AC 2008-1088: A HYDRAULIC HYBRID VEHICLE SIMULATION PROGRAM TO ENHANCE UNDERSTANDING OF ENGINEERING FUNDAMENTALS

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Christopher C. Schroeder is a graduate mechanical engineering student at The University of Toledo. He is working with Dr. Mohammad Elahinia on a project to develop "Multipurpose Educational Modules to Teach Hybrid Vehicle Technologies". Specifically Christopher says I am "working with colleagues to make hydraulic hybrid vehicles more suitable for commercialization…. I am excited and thrilled to be part of a university and a project which have the potential to make big changes in the automotive industry."

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Walter Olson is a professor of Mechanical Engineering specializing in dynamics in the Department of Mechanical, Industrial, and Manufacturing Engineering at the University of Toledo. His research on Hydraulic Hybrid Vehicles is sponsored by the US EPA as well as MIOH UTC.

A Hydraulic Hybrid Vehicle Simulation Program to Enhance Understanding of Engineering Fundamentals

Introduction

Fueled by the interest in reducing dependence on fossil fuels, the hybrid vehicle market has seen significant growth over the last few years. Most passenger car hybrids have been electric/internal combustion engine models, but other hybrid technologies using hydraulic pump/motors, flywheels, and ultracapacitors are also in various stages of development. One advantage of the hydraulic over the electric hybrid is the high power density associated with recharge and discharge of the accumulators compared to the more limited power density of batteries. This advantage is particularly pronounced for heavy vehicles such as delivery trucks that require high braking power and undergo frequent starts and stops.

The hydraulic hybrid is an excellent context for teaching the fundamentals of thermodynamics, fluid mechanics, and vehicle dynamics. A MATLAB/Simulink program has been written to simulate hydraulic hybrid and conventional vehicle performance. Students can input parameters such as vehicle drive schedule, mass, tire size, accumulator volume, pump/motor displacement, and drag coefficients to see the effects on fuel economy, power distribution, and recovered braking energy. The audience for the current work includes students enrolled in thermodynamics and fluid mechanics courses. This paper will elaborate on the objectives of the project, describe model details, present student exercises classified according to level and course, and provide an assessment of how effective the simulation tool and associated assignments were in improving student learning.

Project objectives and outcomes

The project entails the development of learning materials to achieve the following objectives:

1) demonstrate how hydraulic hybrids can improve fuel economy

2) promote understanding of the thermodynamic principles behind accumulator design and IC engine performance

3) highlight the fundamental relationships governing vehicle dynamics

4) promote understanding of the fluid mechanics associated with hydraulic pump/motor units and associated piping

5) enhance the ability to critically evaluate the outputs and understand the limitations of a computer simulation

6) provide experience with the use of MATLAB/Simulink as an engineering tool

In order to meet these objectives, topical exercises were developed. To date, two exercises have been delivered to students in the classes of Thermodynamics I and Fluid Mechanics. Students in the Civil and Mechanical Engineering programs take these courses, with the majority of students typically from Mechanical Engineering. Thermodynamics I is normally taken by first-term juniors, and Fluid Mechanics is normally taken by second-term juniors.

The exercise for the thermodynamics students was entitled *Hydraulic Hybrid Simulation Power Analysis*, covering the power and energy distribution for the IC engine and hydraulic pump/motor. For a student completing the assignment the outcomes were that he or she would be able to:

1) describe the relationship between power and energy
2) describe how a hydraulic hybrid powertrain reduces fuel consumption
3) use MATLAB/Simulink to integrate rate quantities and manipulate outputs
4) use the scope and display functions in Simulink to analyze output
5) use the "Help" function in Simulink to learn how to perform operations

The exercise for Fluid Mechanics was entitled *Analysis of the Pump/motor Unit in a Hydraulic Hybrid Vehicle*, with the following outcomes:

1) explain how a bent axis, axial piston pump/motor works
2) describe how pump/motor displacement and accumulator volume affect hydraulic hybrid fuel economy
3) change Simulink inputs and compare results
4) use the scope and display functions in Simulink to analyze output
5) understand Simulink modeling limitations
6) apply fundamental fluids relationships to analysis of hydraulic system components
7) use the "Help" function in Simulink to learn how to perform operations

<u>Simulink model details</u>

The power to propel a vehicle is given by the following equation (see, for instance, reference 1):

$$\dot{W}_{req} = \left[R_L + Ma\right]V$$

where $\dot{W}_{req}$ is the power required at the wheels to accelerate the vehicle and overcome drag, rolling resistance, and climbing forces. The instantaneous vehicle speed is V. The "road load" is

$$R_L = \frac{1}{2}\rho V^2 C_D A + fW + W\sin\theta$$

where the first, second, and third terms on the right hand side are the aerodynamic drag, rolling resistance, and climbing forces. The quantity f is termed the rolling resistance coefficient, and is often assumed to remain constant through a drive schedule.

The accelerative load, Ma, includes both the force to increase the vehicle speed and the force necessary to increase the angular speed of rotational components within the vehicle like the driveshaft and transmission components. With a particular "drive schedule" input as speed versus time data, vehicle acceleration and thus the instantaneous power requirement can be calculated from the aforementioned equations for each time step. If the hydraulic unit can supply all the required power, the IC engine idles. If the hydraulic unit cannot supply all the required power, the IC engine makes up the difference. The Federal Urban Drive Schedule is illustrated in Figure 1.

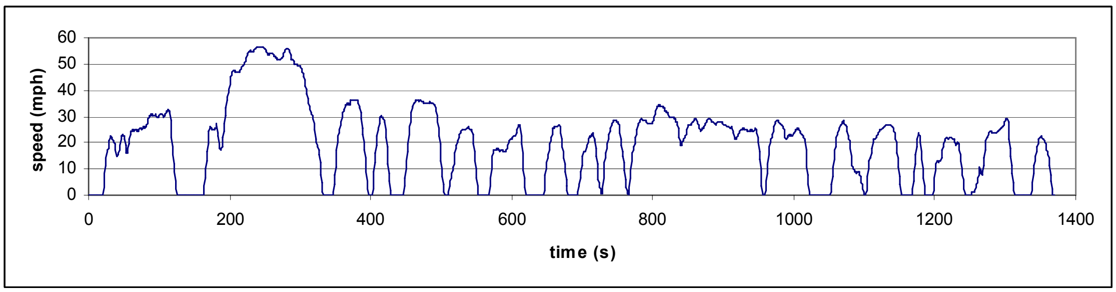

Figure 1. The Federal Urban Drive Schedule[2].

The modeled hybrid uses a hydraulic pump/motor unit operating in parallel with an internal combustion engine (see Figure 2). The pressurized liquid is stored in an accumulator fitted with a separator (shown in Figure 3 as a piston) between the hydraulic fluid and a compressible gas such as nitrogen. When the hydraulic unit operates as a pump (during braking), it pumps hydraulic fluid from a low pressure reservoir to the accumulator; when it operates as a motor (during acceleration and constant-speed driving), pressurized fluid flows in the opposite direction, powering the motor and discharging into the low pressure reservoir.

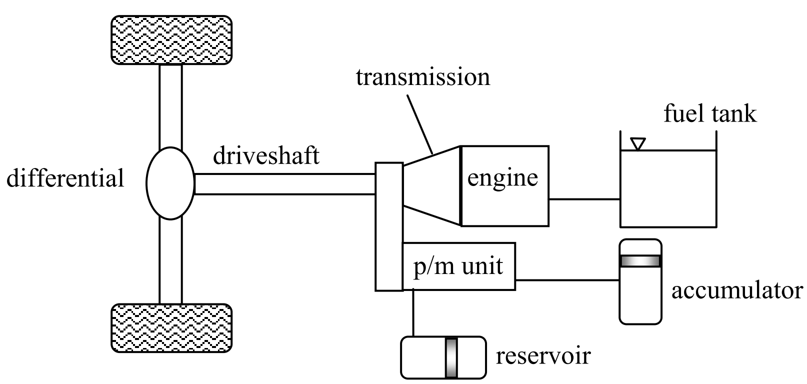

Figure 2. Parallel hydraulic hybrid configuration.

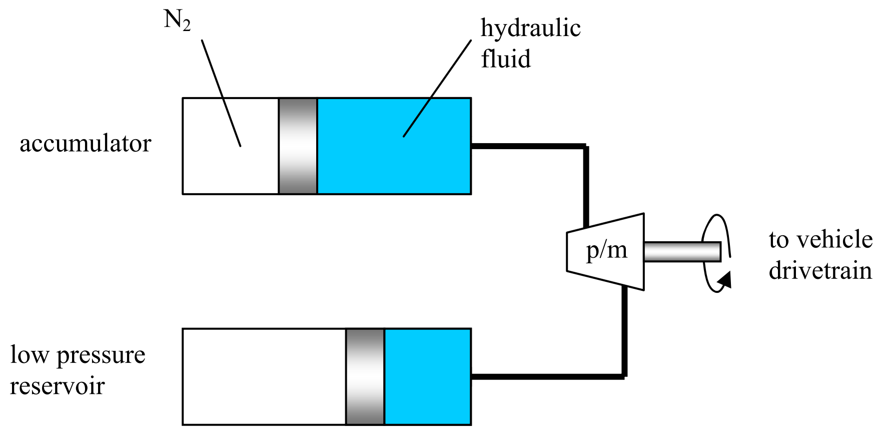

Figure 3. The hydraulic pump/motor unit with accumulator and reservoir.

The power output and power absorption capabilities of the hydraulic unit are limited by two factors: pump displacement and accumulator volume. Since the angular speed of the unit's shaft is proportional to vehicle speed, the volumetric displacement may not be sufficient to provide (or absorb) the required power. Additionally, the hydraulic unit provides no power if the accumulator is empty (i.e., contains no hydraulic fluid) and absorbs no power if the accumulator is full (i.e., is full of hydraulic fluid).

The hydraulic pump/motor power is determined by $\dot{W}_h = \mathrm{T}_h \omega_h$, where T_h is the pump/motor torque and ω_h is the pump/motor angular speed. The torque is $\mathrm{T}_h = \Delta p D$, where Δp is the pressure difference across the pump/motor ($p_{accumulator} - p_{reservoir}$) and D is the pump/motor displacement per radian. (In practice, the pressure in the reservoir is significantly less than that in the accumulator, so we set $\Delta p = p_{accumulator} = p$.) The volumetric flowrate through the pump/motor is $Q = \omega_h D$.

The pump/motor performance is linked to the accumulator thermodynamics through the energy equation relating the time rate of change of internal energy of the accumulator gas to the rate at which work is done by the gas: $mc_v \frac{dT}{dt} = -p \frac{d\forall}{dt}$. Here, m is the gas mass, c_v is the constant-volume specific heat for the gas, p is the gas pressure, and $\forall$ is the gas volume. This equation assumes adiabatic behavior. In many applications, foam is used on the gas side of the accumulator to produce nearly isothermal behavior. The model allows the user to choose either isothermal or adiabatic operation.

The time rate of gas volume change in the energy equation is determined from the physical constraint that the change in gas volume is equal to the change in liquid volume in the accumulator, which in turn is equal to the hydraulic fluid volumetric flow rate: $Q = \frac{d\forall}{dt}$. The gas properties are related by the ideal gas equation $p\forall = mRT$.

For power absorption (pump) mode, the quantities $\dot{W}_h$ (and $\dot{W}_{req}$), D, and Q become negative. Variation in pump/motor demand is accomplished through variation in pump/motor displacement, D. D is limited to $\pm D_{max}$, which is plus or minus the maximum pump/motor displacement (per radian). See reference 3 for a more complete description of regenerative hydraulic system modeling.

Fuel economy is determined by monitoring the fuel mass flow rate to the engine during idling or when the engine is called upon to provide part or all of the required power. The engine power, $\dot{W}_e$, is related to the heat transfer rate in the engine, $\dot{Q}_H$, via the thermal efficiency: $\eta = \frac{\dot{W}_e}{\dot{Q}_H}$. The mass flow rate of fuel can then be determined from $\dot{Q}_H = \dot{m}_f\, Q_{HV}$ where Q_{HV} is the "heating value" of the fuel expressed in units of energy/mass and $\dot{m}_f$ is the fuel mass flow rate. Once the mass flow rate is known, we can determine an average fuel economy from

$$FE_{avg} = \frac{\int_0^{t_f} V dt}{\frac{1}{\rho_f}\int_0^{t_f} \dot{m}_f dt}$$, where ρ_f is the fuel density.

The foregoing development ignores component inefficiencies for simplicity of presentation. The Simulink model does, however, include component inefficiencies, but ignores line friction losses and does not account for real gas behavior.

Figure 4 shows the algorithm for the model. The Simulink block diagram is shown in Figure 5 (this figure shows a simplified diagram for illustrative purposes). Figure 6 shows an example of the power distribution (required power, hydraulic power, and IC engine power) for a delivery truck traveling the Federal Urban Drive Schedule. Results compare favorably with those from reference 4.

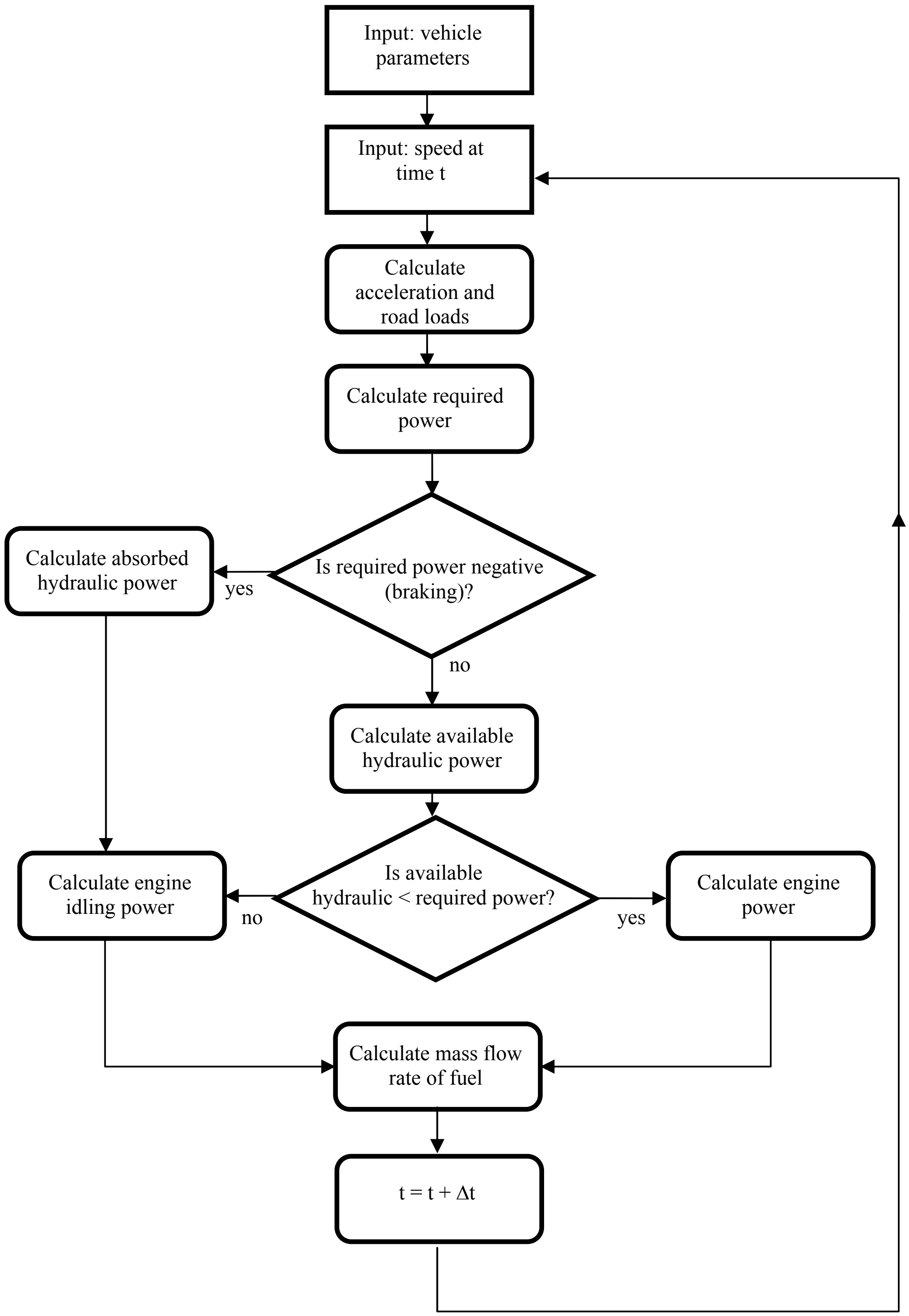

Figure 4. Hydraulic hybrid vehicle model algorithm.

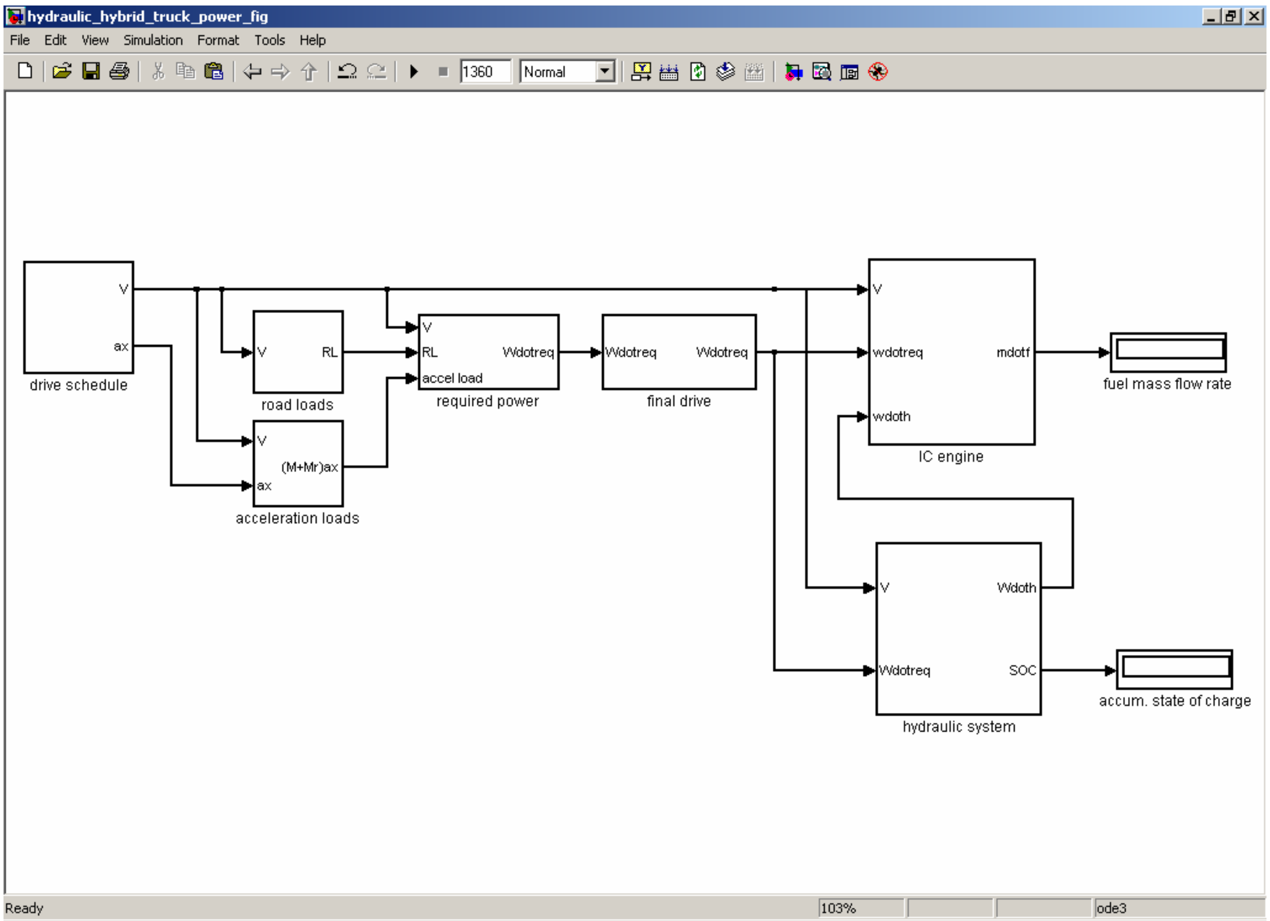

Figure 5. Simplified Simulink block diagram for hydraulic hybrid vehicle.

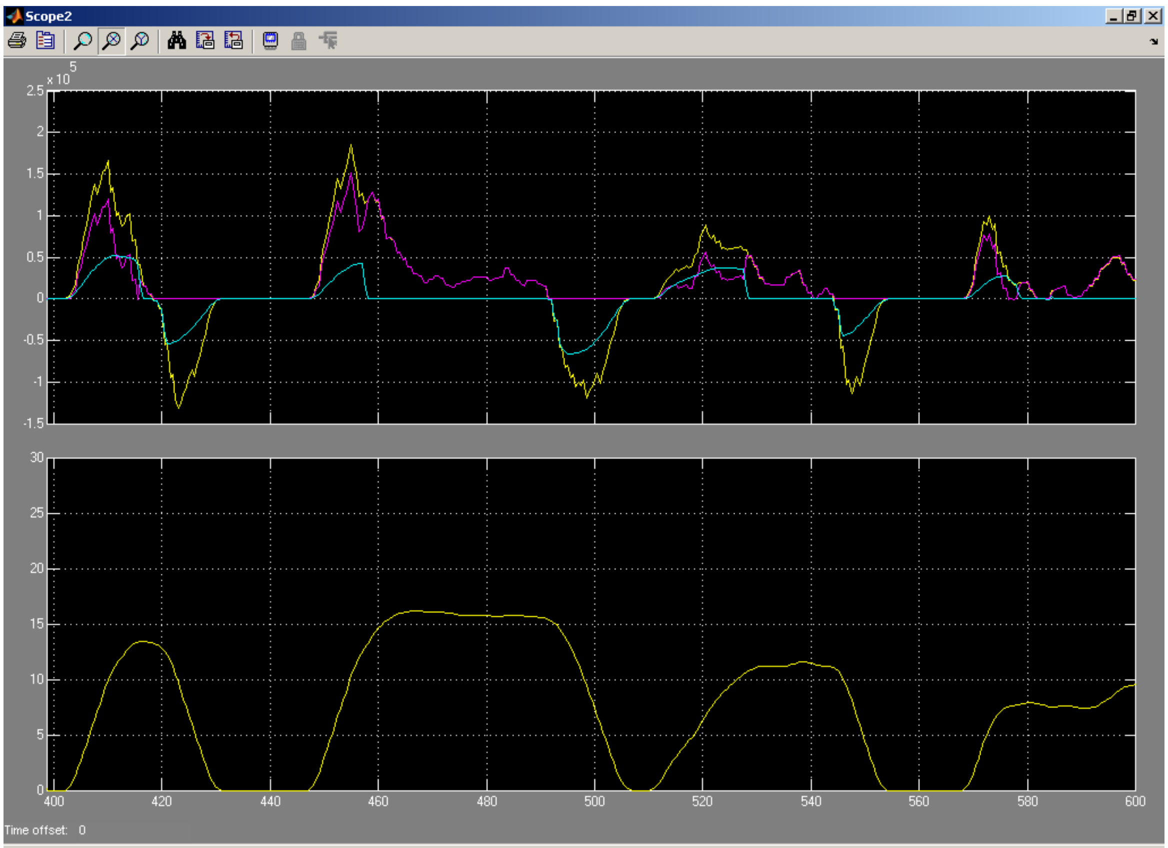

Figure 6. Power distribution (top) and vehicle speed (bottom) for a hydraulic hybrid delivery truck during the 400 – 600 s range of the Federal Urban Drive Schedule. In the top graph, the required power is yellow, the hydraulic power is blue, and the engine power is purple. Units for the *x*-axis are seconds, units for the *y*-axis in the top graph are watts, and units for the *y*-axis in the bottom graph are meters per second.

Student exercises

The two exercises mentioned above were developed and offered to students in the fall term 2007-08. The exercises themselves were in the form of handouts (interested readers may contact Mark Schumack at schumamr@udmercy.edu for copies). In addition to the handouts, students were provided with brief primers on fuel economy simulation and hydraulic hybrid technology. For each exercise, a single class lecture was dedicated to showing students the fundamentals of Simulink (adding displays, using integrator blocks, performing mathematical calculations) and elaborating on the outcomes for the exercise. In Thermodynamics I, the exercise was mandatory and worth five percent of the final grade. In Fluid Mechanics, the exercise was for extra credit, and every student participated. Students performed the exercises in teams of two or three people.

Each exercise consisted of introductory text, a set of instructions and tasks for the students to perform, and questions requiring written responses. Students downloaded the Simulink model file from the course website, along with an input file containing parameters such as vehicle mass, engine size, accumulator size, and fuel properties.

The exercise for Thermodynamics I, *Hydraulic Hybrid Simulation Power Analysis*, concentrated on the power distribution for the IC engine and hydraulic pump/motor (see Figure 6). We expected the students to recognize that energy expended (or absorbed) is the area under (or above) the power curve. By analyzing curves such as that shown in Figure 6, students were expected to judge how well the hydraulic system assisted the IC engine during acceleration and absorbed energy during braking. Using the Simulink integrator block, students were able to calculate energy values for the entire drive schedule, and make comparisons such as total energy absorbed by the hydraulic system (the area above the negative portion of the blue curve) versus total braking energy (the area above the negative portion of the yellow curve). Students were also expected to determine fuel economy with and without the hydraulic system by integrating curves for speed and fuel mass flow rate and performing the necessary mathematical manipulations (the fuel economy was 10.9 mpg for the IC engine only, rising to 12.7 mpg with the hybrid configuration).

The exercise for Fluid Mechanics, *Analysis of the Pump/motor Unit in a Hydraulic Hybrid Vehicle*, concentrated on the fluid mechanics of the pump/motor unit and associated hydraulic lines. Students analyzed vehicle performance for a simple drive schedule consisting of a period of constant acceleration, followed by a period of constant speed, and completed with a period of constant deceleration. They were expected to use the equations for pump/motor units to confirm the power as indicated on output graphs and displays for pressure, angular speed, and displacement. They were also expected to recognize that differences might be explained by the fact that the equations they used did not account for inefficiencies, while the Simulink model does. They used pipe flow relationships from class to determine pressure drop in hydraulic lines, and to make a judgment as to whether the model was justified in ignoring the drop. Finally, students increased pump/motor displacement and accumulator volume to see the effect on performance for the simple drive schedule, then ran the Federal Urban Drive Schedule with and without the adjustments to gauge the effect on fuel economy.

Assessment

Outcomes were assessed by grading the exercise questions and relevant questions from a questionnaire given to each student after completion of the assignment. As seen earlier, each exercise had its own set of "local" outcomes which were linked to the global project objectives. Table 1 shows the linkages between exercise outcomes and project objectives, along with the exercise questions and questionnaire items used to assess the outcomes. Answers were given numerical scores of "2" for good, "1" for fair, and "0" for poor. There were 14 team reports for Thermodynamics I and five team reports for Fluid Mechanics. After the assignments were turned in, the Thermodynamics I questionnaire was filled in by 28 students and the Fluid Mechanics questionnaire was completed by eight students.

Figure 7 shows average scores for each of the project objectives based on the linkages shown in Table 1. The first (*demonstrate how hydraulic hybrids can improve fuel economy*) and last (*provide experience with the use of MATLAB/Simulink as an engineering tool*) project objectives were assessed most robustly, judging by the number of assessment methods listed for those objectives in Table 1. These objectives both received high scores, indicating with a fair degree of certainty that students understood how hydraulic hybrids work and gained significant experience with MATLAB. Two of the other high-scoring items, *promote understanding of the thermodynamic principles behind accumulator design and IC engine performance* and *highlight the fundamental relationships governing vehicle dynamics*, had fewer assessment techniques. The major thermodynamics outcome that was assessed was the relationship between power and energy, and the only assessments related to vehicle dynamics were questions probing student observance of the relationship between power required and power delivered or absorbed by the hydraulic system. Regardless of the lower number of assessment points, the high score for the outcome regarding the relationship between power and energy indicates that this key thermodynamic concept was successfully reinforced by the exercise.

The lowest scoring objective, *promote understanding of the fluid mechanics associated with hydraulic pump/motor units and associated piping*, received its score due mainly to student responses to the questionnaire item: *Briefly explain how a hydraulic piston pump works.* Most students interpreted this to mean "how does a hydraulic hybrid vehicle work?" and thus missed the intent. On the other hand, students largely answered the exercise question dealing with calculation of pressure drops in hydraulic lines correctly–an indication that this fundamental fluid mechanics topic was adequately reinforced.

The second-lowest scoring objective, *enhance the ability to critically evaluate the outputs and understand the limitations of a computer simulation*, was assessed by a single exercise question in the pump/motor handout dealing with solution dependency on time step size. Students were expected to recognize that the solution is dependent upon time step size, sometimes significantly so, changing the predicted fuel economy by nearly four percent as the time step size is changed from 1 to 0.1 second. Most students reported similar results, and felt the smaller time step was more accurate, but failed to note that the real solution should be independent of time step size, and that smaller time steps should lead to convergent results. The outcome could be improved with more probing questions exploring the fact that a simulation is only as good as its assumptions.

	Project objectives / Exercise outcomes	demonstrate how hydraulic hybrids can improve fuel economy	promote understanding of the thermodynamic principles behind accumulator design and IC engine performance	highlight the fundamental relationships governing vehicle dynamics	promote understanding of the fluid mechanics associated with hydraulic pump/motor units and associated piping	enhance the ability to critically evaluate the outputs and understand the limitations of a computer simulation	provide experience with the use of MATLAB/Simulink as an engineering tool
Power analysis (Thermodynamics I)	1) describe the relationship between power and energy		exercise question 6				
	2) describe how a hydraulic hybrid powertrain reduces fuel consumption	exercise questions 4,5 and questionnaire item 5					
	3) use MATLAB/Simulink to integrate rate quantities and manipulate outputs						exercise questions 7,8,9,10
	4) use the scope and display functions in Simulink to analyze output			exercise questions 4,5,10			exercise questions 4,5,10
	5) use the "Help" function in Simulink to learn how to perform operations						questionnaire item 2
Pump/motor (Fluid Mechanics)	1) explain how a bent axis, axial piston pump/motor works				questionnaire item 4		
	2) describe how pump/motor displacement and accumulator volume affect hydraulic hybrid fuel economy	exercise questions 11,12,13					
	3) change Simulink inputs and compare results						exercise question 13
	4) use the scope and display functions in Simulink to analyze output						exercise questions 5,6,7
	5) understand Simulink modeling limitations					exercise question 14	
	6) apply fundamental fluids relationships to analysis of hydraulic system components				exercise questions 8,9,10		
	7) use the "Help" function in Simulink to learn how to perform operations						questionnaire item 2

Table 1. Linkages between project objectives and exercise outcomes. Also shown are the exercise and questionnaire questions used to assess the outcomes.

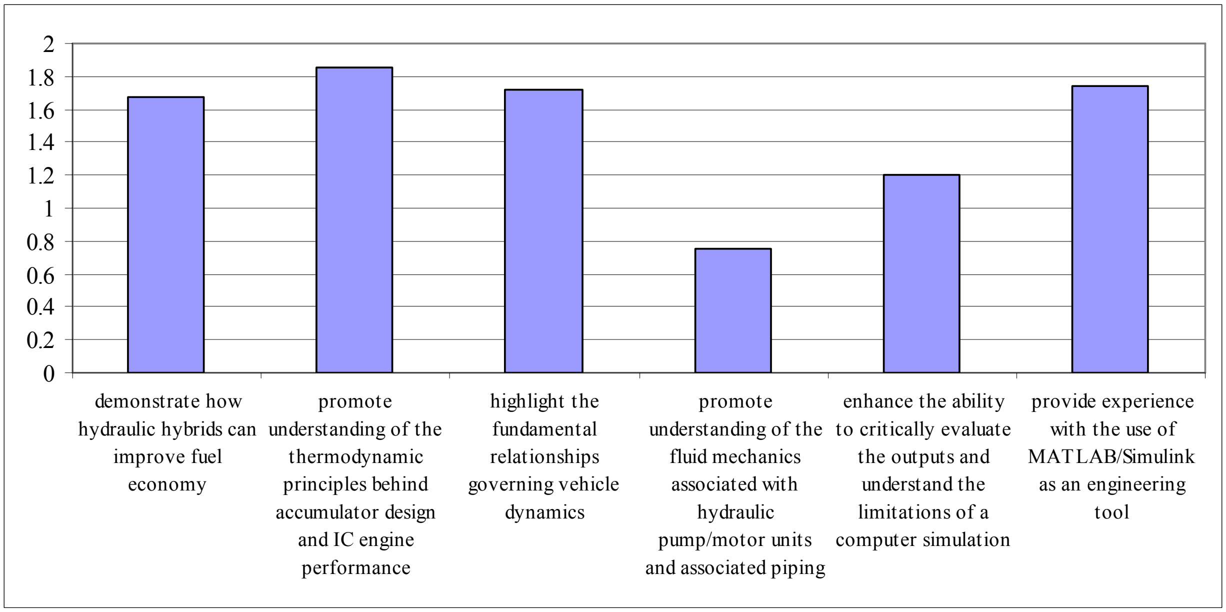

Figure 7. Project objective average scores based on the linkages shown in Table 1. The numerical values in the figure were calculated by assigning scores of 0 (poor), 1 (fair), and 2 (good) to student responses to the relevant exercise questions or questionnaire items.

As mentioned earlier, essentially a single lecture was devoted to introducing hydraulic hybrid technology and MATLAB fundamentals. Recognizing that we could not possibly cover everything students needed to know to run the simulation and answer the exercise questions, we counted on the students using the help function in MATLAB to learn how to use blocks like numerical displays, scopes, and for mathematical operations. As will be seen, a large number of students indicated in their comments that they felt not enough time was spent in explaining certain aspects of MATLAB usage. Figure 8 shows that 52% of respondents did not use the help menu, while the remainder either did use it or did not remember using it. In future offerings, the situation may be rectified by emphasizing that not all information to run MATLAB is provided in the lecture, and that students must use the help menu to do the assignment.

The assignments were designed to be completed in between one and two hours. Figure 9 shows that most students took over two hours, a fact that could be a reflection of the need to undergo a significant amount of trial and error to figure out how to use certain features of the program.

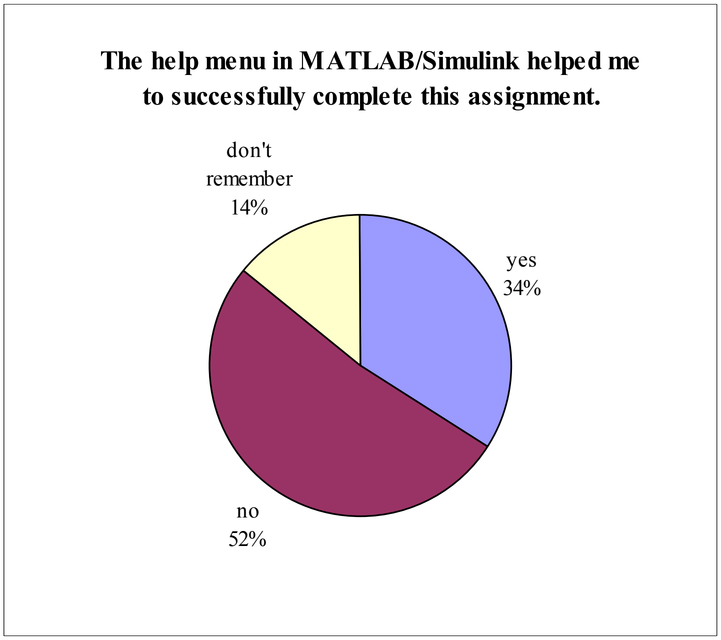

Figure 8. Percentage of students using the MATLAB help menu.

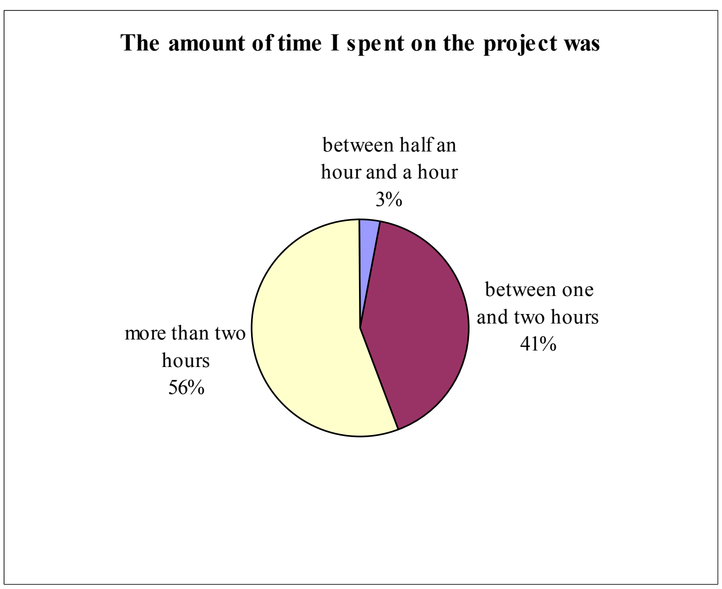

Figure 9. Student time spent completing the assignment.

Finally, Figure 10 shows that a significant majority of students desire to use MATLAB in the future, indicating that in spite of their struggles, they recognize its utility.

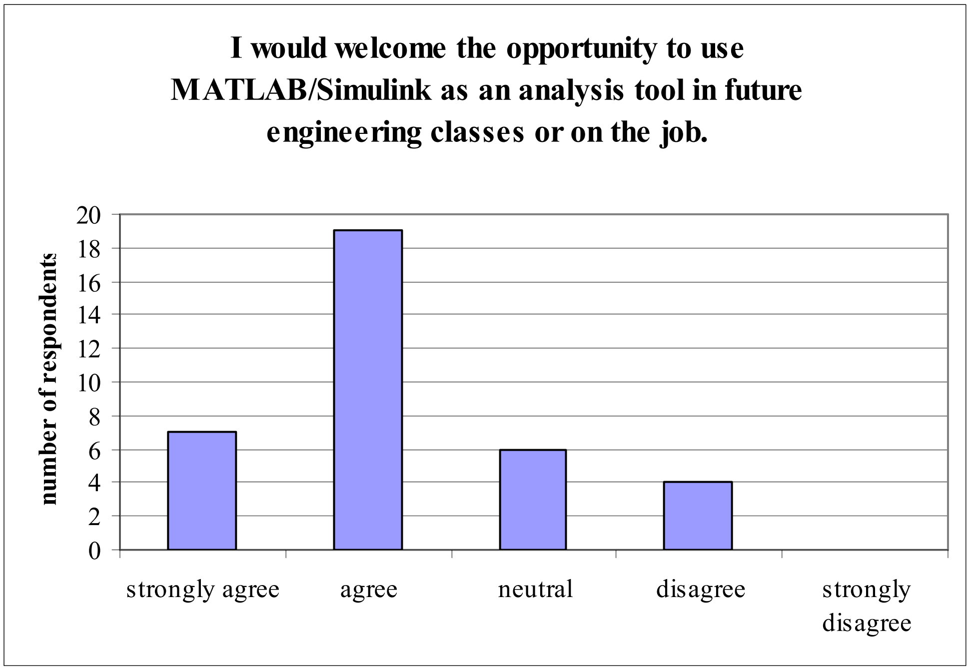

Figure 10. Student perception of future use.

The last question on the questionnaire was "Please comment on how future offerings of this project could be improved." Samples of the most frequent comments follow:

> "The units in MATLAB were not clear to me."
>
> "The project can be improved by giving the user a little more information so there is not so many unknowns and assumptions to be made."
>
> "I think the instructions could be a little more precise."
>
> "I think there should be more similar projects to the one given."
>
> "Not so close to end of term."

By far, the most frequent concern was the perceived lack of guidance prior to actually sitting down behind the computer. In the future, we will consider offering a simpler exercise demonstrating some basic MATLAB/Simulink features prior to assigning the hydraulic hybrid project.

Conclusions

The two Simulink exercises described here successfully reinforced key thermodynamics and fluid mechanics concepts. Future exercises are planned to emphasize accumulator thermodynamics, which is an excellent application of the classical "cylinder/piston" problem seen ubiquitously in thermodynamics courses. Plans are in the works to develop exercises highlighting vehicle dynamics in either freshman engineering or energy system courses. Results from the Simulink model have also been used to develop an Excel Visual Basic macro to teach high school students about hybrid vehicles.

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References

1) Gillespie, Thomas D., *Fundamentals of Vehicle Dynamics*, Society of Automotive Engineers, 1992.

2) http://www.epa.gov/nvfel/methods/uddscol.txt accessed on 1/17/08.

3) Pourmovahed, A., Beachley, N.H., and Fronczak, F.J., "Modeling of a Hydraulic Energy Regeneration System – Part I: Analytical Treatment," *J. of Dynamic Systems, Measurement, and Control*, March 1992, vol. 114, pp. 155 – 159.

4) Wu, B., Lin, C-C., Filipi, Z., Peng, H., and Assanis, D., "Optimal Power Management for a Hydraulic Hybrid Delivery Truck," *Vehicle System Dynamics,* 2004, vol. 42, nos. 1-2, pp. 23-40.