Using Model Solar Racers as an Introduction to Engineering

Abstract

This engineering first-year seminar course was first offered in spring 2001 and is based on the successful middle school program, the Junior Solar Sprint. Student teams compete to design, build and race small-scale photovoltaic (PV)-powered vehicles. This hands-on experience serves many goals, most notably as a fun introduction to engineering design, analysis, and testing. Solar Racers makes a great topic because of the many relevant issues that first-year students can understand including renewable energy, vehicle physics, electrical circuits, team work, experimentation, material selection, design processes, mathematical analysis, and computer tools like spreadsheets and equation solvers. The use of knowledge and techniques from various courses and subjects helps demonstrate the application and integration so uncommon in the traditional first year of engineering. The culmination of the course is a race day where student teams compete with their classmates in a straight 70 foot long race. Two race heats are carried out, one with PV power and another with battery power. Teams prepare a summary report that describes their car details and highlights. Hands-on work is supplemented by brief lectures, readings, and homework problems. This paper describes the course and related resources sufficient to allow other interested faculty members to develop similar courses at the university level. Some of the engineering analysis may also be useful to middle school teachers and students to further the level of engineering rigor in similar projects. Experiences from five semesters of the course will be reviewed, along with recommendations for further improvement.

Introduction

This course was first offered in spring 2001 and has been described in two previous conference papers.\textsuperscript{1,2} This paper reviews the relevant information from these earlier papers and describes new developments in this course including use of a new PV panel and motor combination. The course is a one-credit first-year seminar, Solar Racers, in the College of Engineering at Penn State, and is based on the successful middle school program, the Junior Solar Sprint (JSS).\textsuperscript{3} At the middle school level, student teams compete to build and race small-scale solar-powered vehicles. The program is highly successful and serves many goals: team building, introduction to engineering design, confidence building, and demonstrating that engineering can be fun. This engineering first-year seminar shares these goals, while significantly advancing the use of engineering analysis, testing, and design in the development of the prototypes. Our students also serve as mentors for local middle school students who compete in a regional solar race competition hosted by Penn State.
Up until 2003, we used the same solar cells and DC motor as used in the JSS, available from Solar World (www.solarworld.com). The first conference paper describes the results and experiences using this system. While this system performed well, there were two drawbacks. Most important was the fragility of the PV-panel, made of three single-crystalline cells (3.4 V, 3.0 W, for the panel) mounted on foamcore board and covered with a thin layer of plastic. This assembly was too fragile to withstand the day-to-day use and handling, resulting in many cracked cells. The second drawback was that the panel was relatively expensive (currently about $28), particularly for use by the middle schools.

In 2003, less expensive components were identified. This package is still used in the local middle schools, and consists of six individual amorphous solar cells (each cell is 4.5 V, 0.27 W). These inexpensive cells (about $3 each) are encapsulated in a polymer that makes them very rugged, and were apparently designed for use in small solar-powered lights like those marketed for landscape or path lighting. A different DC motor was chosen to match the lower power output (1.62 W) and higher array voltage possible with the new cells (Johnson 12 VDC, Goldmine electric G14072). One of the challenges in using this system is that the solar cells are at times unavailable for purchase, plus it requires attaching wires to the cells and interconnecting them and mounting them on some type of base. In our case, local volunteers pre-assemble the panels, wiring them with two sets of leads so that they can be connected with all of the cells in series (27.0 V), or with a parallel arrangement of three cells in series (13.5 V). The cells are assembled with hot glue or double-stick tape onto a polystyrene tray that is donated by a local supermarket (Figure 1).

![Figure 1 Photovoltaic module assembly used by local middle schools](image)

Our middle school partners have been using these less expensive components successfully in their programs. The volunteer parent leader, Tobin Short, had noticed that the wiring of the six cells – whether all in series, parallel, 2 series / 3 parallel, 3 series / 2 parallel – greatly affected car performance, and the best wiring depended on sunlight intensity. Sunlight intensity is a big variable in central Pennsylvania in late April and May when we hold the races. The need to schedule the races and proceed whatever the weather led to the panel wiring described in the previous paragraph. This allows students to change the wiring to adapt to the sunlight intensity. Students are also encouraged to design their cars so that they can change the gear ratio to adapt to the race day weather.
The unpredictability of sunlight during the late winter car design and development phase, as well as the possibility of cloudy weather on our early-spring race day, led to another modification. In 2005, the option of using a 9 V, 200 mAh, nickel metal hydride (NiMH) battery was added. This allows the races to be held in very cloudy conditions, or even indoors in rainy conditions, while adding another design challenge for the students. The 2005 American Solar Energy Society paper describes results and experiences with this system, including performance with battery power $^2$.

These two modifications are significant improvements to the basic JSS guidelines. Besides facilitating the races regardless of weather, they also better represent some of the challenges of operating a solar-powered car and responding to the varying level of sunlight. They do of course complicate the design and operation of the cars. A future modification may be to recharge the battery with the solar module.

One other important distinction of our solar races is that they are done without any guide wires or strings to cause the cars to follow a straight line. In the FYS course, students race in two car heats on a tennis court, from back line to opposite back line. In the middle school event, because of the larger numbers of racers, six to eight cars race side-by-side on a tennis court. The cars must cross the opposite back line without going outside the side boundaries of the court. Therefore, an additional challenge of our races is for the cars to run straight.

In spring 2006, a different PV-panel was selected for trial use in the FYS, a Kyocera Mini-module that comes wired with two sets of leads similar to our custom-made modules (9.9 V$_{oc}$ or 19.8 V$_{oc}$, 1.12 W$_p$). This panel was chosen because it is very rugged, utilizing single-crystalline cells encapsulated in acrylic with built-in mounting holes in the corners. Approximate cost was $18 per module but is now $23 per module.

This paper describes the current FYS course, with emphasis on the experimentation, analysis, and modeling of the current system using the Kyocera Mini-modules. The different sections will address:

a. Course overview
b. Use of experimental results for the PV panel and DC motor to define the torque/speed characteristic of the combined system, both with PV panel and battery power
c. Use of an equation solver to predict system performance and subsequent use of the model to find optimum gear ratios and to do parametric studies of the sensitivity of optimum gear ratio to estimated parameters such as friction coefficient
d. Review of experiences and recommendations for improvement.

The purpose is to allow other interested faculty members to develop similar projects at the university and middle school levels.

**Course Overview**
This course is a one-credit FYS in the College of Engineering. First-Year Seminars became a university-wide requirement in 1999 and have two overarching goals: engage students in learning and facilitate the transition to college life. In the College of Engineering, we seek to provide a small class experience that provides them with a meaningful and interesting introduction into some aspect of engineering practice. Class size is limited to 20 students and nearly all FYS’s are taught by regular faculty members. There are over sixty different seminar topics in engineering; for more information consult the web site at www.engr.psu.edu/fys.

The Solar Racers FYS evolved from projects used in a three-credit technical elective on solar energy taught by the author at Penn State Harrisburg since the 1980’s. It was modeled on the successful middle school initiative, the Junior Solar Sprint. Significant development work was applied to improving the experimentation and modeling associated with designing a model solar car to make the course appropriate for first-year engineering students. In its current form, the students completing the course should be able to:

- Explain the basic principles of solar energy application and use these principles to design and build a model solar-powered vehicle
- Describe and interpret the performance of photovoltaic modules, DC motors, and batteries
- Define and analyze the major energy flows in a vehicle, and understand how engineers model system performance
- Work more effectively in a group
- Utilize the University’s resources for academic study, including ANGEL, e-mail, and the world wide web.

The course meets once a week for two hours in a lab equipped with computers and fabrication tools where students can work in class on their design development. Each team of two students is given a PV panel, DC motor, 9V rechargeable battery, and access to a tool kit containing an array of parts including axles, wheels, gears, battery clips, wires, and switches. The only requirement is to use the PV panel (or battery) and motor as the sole source of power. Students test the PV panels and DC motors, deriving empirical relationships that are eventually combined with physics relationships including gearing, air drag, friction, and inertia. These relationships are entered into Engineering Equation Solver to predict the car’s performance during the race, and to do parametric studies. Designs are judged for ingenuity, appearance, performance, materials, and use of engineering skills. The highlight of the course is a race day where student teams compete with their classmates in a straight 70 foot long course. Two race heats are carried out, one with PV power and another with battery power. Teams prepare a summary report that describes their car details and highlights.

Hands-on work is supplemented by brief lectures, readings, and homework problems. Solar principles to be demonstrated include solar angles, solar resource, and conservation of energy. Students also use spreadsheets for solving problems and computer models to perform parametric studies as an aid in the design process. Homework assignments are designed to help guide students through appropriate analysis and tools that support their car design. Grading is based on individual homework (30%), evaluation of the car design (35%), and the team report (35%).
An example of the report that students submit is included as Figure 2. This relatively simple report was developed as a way to record some of the important design characteristics of the cars to help inform future designs. It does not require excessive time to prepare nor to evaluate. Note that a photo is taken of the car in front of a grid (in inches) that allows one to estimate the frontal area of the car. The other most important characteristic is the weight which is measured on a sensitive scale.

<table>
<thead>
<tr>
<th>ENGR 0975.101</th>
<th>Solar Racers</th>
<th>Design Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semester: Spring 2006</td>
<td>Team Speed of Light</td>
<td></td>
</tr>
<tr>
<td>Team Members:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student 2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Photographs of Car:

Figure 2  Sample final report from spring 2006 (first-place solar-powered)

Car Details:

<table>
<thead>
<tr>
<th>Solar-powered</th>
<th>Battery-powered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>336</td>
</tr>
<tr>
<td>Frontal area²</td>
<td>14.6</td>
</tr>
<tr>
<td>Gear ratio</td>
<td>4:1</td>
</tr>
<tr>
<td>Drive wheel radius</td>
<td>1.0</td>
</tr>
<tr>
<td>Place</td>
<td>1</td>
</tr>
</tbody>
</table>

Special Features: Light-weight balsa wood construction, sturdy and rigid body, adjustable PV panel angle, adjustable steering, removable PV panel, aerodynamic shape, easy access to components, hot-rod pink fairings, low-friction axle mounts, gear ratio set for acceleration.
Four homework assignments are currently required, three of which guide the students through analysis that is relevant to their project. The first is focused on the solar resource and particularly solar angles and geometry. In class the related lecture covers solar angles, sun path diagrams, solar time, solar intensity, and magnetic declination. Two spreadsheet tools are made available on the course website: one to calculate the equation of time and another that determines the solar incidence angle with angular inputs of solar altitude, solar azimuth, surface azimuth, and surface tilt. The main lessons for students are that solar time is different than clock time, solar position can be predicted, and the solar energy received by a panel depends on how nearly it is facing the direction of the sun. The orientation of the race course (cars race toward the southeast) and time of race (around 11:00 a.m. Eastern Daylight Savings Time in late April) are used to examine the effect of PV panel orientation on solar incidence angle.

The second homework assignment addresses two topics related to modeling the performance of the car: gear ratio and power requirements. Students develop a spreadsheet that determines the effect of gear ratio on car speed relative to motor speed (for a given wheel size), for the various possible combinations of the standard gears that are available. The second part involved using a spreadsheet to calculate and plot the power consumption of a model car for friction, aerodynamic drag, and the sum of the two, as a function of car speed. One lecture prior to this assignment covers the relationship between motor speed and wheel speed, developing the concept of gear ratio and the basic equations that apply. Assuming a simple gear drive, the relationship between motor speed, $\omega_m$, and axle speed, $\omega_a$, is:

$$R_G = \text{gear ratio} = N_a / N_m = \omega_m / \omega_a \tag{1}$$

where:

- $N_a$ = number of teeth on axle gear
- $N_m$ = number of teeth on motor gear

If using a pulley and belt drive system, $N$ can be replaced by the pulley radius.

Further, the car speed, $v$, can be related to axle rotational speed and wheel radius, $r_w$, by:

$$v = r_w \omega_a \tag{2}$$

Plugging in for $\omega_a$ from [1] yields:

$$v = (r_w / R_G) \omega_m \tag{3}$$

One issue that is addressed with this assignment is doing reality checks on calculations. The problem states that the motor speed is 3,000 rpm which is a representative high-end speed for the motor used in the model cars. The wheel size is stated as 1-3/8 inch diameter which is one of the wheels students have available to them. The gears they are asked to try have teeth numbers of 8, 10, 12, 56, and 65, and they are asked to determine the vehicle speed for every possible gear combination. For the large gears on the motor and small gears on the axle, the car speed is in the range 60 to 100 mph, clearly an unlikely scenario. For the more likely combination of the small
An important observation from equation 3 is that the relation between car speed and motor speed is dependent on the ratio of wheel radius to gear ratio. Changing either one of these will change the performance of the car. This knowledge is relevant to optimizing the car’s performance as will be discussed later. Because wheels and gears are only available in certain sizes, the best gear ratio for a certain wheel size may not be obtainable. By using a different wheel size, a gear ratio closer to the optimum may be possible.

Another lecture is used to review the physics that governs the forces acting on the car. The analysis starts with Newton’s First Law:

$$\sum F = m \frac{dv}{dt}$$

where:
- \(F\) = the forces acting on the car
- \(m\) = total mass of the car
- \(a\) = acceleration
- \(t\) = time

The force applied by the wheels is balanced by the forces of friction, aerodynamic drag, gravity, and acceleration. For the PV model cars, we can eliminate gravity as the course is a flat tennis court.

The expanded equations are:

$$F_w - F_f - F_d = m \frac{dv}{dt}$$

$$T_w / r_w - \mu m g - \frac{1}{2} \rho A_f C_d v^2 = m \frac{dv}{dt}$$

where:
- \(F_w\) = force applied by wheel on road
- \(F_f\) = force due to friction
- \(F_d\) = force due to aerodynamic drag
- \(T_w\) = torque applied by the wheel
- \(r_w\) = wheel radius
- \(\mu\) = friction coefficient (lumps all friction together)
- \(g\) = acceleration of gravity
- \(\rho\) = air density
- \(A_f\) = car frontal area
- \(C_d\) = drag coefficient

Equation 5 is a non-linear first-order differential equation with one complication; torque is variable and depends on the PV panel, DC motor, solar intensity, and drive ratio. But we can
determine a model for the drive system that relates torque to motor speed, and ultimately to car speed. Thus we can combine all of these known relationships and solve for velocity and hence displacement – if we have an appropriate equation solving tool.

One more concept is developed in preparation for the homework – power. For this case of forces acting through some distance, x:

\[ P = \frac{W}{t} = \frac{F}{t} x = F v \]

where:
- \( P \) = power
- \( W \) = work

The homework assignment related to car power asks the students to develop a spreadsheet that determines the frictional power, drag power and the sum of the two, and then to plot the power (in Watts) versus car speed (in mph), from 0 to 14 mph. Representative values are given for friction coefficient (0.020), drag coefficient (0.75), and air density (1.2 kg/m\(^3\)). Students are asked to estimate their car mass knowing the PV panel and motor combined mass is 155 g. They are also asked to estimate their own car’s frontal area. To put the results in perspective, the peak motor output of about 0.30 W is given to get a sense for what maximum speed might be obtainable by comparing with the calculated power use. For a mass estimate of 300 g and frontal area of 15 in\(^2\), the resultant plot is shown in Figure 3. The estimated maximum car speed is around 7 mph, which is in the range of experience from previous races. Students also observe how frictional power increases linearly with speed, while drag power is a function of speed cubed. At low speeds, friction power dominates while at higher speeds, drag power dominates and becomes quite large. For the range expected (<7 mph), friction is considerably higher than drag.

![Figure 3 Estimated car power use from homework.](image-url)
The third homework assignment is a vestige of when the course attempted to review solar applications more comprehensively, rather than focusing on solar electricity and solar cars. While nearly all of the remainder of the current course is tied to the solar racers, this assignment is an opportunity for students to learn about some other solar application that interests them. They are required to do an information search in two ways. One is to find at least two commercial products that are available by using typical internet searching tools. Two is to utilize the web-based databases that are available via their student accounts to find at least two articles related to their technology. This latter aspect is significant because many students are not aware of these additional resources or the process for accessing them. They must submit a two-page paper summarizing their findings and documenting their sources.

The last homework assignment requires the students to use Engineering Equation Solver (EES) to find the optimum gear ratio for their design, similar to that described later in this paper. This gets them familiar with using EES and encourages them to use it to develop their design. Extra credit is given for additional parametric studies such as friction coefficient, car mass, drag coefficient, and frontal area.

The next sections describe the experiments used to derive the drive system model and the results for the latest combination of PV panel and DC motor.

**Solar Panel and Motor Testing and Drive System Analysis**

We currently use a completely empirical model of the combined performance of the solar panel-motor system, as opposed to our previous partly-theoretical model. This change was made because the theoretical model of the motor did not accurately predict the motor performance over its range of operation, and because an empirical model is easier for students to understand. The basic process is intended to end up with an equation that determines the motor torque as a function of the motor speed so that it can be used in the EES model to predict performance.

One way to do that would be to connect the PV panel (or the battery) to the motor and test it as a system. This presents some practical challenges, plus testing the individual components demonstrates how to combine their performance characteristics together as a system. The PV panel is tested to determine its I-V characteristic and the DC motor is tested with a DC power supply to determine its output torque and speed versus the I-V inputs. Then these are combined using graphical analysis as described below.

We use the apparatus shown in Figure 4 to measure sufficient data points to describe the I-V characteristic of the solar panels. The preferred test weather is a clear sky and the solar panel is positioned outside the window facing toward the sun. It should be noted that the PV panel performance is highly dependent on the intensity of the solar radiation, so care should be taken to test under clear skies with the panel facing the sun. An alternative to testing is to use the I-V characteristic from the manufacturer if available.

An option to the Decade Box, a device that allows resistances from 1 to 999,999 Ω to be selected, is several 1-watt resistors that are chosen to produce I-V data points ranging from short-circuit (low resistance) to open-circuit (high resistance). Several data points around the “knee”
of the curve are desirable to help illustrate the maximum power point of the panel. Figure 5 shows a plot of some test results produced on a clear day.

Figure 4  Schematic of the solar cell testing apparatus.

Figure 5  Sample test results for photovoltaic panel.
In class, we examine these curves and point out several salient features. Most important is the power curve and its peak that occurs around the “knee” of the I-V curve. Operating near this peak power point is desirable to get the most power, and the fastest race performance. Another important observation is how quickly voltage and power drop as you move to the left of the knee.

Testing small DC motors is challenging due to their low torque and power output. A custom-built dynamometer was developed for this course that performs quite well and can readily be duplicated by others \(^1\); see Figure 6. One limitation of this apparatus is that it must be at an elevation of about 25 feet to allow reasonable timing as the weights are reeled in. Operation is described in a previous paper.\(^1\) The process is to reel in known weights using several representative input voltages, measuring the time to reel in a known length of line and the corresponding input current. This apparatus allows the motor torque and motor speed to be determined for various input voltages and currents.

Knowing the torque/speed output characteristic of the motor as a function of I/V input allows us to combine the motor and solar panel I/V output to get the torque/speed characteristic of the system. The process is as follows:

1. First the I/V motor characteristic curve for each of the tested loads (torque) is plotted along with the solar panel I/V curve, see Figure 7. Note that the motor data in Figure 7 reflects additional data taken to investigate the stalled motor and subsequent start-up as voltage increases from 0.

2. The intersection of each motor characteristic curve and the solar panel curve are the operating conditions of the motor under each load (circled points in Figure 7). These points can be found from the graph directly. Or best-fit curves can be determined from the data and the resulting equations solved for a more exact measurement of the intersections.

3. The voltage from these I/V intersection points are used with a plot of motor speed versus voltage for each torque to find the motor speed at the specified torque. If three weights or torques are tested, this yields three points of torque and speed that defines the combined operation of the solar panel and the motor; see Figure 8. An additional fourth point is obtained from the stall condition.

Note that the operating points tend to center on the knee of the PV curve (where maximum PV power is obtained), indicating that the motor is a reasonably good match to the PV characteristic.
Figure 7  Combined characteristics of motor and solar panel.

Figure 8  Mapping the PV-motor points to determine motor speed.
The three solar panel/motor operating points obtained from Figure 8 are listed in Table 1 and plotted in Figure 9. We add a fourth point which is the torque at which the motor stalls. This is where the steep part of the motor I/V curve (where the motor is not turning, or stalled) crosses the solar I/V curve. From Figure 7 we estimate that stall would occur at a torque of about 0.41 oz-in. A slight upward adjustment was made to the estimated stall torque (from 0.40 to 0.41) so that the best fit third-order polynomial has the stall condition as the maximum torque. Using a curve-fit that has a peak other than the stall point is not realistic and would result in instability in the subsequent equation solver.

Table 1 Combined Solar Panel/Motor Operating Points

<table>
<thead>
<tr>
<th>Torque (oz-in)</th>
<th>Speed (rpm)</th>
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<tbody>
<tr>
<td>0.072</td>
<td>3020</td>
</tr>
<tr>
<td>0.211</td>
<td>2480</td>
</tr>
<tr>
<td>0.348</td>
<td>1600</td>
</tr>
<tr>
<td>0.410</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 9 The combined solar array/motor operating characteristic.

The curve in Figure 9 is typical of a well-matched system. As speed decreases, the torque drops off more rapidly because the solar array is operating well to the left of the knee, and voltage is dropping rapidly. The equation that is input to the equation solver to predict the car performance is obtained from the curve fit in Figure 9, or in the example shown:
\[ T_m = -8.11 \times 10^{-12} \omega_m^3 - 1.41 \times 10^{-8} \omega_m^2 + 4.52 \times 10^{-6} \omega_m + 0.410 \]  

[6]

It is important to recognize that the units are rpm for motor speed and oz-in for torque in this equation.

This process can be applied to other power source I/V characteristics, including a different array wiring, lower sunlight conditions, and battery power instead of solar.

**Performance of the Motor When Powered by Batteries**

We chose nominal 9V batteries because when placed two in series, they match the DC motor characteristic better than other available batteries. When deciding to include batteries as an optional power supply, we considered performance as well as limiting the price and environmental impact. For these reasons, we chose 8.4V, 200 mAh NiMH rechargeable batteries. Each team gets two batteries and a charger to use as they develop their prototype, and on race day, fully-charged batteries are provided.

The I-V data for the batteries was obtained in a similar manner as the solar panel, taking care to minimize the time that the resistive load was connected so as to not discharge the battery. We also tested the longevity of the batteries under load levels close to the requirements of the car. This test yielded a functional operation time estimate of at least 30 minutes, more than adequate for the races.

The battery I/V data is shown in Figure 10 along with the motor data previously graphed. While the two batteries in series cannot provide as high a voltage as the solar panel, they do provide a nearly constant voltage and produce much higher maximum torque. If we continue the analysis to arrive at the torque/speed characteristic of the battery/motor system, we get the result shown in Figure 11. Top motor speed is slightly lower, but the torque at low speed is much higher, reaching 1.0 oz-in at stall. The cars powered by batteries will tend to accelerate much faster but have a similar top speed. Their low-end torque would also allow much steeper hills to be climbed. For this reason, a hill climb contest was added to the local middle school competition.

**Predicting System Performance and Finding Optimum Gear Ratio**

An Engineering Equation Solver, EES\(^4\), is used to solve the complex system of equations that describe the performance of the car. These equations have been presented previously as equations 1, 3, 5, and 6, plus any necessary unit conversions and constant parameters such as friction coefficient, drag coefficient, air density, wheel radius, gear ratio, car mass, and frontal area. A copy of the EES inputs is included in Figure 12. This section demonstrates how the model can be used to guide the selection of gear ratio.
Figure 10  Characteristics of the motor and batteries.

Figure 11  Torque/speed characteristics of the motor/solar system and the motor/battery system.
The EES model predicts the car displacement as a function of time. The time to reach a displacement corresponding to the finish line at 70 ft is determined for each value of gear ratio. For a given set of assumptions and using the torque-speed characteristic described previously, the finish time as affected by gear ratio is illustrated in Figure 13 for various gear ratios near the optimum. This figure also shows the results of a parametric study of the impact of friction coefficient on the performance and the optimum. The best gear ratio ranges from just over 2 to just under 3, indicating that the optimum is not highly sensitive to the friction coefficient. It can
be seen that the curves are reasonably flat near the optimum, indicating that a range of gear ratios would perform well.

Figure 13  Racer performance under full sun as a function of gear ratio and for several coefficients of friction.

Because only certain gear combinations are available, the precise optimum may not be obtainable. Figure 14 shows the gear ratios that are possible with the standard set of gears which have teeth of 8, 10, 12, 56, and 65. The closest to the optima are 1.2 and 4.7 which would result in poor performance relative to the optima. One option is to find other gear sets that are closer to that desired. Another is to recognize that it is ratio of wheel size to gear ratio that governs the speed of the car relative to the motor speed (Equation 3). Using a larger wheel will result in a larger gear ratio being the optimum.

Figure 14  Gear ratios available with standard gears.
Results Using the Batteries for Power

The analytical process can be applied to the battery-driven car as well by substituting the torque-speed characteristic equation into the equation solver. For the same parameters used in the previous analysis and a friction coefficient of 0.02, the resulting optimum graph is shown in Figure 15. In this case, the optimum gear ratio is lower, about 1.8, and one of the standard gear sets with a gear ratio of 1.2 could be used with near optimal performance.

![Figure 18 Racer performance using battery power.](image)

Review of Experiences in the Course

This course has been offered in its current form for six semesters in the spring. Spring semester works best because the weather near the end of the semester is more conducive to outside racing than in a typical fall semester. One significant improvement over this period is a better integration of course lectures and homework assignments with the tasks needed to design a well-performing solar car. While this reduced the coverage of other applications of solar energy, it has resulted in much better cars at the end, and less stress on the students. By focusing the instruction on the design and analysis of the solar cars, more class time is available for the students to work on their designs, construction, and testing. This has allowed the scheduling of a preliminary race followed by a week to modify the cars prior to the final race day. Students learn that even the best analysis does not ensure that their cars will actually perform as modeled.

Some of the more lessons learned during car construction and testing are:

- Steering: Because the cars must complete the 70 foot tennis court course without straying outside the side boundaries, a car that runs straight is critical. This problem is emphasized to students as they begin their designs with the recommendation that they include an ability to make adjustments in the field.
• Gear meshing: The gears are sensitive to alignment, especially proper spacing between the motor and axle. If the gears mesh too tightly, excess friction results and sometimes the wheels will not even turn. If they mesh too loosely, they can slip and even lose contact. Students are advised to design to allow adjustment to be made as needed.

• Gear ratios: Because we do two different races, one with solar power and one with battery power, it may be advantageous to be able to change the gears to achieve a different gear ratio, or alternatively, to change the wheel size appropriately. Being able to change the position of the motor can facilitate this goal.

• Wiring: Students often try to attach wires simply by twisting them together. This frequently results in poor connections and poor race performance. In the last two years, small double-pole switches are provided to allow power to be switched from PV to battery without disconnecting any wires. Terminal blocks are also provided to allow wiring changes in the field. Under overcast sky conditions, it is possible that rewiring the panel for nominal 6V operation will result in better performance.

• Variable gear ratios: Some student teams have attempted to design and build a transmission that allows the gear ratio, or pulley ratio, to change as the car proceeds, with the goal to operate the system near its maximum power point. This has not yet been successful but if it could be accomplished without requiring much power, it should lead to a faster car than a single gear ratio.

Experience on race days has shown that the best cars perform similar to the modeled results. The fastest solar-powered cars cross the finish line in about 10 seconds, while battery-powered ones are closer to 9 seconds. Most of the cars eventually complete the race course, a percentage that has improved as the course has evolved and lessons from previous semesters are shared with new students.

In addition to the fun of racing their cars, the course is successful in introducing students to many aspects of the engineering process. In the area of experimentation, they learn to take data, analyze it with spreadsheets, plot results, and fit curves to obtain equations to predict performance. In the area of modeling, they learn how the performance of two components can be combined to obtain the system performance. They also learn how basic physics can be applied to obtain a relationship that can be solved to predict performance of a reasonably complex system. They also get to use this model to investigate the effect of different parameters on the overall performance, aiding in the design of a successful product. Finally, they get to take all of this theoretical analysis and apply it to a hands-on process of building a functional model solar car.

Conclusions

Designing solar racers and using the testing and analysis described here provides an excellent introduction to engineering for first-year engineering students. Students gain experience in testing, data analysis, system modeling, and equation solving, all in a hands-on environment that allows them to test their design ideas and make refinements. This paper shows that:

• An empirical model of the power supply and motor can be developed using relatively simple apparatus and procedures.

• This modeling can be extended to the entire vehicle and used to find the best gear ratio.
• The modeling can also be used to investigate car performance with a battery power supply.
• Finally, the use of an engineering equation solver allows optimization and parametric studies and demonstrates the value of mathematical analysis in the engineering design process.

This paper has primarily addressed the analysis used with first-year engineering students, but the lessons learned here are useful for guiding middle school students. We have successfully used engineering analyses to better engineer the next generation of solar racers.

Bibliography