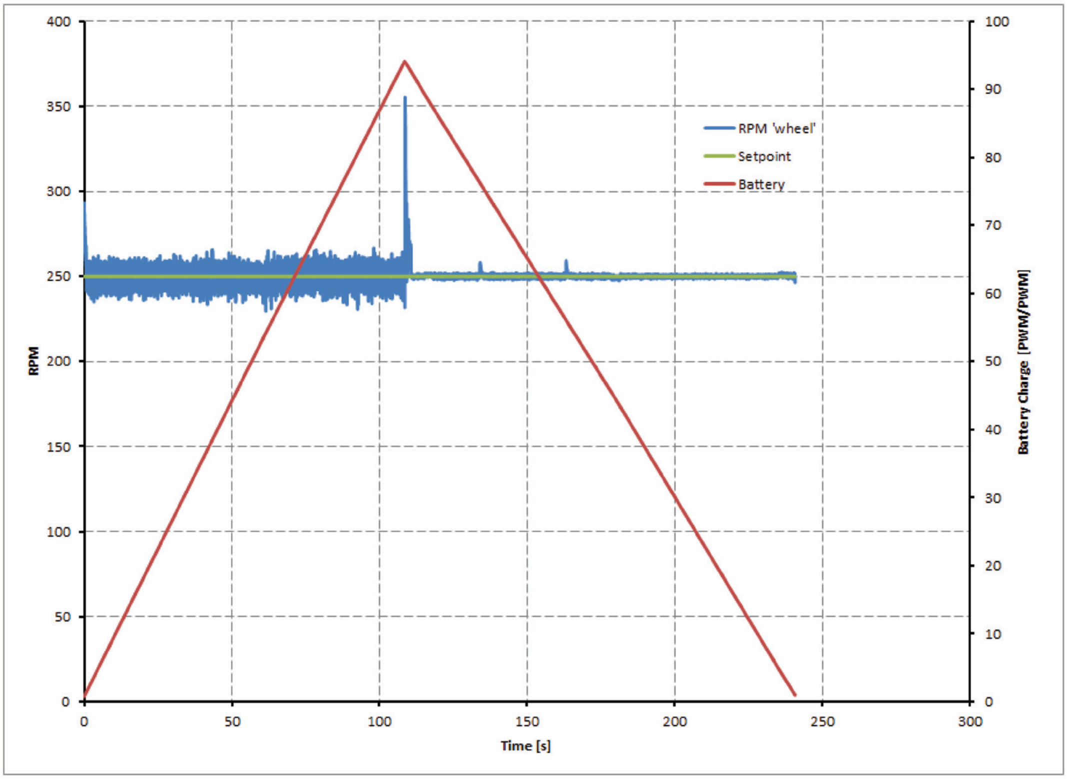

Figure 10. Performance of student hybrid powertrain during one load cycle. The maroon curve is the state of charge of the "battery" and the blue curve is the output speed of the powertrain.

cycle where the powertrain is running on air engine alone. The output speed is regulated by controlling how much power is sent to the generator to charge the battery. If the output is too fast, the generator is asked to charge the battery more rapidly, and vice versa. Once the battery has sufficient charge, the remainder of the cycle is run using the DC motor alone. It is simpler to control the output speed of the DC motor, so this portion of the cycle (after 120 seconds) is much smoother.

Benchtop Workstations

The senior-level projects completed by the students were the *DC Motor Speed Control*, *Air Motor Speed Control* and *Overall Control System*. To undertake the latter two projects, the students needed a functioning air motor, which they had built in an earlier module during their Junior year. During the Air Motor project, emphasis (and grading credit) was placed upon energy efficiency and speed, but not reliability. When many of the student teams tried to use their air motors during the senior year projects, they discovered that many of the parts tended to wear or break under long-term use. For example, most of the students built their pistons using Delrin plastic, which is easy to machine and has low friction against aluminum. Unfortunately, the Delrin pistons tended to wear rather quickly when the air engines were run for a long time (as when developing a control scheme) and rendered many engines inoperative. The result was that many teams spent an inordinate amount of time rebuilding their engines, rather than fine-tuning their control schemes. The investigators have learned two major lessons from this experience:

- Emphasize reliability during the Air Engine project, and reward reliability (such as the ability for an engine to run for 60 minutes nonstop) with graded credit.
- Have “faculty prototype” air engines available for students to use in developing their control schemes if their own air engines are out of commission. Of course, bonus points are awarded to teams that use their own air engines.

As a result of having learned these lessons, the investigators undertook to create three “hybrid powertrain workstations” containing all of the components shown in Figure 2. The workstations are constructed in such a way as to allow student teams to insert their own modules as needed. If a team’s air engine (or planetary gearset) is temporarily out of commission, the team can use the engine (or gearset) on the workstation to develop their control scheme. The workstations have made the control projects run much more smoothly for the second and third cohorts. Each station is shared by four teams and includes:

Faculty-model Air Engine: Students are allowed to use the faculty-model air engine if their own is out of commission.

Faculty-model Planetary Gearset: Many of the planetary gearsets suffered the same kind of wear and tear as the air engines, so students were allowed to use the faculty-model planetary gearset as needed.

Load Box and Load Motor: the load box is used to simulate uphills and downhills on a road. It has a motor/generator (AmpFlow M27-150) and three 10ff power resistors in parallel. When simulating down grades the motor/generator acts as a motor in order to drive the output shaft. It is powered by a benchtop power supply. When simulating uphill grades the motor/generator applies a load to the system by generating power across the resistors. The intensity of both situations is varied using Pulse Width Modulation (PWM).

DC Motor and Generator: both the DC motor and generator are AmpFlow M27-150 model electric motors. In the first benchtop hybrid design, the generator was used to charge a battery in order to store power for heavier parts of the load cycle. Upon implementation, we discovered that several complications were introduced by the batteries (storage capacity as a function of battery age, etc.) that did not enhance the educational goals of the project. As a remedy, we have chosen to use the generator to produce power across a set of power resistors, in a similar manner to the load box. By monitoring the electrical current flowing through the resistors, we can compute the "state of charge" of a theoretical battery. The charge can be used by the students to drive the DC motor for load leveling during the drive cycle.

The students regulate the speed of the DC motor using the same power MOSFET circuit that was used for their PI controllers in the previous semester. A laboratory power supply is used to drive the motors and we monitor the electrical current used by the DC motor to ensure that it does not exceed the amount stored in the "battery".

Assessment of Student Learning and Concept Retention

The purpose of the assessment effort was to test the two research hypotheses:

1. A long-term design project that integrates knowledge from multiple courses strengthens student knowledge retention.
2. A large-scale design project requiring tools from many courses improves student problem-solving and design skills.

Knowledge retention was tested using concept inventories (Solid Mechanics and Thermodynamics) and design skill level was assessed using simple design exercises. Each assessment instrument was tested on the control group (Class of 2013) and two experimental groups. Each assessment instrument is discussed separately below.

Solid Mechanics Concept Inventory

The purpose of this assessment was to determine if a five-semester design project aided in students' retention of concepts from their Sophomore-level Solid Mechanics course. The 24-question concept inventory was based on questions from Brown and Poor [23], and covered concepts such as load, displacement and stress/strain under axial, torsional and bending loads. The test was given in multiple-choice format on paper, and the students were given 30 minutes to finish. Student participation was completely voluntary, anonymous, and concept inventory performance had no negative course grade implications. Completing the concept inventory at the end of the Solid Mechanics course (the "post survey") was rewarded with a small extra-credit bonus. In addition, students who completed the same concept inventory a year later (the "retention survey") were rewarded with free pizza. A summary of the concept inventory results is shown in Table 2.

Both the control and experimental cohorts had similar performance on the concept inventory, answering over half of the questions correctly. On average, students correctly answered axial and torsion questions more often than those about bending. In the experience of the authors, these results are typical for sophomores in a Solid Mechanics course.

The results in the table indicated that student retention of Solid Mechanics concepts dropped slightly over time, which was expected since the students had not seen the material for a year. Thus, it appears that the integrated design project did not improve student retention of Solid Mechanics concepts over time. Unfortunately, a marked drop in student participation limits longer-term retention results for this study. Providing students with a better incentive than free pizza, or holding the concept inventory tests at a time other than Finals Week may increase the response rate for the retention group. Confounding factors such as course instructor and differences in student ability across cohorts, and the small number of students repeating the retention assessment, are limitations.

Table 2. Percentage of Solid Mechanics Concept Inventory questions answered correctly by cohort.

	Control post (n=38)	Control retention (n=6)	Exp 1 post (n=36)	Exp 1 retention (n=7)	Exp 2 post (n=36)
All questions (24)	53%	48%	63%	57%	54%
Axial (10)	58%	44%	73%	64%	59%
Torsional (5)	65%	49%	80%	60%	58%
Bending (9)	42%	51%	44%	36%	40%

Additionally, this type of assessment instrument may not be well suited to determine whether a five-semester project aids student retention of Solid Mechanics concepts since students are more accustomed to more traditional problem-solving, calculation-based assessments.

Thermodynamics Concept Inventory

The second set of concept inventories taken by the students was in thermodynamics. To establish a baseline, a pre and post course concept inventory was conducted in the Fall 2011/Spring 2012 semesters on students enrolled in Rowan's Thermodynamics I and II courses. These students are henceforth referred to as the "Control Group". This group of students was not involved with the long-term design project and thus was useful as a baseline for future comparison. The pre and post assessment was also conducted on students enrolled in the Fall 2012/Spring 2013 and Fall 2013/Spring 2014 Thermal-Fluid Sciences I and II courses. These two groups are henceforth referred to as "Experimental Group 1" and "Experimental Group 2" since they participated in both the new integrated curriculum and long-term sustainable design project. Both groups had the same professor for coverage of thermodynamics subject material (in either the Thermodynamics 1 & 2 sequence for the control group or Thermal-Fluid Sciences I & II for the experimental groups).

For the assessment, a 35-question Thermodynamics concept inventory, developed by Prince et al, was used [24]. The inventory covered five concept categories relating to entropy, reversibility, types of energy, steady state vs. equilibrium states, and reaction rates/chemical kinetics. Before going into results, a few details regarding the inventory are needed. First, the concept inventory is a multiple-choice test on paper and takes roughly 30 minutes to complete. Secondly, questions on the inventory are not typical of those seen in undergraduate engineering coursework. Unlike analytical questions on, say, the Fundamentals of Engineering examination (which are problem & calculation based) these concept inventory questions involve no calculations. Instead, they attempt to test knowledge of underlying concepts and understanding. In addition, this inventory was originally developed for students in an undergraduate chemical engineering program and thus contain several questions and an entire subject category (reaction rates/chemical kinetics) which is not covered in our Mechanical Engineering thermodynamics coursework (a validated Mechanical Engineering Thermodynamics CI was not available at the time the research was conducted). Lastly, student participation was completely voluntary, anonymous, and concept inventory performance had no negative course grade implications. Simply attempting the concept inventory resulted in a small course extra-credit and was used to motivate participation. A summary analysis of concept inventory results is shown in Table 3 and illustrated in Figure 11, Figure 12, Figure 13 and Figure 14.

Table 3. Pre and Post Thermodynamics Concept Inventory Results.

		Control Group (2011 – 2012)		Experimental Group 1 (2012 – 2013)		Experimental Group 2 (2013 – 2014)	
		Pre-Test	**Post Test**	**Pre-Test**	**Post Test**	**Pre-Test**	**Post Test**
Group	Number of Students	38	35	35	33	23	24
	Number of Questions	35	35	35	35	35	35
Correct Response Rate	All Questions	45.34%	51.35%	54.45%	51.26%	49.32%	51.31%
	95% Confidence Interval ±	2.98%	4.01%	4.67%	6.29%	3.83%	5.74%
	Entropy	51.32%	65.36%	62.50%	65.15%	52.17%	65.63%
	Reversibility	53.00%	48.98%	57.14%	56.28%	47.20%	47.62%
	Int. Energy vs. Enthalpy	32.46%	37.62%	49.05%	37.37%	47.10%	43.75%
	Steady State vs. Equilibrium	46.49%	55.87%	59.37%	55.56%	55.56%	57.41%
	Reaction Rates and Kinetics	38.42%	40.57%	35.43%	30.91%	39.13%	31.67%

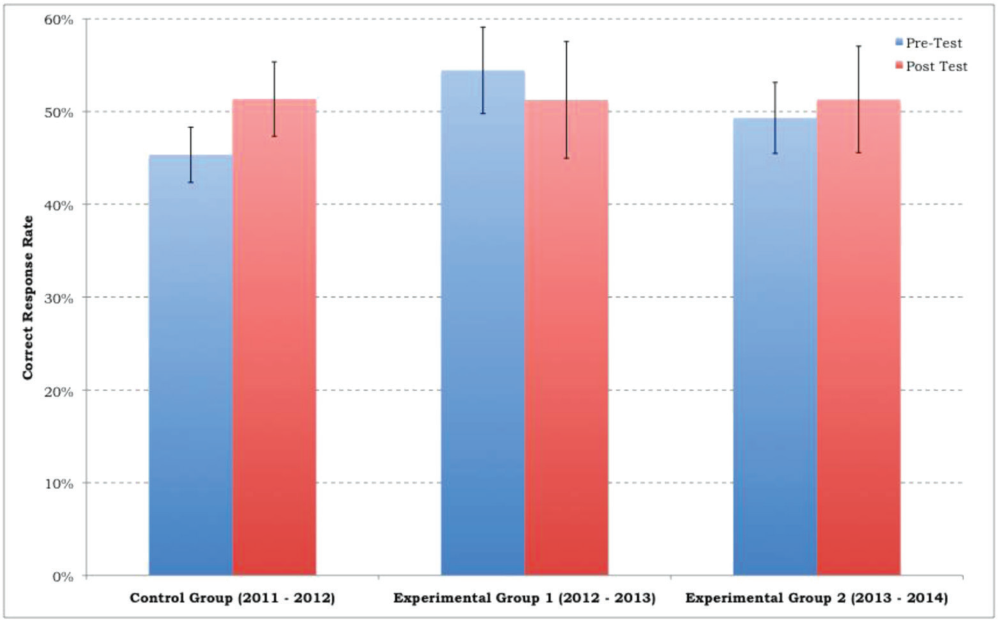

Figure 11. Control Group Pre and Post Thermodynamics Concept Inventory Results, Overall Correct Response Rate with 95% Confidence Intervals.

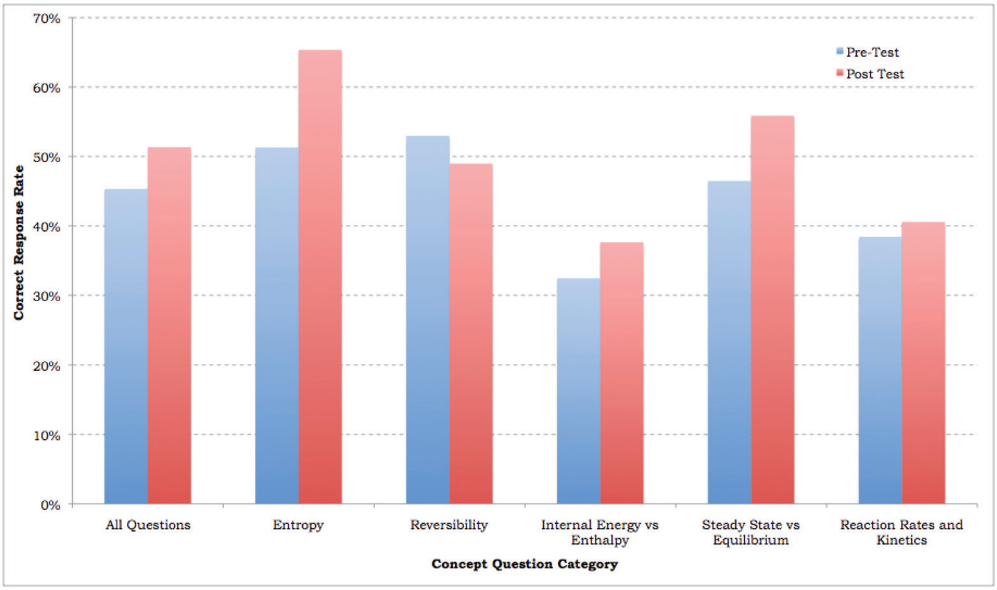

Figure 12. **Control Group Pre and Post Thermodynamics Concept Inventory Results (Correct Response Rate by Question Category).**

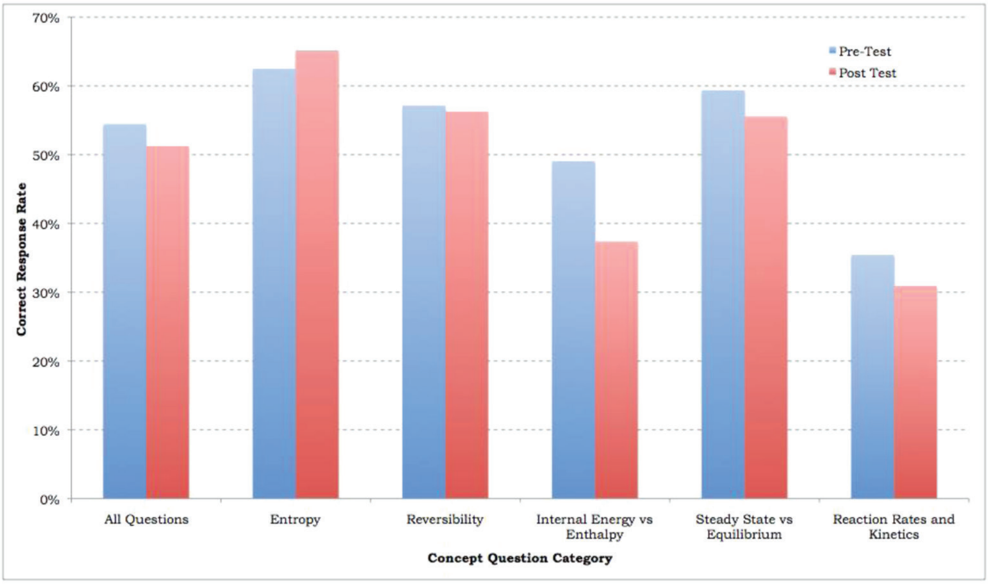

Figure 13. **Experimental Group 1 Pre and Post Thermodynamics Concept Inventory Results (Correct Response Rate by Question Category).**

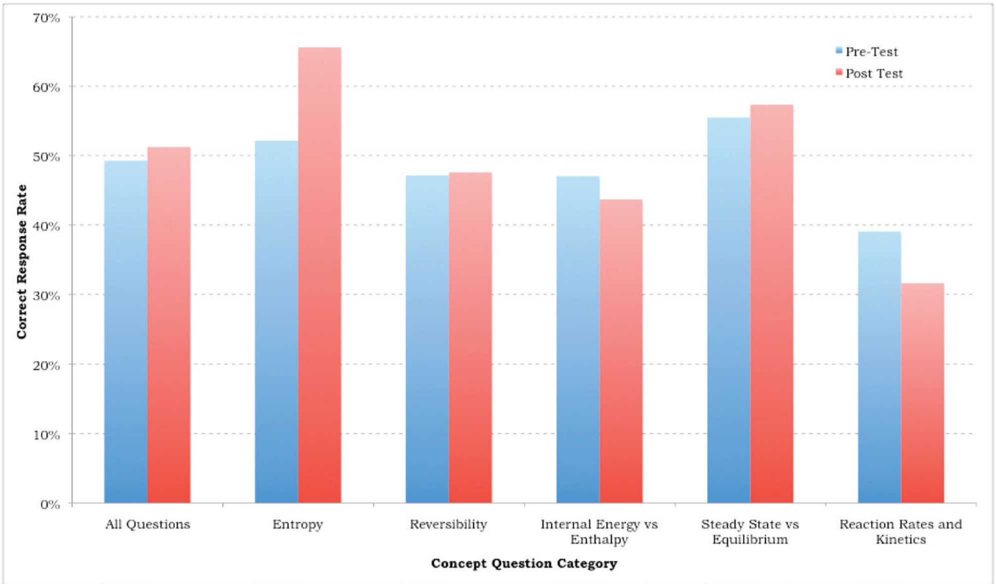

Figure 14. Experimental Group 2 Pre and Post Thermodynamics Concept Inventory Results (Correct Response Rate by Question Category).

As shown in Table 3, the control group not participating the sustainable design project showed an overall small increase in correct response rate on the concept inventory before and after taking the Thermodynamics course (45% to 51%). Given that the inventory is comprised of 35 questions, this small increase in correct response rate translates into the average student getting only two additional questions correct. As illustrated in Figure 11, confidence intervals were large and overlapping between the pre and post test for the control group, and thus the small increase in correct response rate is not considered significant. Experimental Group 1 showed a drop in overall correct response rate (54% to 51%) while Experimental Group 2 showed a small increase (49% to 51%). However, like the control group, great variability existed in the correct response rate and therefore changes between pre and post test are not considered significant for either of the experimental groups. Figure 12, Figure 13 and Figure 14 show the pre vs. post test results by student group broken down by concept question category. Across all three student groups and question categories, no statistically significant trends pre vs. post test were observed.

Given the results, a few issues have emerged. The small class size, small number of inventory questions, and small changes from pre to post test resulted in no statistically significant findings. In other words, with the inventory as the measurement tool of thermodynamics knowledge, no differences between the control or either experimental group were found. In addition, given the insignificance of changes pre vs. post test for any of the three groups, the inventory results suggest that no gains were made in conceptual understanding of thermodynamics material despite taking a year-long sequence of courses related to it. It does seem difficult to believe that none of the three student groups gained any conceptual knowledge of thermodynamics throughout the year, and raises a number of important questions. First and foremost, does this inventory accurately measure student gains or would an analytical test, similar to the FE exam, be more appropriate? As noted earlier, inventory questions are not at all typical of the type of analytical questions student saw on course homework, quizzes, and exams. Did student anonymity play a role in the results? Unlike an exam, were students dismissive of the inventory since it had no negative grade impacts? Lastly, was the chemical engineering focus of the inventory inappropriate for a mechanical engineering student body? These questions would need to be addressed in a future study.

Design Challenges

An open-ended Design Challenge was developed and administered to students during their Junior year, in the middle of the air engine project. The task was to be completed in 30 to 40 minutes outside of class, and was completely voluntary. In the Design Challenge, students were asked to describe the steps and concepts needed to design an engine. The results from this assessment were used to answer the research question: does a five-semester design project aid in students' understanding of the interconnectedness of engineering subjects (i.e. ability of students to draw from concepts from more various courses). The student responses to the Design Challenge were coded by concepts listed in Table 4 and Table 5 and show that students across all cohorts largely considered concepts of power, thermodynamics, temperature and thermal working conditions, which were taught in the course in which the engine was designed and built. Additionally, students across all cohorts considered concepts from Solid Mechanics regarding stresses, sizing and material choices. Students in the experimental cohorts were more likely to consider fatigue analysis, model and test, and redesign.

A summary of the average number of different primary, secondary and total concepts described by students in each of the cohorts is given in Table 6. Students in each of the two experimental cohorts described more primary, secondary and total concepts for their designs as compared to the control group. For the students in Experimental group 1, the results for the secondary and total average scores are statistically significantly different (** $p<0.05$) and show a trend (*$p<0.1$) for primary average scores alone when compared to the Control group average results. For the students in Experimental group 2, the results for the secondary concept scores show a trend (*$p<0.1$) when compared to the Control group average scores.

Students likely recognized, as hypothesized, that concepts from many courses within the curriculum were interconnected and necessary for the five-semester hybrid powertrain project as well

Table 4. Primary concepts relevant to the design of an air engine. The figures show the percentage of students who mentioned a given concept when completing their design challenge.

Primary Concepts	Control n=24	Exp 1 n=30	Exp 2 n=20
Define the requirement of power (dynamic load/torque and rpm)	42%	40%	40%
Use/describe mechanical power relationship	42%	23%	55%
Use 1st law and IGL or engine cycle to est. gas pressure force	33%	13%	20%
Free body diagram of dimensions and forces	63%	57%	75%
Apply dynamics and kinematic analysis	17%	23%	35%
Apply solid mechanics to compute stresses and compare to yield	58%	87%	45%
Determine vibration/oscillatory load	17%	3%	5%
Describe material choice and its property based on conditions	58%	93%	80%
Determine Temperature / Thermal - Working and op. conditions	71%	60%	45%
Estimate gas and rod temp, find thermal stresses and deflections	8%	33%	10%
Check lubrication and friction	25%	23%	5%
Fatigue analysis – will it last – Machine Design	8%	33%	65%
Test/experiment/model	8%	53%	30%
Repeat/iterate/redesign	8%	17%	15%

as for the half-hour engine design challenge. One limitation on these results is that the instructors of these courses changed over the course of the study. Additionally, a confounding factor is that the Control cohort took a slightly different curriculum than the Experimental cohorts. The Control cohort took 10 credits of Thermodynamics, Fluid Dynamics and Heat Transfer while the Experimental cohorts took 12 credits of integrated Thermal-Fluid Sciences during the junior year. Further, students

Table 5. Secondary concepts relevant to the design of an air engine. The figures show the percentage of students who mentioned a given concept when completing their design challenge.

Secondary Concepts	Control n=24	Exp 1 n=30	Exp 2 n=20
Low cost yet reliable	13%	20%	40%
Conduct background research	13%	17%	55%
Efficiency	0%	13%	20%
Manufacturing process	0%	13%	75%
Fuel and compression ratio	0%	23%	35%
Other constraints (quality, tolerance, etc.)	13%	20%	25%

Table 6. The average number of different primary, secondary and total concepts described by students in each of the cohorts.

Cohort	Average Primary	Average Secondary	Average Total
Control (*n* = 24)	4.88 (SD 2.02)	0.38 (SD 0.58)	5.29 (SD 2.13)
Experimental 1 (*n* = 30)	5.88 (SD 1.80)*	0.87 (SD 0.94)**	6.63 (SD 2.09)**
Experimental 2 (*n* = 20)	5.45 (SD 1.93)	0.90 (SD 1.07)*	6.42 (SD 2.65)

in the Experimental cohorts took four credits of Machine Design in the junior year compared to only two credits in the sophomore year for the Control cohort.

Summary of Assessment Efforts and Lessons Learned

Overall, the results show that students had some drop in performance on the Solid Mechanics and Thermodynamics Concept Inventories, thus, an integrated design project did not improve student knowledge retention. Thus, the investigators have rejected the first research hypothesis. On the other hand, students did show an improvement on a Design Challenge assessment, signaling their ability to identify various concepts needed to design an engine and the interconnectedness of courses in the mechanical engineering curriculum. Thus, the investigators tentatively accept the second research hypothesis.

Owing to the unique nature of the five-semester design/build project, several assessment challenges presented themselves. Some of the challenges (e.g. the impossibility of keeping the same set of instructors for all test cohorts) were anticipated before the research project began. Other challenges came as a surprise to the investigators, and are discussed below. We believe that many of the lessons learned during this research effort have a broad application to many other types of design/build projects and to other institutions.

Consider the type of assessment: Students are not typically familiar with the concept inventory as an assessment tool, thus using them for this study may not have been as helpful as we had anticipated. Students are more familiar with “traditional” problem-solving questions and are encouraged at many institutions to take the national Fundamentals of Engineering (FE) exam. Thus, using practice (FE) exam questions may be a more appropriate assessment measure. The scores of the students under study could also be compared to national test results, with the caveat that the actual test questions might not be the same.

Consider assessment timing and assessment fatigue: The assessment plan for concept retention was scaled back from that which was originally proposed in the grant proposal. Since the assessment measures were voluntary, with only small incentives such as pizza, very few seniors in their final semester participated. Second-semester junior year students took three assessments – 1) Design Challenge, 2) Thermo CI post and 3) Solid Mechanics CI retention. Considering again that the assessments were voluntary, students had final exams and projects to complete and minimal incentive was given for the Solid Mechanics CI, student participation or level of effort may have been compromised.

If our team were to conduct a similar integrated project and assessment study, moving the Solid Mechanics retention assessment to the first-semester of the students' junior year would alleviate the issues mentioned. Students would take fewer assessments at the end of sophomore year and could be given further incentive with extra credit tied to the Machine Design course that students take in the first semester of the junior year. In other words, a more *targeted* assessment effort (as opposed to the *broad-based* approach adopted by the authors) would likely have yielded more complete results.

CONCLUSION AND LESSONS LEARNED

Two cohorts have completed the full, five semester design project and a third is underway. Having successfully implemented the project, we believe that similar efforts can be undertaken at other institutions. This may be done on a module-by-module basis or in full, as appropriate. Below we describe some of the lessons learned in conducting this research that may be helpful to others who wish to adopt this type of integrated design project.

As one might expect, the development and implementation of such a large-scale design project was quite challenging for the students and the authors alike. The authors learned several valuable lessons as the first and second cohorts made their way through the project. As an example, senior exit interviews made it clear that many of the students' air-powered motors (built during the junior year) were too unreliable for extended use in developing the overall control scheme (developed during the senior year). As discussed above, we chose to make several "faculty model" motors available to students in the second cohort during their senior year. Therefore, the second cohort experienced an improved design project experience, and represented a much more valid test of the research hypotheses. The lesson is that a long-term design project requires much more emphasis on reliability and durability than traditional design projects that end with the semester. We now assign extra credit to teams that are able to use their own air engines throughout the project, rather than relying on the faculty model.

Additionally, the project has generated a surprising amount of excitement and fascination among the students, and we observed the kind of "nights and weekends" commitment from students that is so desired by educators. It has even become a recruiting tool at open houses because of the obvious interest shown by prospective students and their parents. The authors are convinced of the value of the project, and we plan to deliver components of it for the next two or three cohorts of students.

Long term sustainability of the project as a whole has proven to more challenging than we anticipated. The Rowan Mechanical Engineering program has experienced an unprecedented amount of growth in the past few years, which has led to major staffing changes. We have kept the major components of the project (e.g. air engine, tachometer, planetary gearset) for the three cohorts of students who are currently in the "pipeline", but maintaining the rigorous assessment effort described above has proven impossible. Overall, however, the authors believe that a large-scale, long-term design project that integrates several courses within an engineering curriculum is a worthwhile effort, especially for engineering programs that have reached "steady state" in terms of student enrollment and staffing. We are currently brainstorming a follow-on project to the hybrid powertrain, to be implemented once we have reached our own steady-state.

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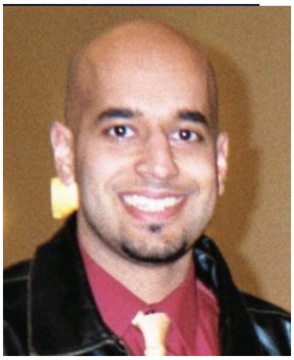

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