Chapter 13
Energy Management

13.1 Introduction

This chapter emphasizes energy management. But this skill is not practiced alone; it is practiced within the context of race management, and it is influenced by the preparations for the race. The fastest racing *system* wins. Therefore, to put energy management in its proper context, these topics will be touched upon as well. For an alternative view of energy management, readers may wish to study the variational calculus-based method reported in MacCready et al. (1990). A complete description of the theory of this method is beyond the mathematical scope of this book. Wright (1997) describes an energy management strategy used by a 1995 Sunrayce™ team. Shimizu et al. (1998) give a description of the energy management strategy and its supporting energy management system used by the winner of the 1993 World Solar Challenge.

13.2 Energy Management

Energy management refers to the way the solar energy available during the race is expended. The goal is to win the race, not necessarily a particular race day. To do this, the car must maintain the highest average speed of any entry over the period of the race. Energy management has two parts: planning period management and micromanagement.

The *planning period* is the longest period for which reliable hourly weather data are available. Probably this will be the next race day plus the day after. However, forecasts of general daily conditions are available for periods as long as a week. These should be used to guide long-term strategy. *Micromanagement* is the moment-by-moment adjustment of the car's energy consumption to keep it within the planning-period strategy. Micromanagement also includes strategies for passing through shadows, climbing and descending hills, regeneration, and city driving.

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We begin with planning period management. Study the following example for the first 2 days of a race.

13.3 Example 13.1

Cornflower University's (C.U.) solar car uses Ni-Cd batteries and has the characteristics in Table 13.1. Also, the motor controller in C.U.'s car will shut down at a battery bus voltage of 47 V.

C.U. measured the rolling resistance coefficients in Table 13.1 on dry asphalt pavement.

Rain or overcast clouds have been predicted for both day 1 and day 2, but day 3 should be mostly sunny. The average air pressure and temperature will be 101.3 kPa and 27 °C, respectively, for both days, and negligible head winds are expected. The travel distance will be 115.5 miles for day 1 and 198 miles for day 2. The net change in elevation for each day will be zero. Is there an average speed for each of the first 2 days that will maximize the average speed over both days, that is, minimize the total travel time?

Solution We construct a simplified model of the situation in order to highlight the important issues. Suppose that:

1. The average acceleration of the car will be small.
2. The drag area and rolling resistance coefficients are constant.
3. The drag area is independent of the relative wind (note that this is conservative if c_D has the falling characteristic with increasing yaw angle shown in Fig. 2.14, but not otherwise).
4. The array efficiency, battery efficiency, and drive efficiency are constant.
5. The average speed may be used to compute the drag.
6. The car is in the cruise condition.
7. Race route information shows that the pavement will be almost exclusively asphalt and that the average grade is about zero.

The foregoing are the major simplifications; other assumptions will be introduced as the need arises.

The total time to travel distances S_1 plus S_2 miles is:

Table 13.1 Data for example car

$c_D A_D$	0.15 m^2
μ_1	0.004
μ_2	0.0002 s/m
M	408 kg, gross
M_e/M	1.01

$$\Delta t = \frac{S_1}{\bar{V}_1} + \frac{S_2}{\bar{V}_2}, \tag{13.1}$$

where the over-bars denote the average speeds for a day.

The average speed over both days is:

$$\bar{V} = \frac{S_1 + S_2}{\Delta t}. \tag{13.2}$$

This is to be maximized (Δt minimized) subject to energy balance equations and the following two constraints:

$$\bar{V}_1 \geq \frac{S_1}{\Delta t_{\mathrm{M}}}, \qquad \bar{V}_2 \geq \frac{S_2}{\Delta t_{\mathrm{M}}}, \tag{13.3}$$

where Δt_{M} is the maximum travel time allowed before C.U. must trailer its car, taken to be 8 h. For this example, the average speeds for days 1 and 2 must be at least 14.44 mph and 24.75 mph, respectively.

Write an energy balance on the power bus between the start and finish times for day 1. The initial and final speeds are zero. The array and battery each feed the power bus. The balance is:

$$(W_{12})_1 = (Q_{12})_1 + (E_{\mathrm{B1}} - E_{\mathrm{B2}})_1. \tag{13.4}$$

The subscript "12" refers to the time between start and finish times, t_1 and t_2. The additional subscript "1" appended to each term denotes the day.

W_{12} is the total work done by the drive (or energy supplied to the drive) to overcome the opposing forces of drag and rolling resistance. Hence, the division by η_{D}, the drive efficiency, in Eq. (13.5):

$$\left(W_{12}\right)_1 = \left[c_{\mathrm{D}} A_D \frac{1}{2} \rho \bar{V}_1^2 + Mg\left(\mu_1 + \mu_2 \bar{V}_1\right)\right] \frac{S_1}{\eta_{\mathrm{D}}}. \tag{13.5}$$

For either day, the solar energy delivered to the drive wheel is:

$$Q_{12} = \eta_{\mathrm{A}} Q_{\mathrm{S12}}, \tag{13.6}$$

where η_{A} is the array efficiency and Q_{S12} is the total solar energy intercepted by the array,

$$Q_{\mathrm{S12}} = (\overline{GR})_{12} A_{\mathrm{A}} (t_2 - t_1). \tag{13.7}$$

G is the irradiance on a horizontal surface, and R is the tilt correction factor. Hence $(\overline{GR})$is the average irradiance on the array surface. A_A is the array area and $t_2 - t_1$ is the time spent racing.

For the battery,

$$\eta_B (F_1 - F_2) E_{B0} = E_{B1} - E_{B2}, \tag{13.8}$$

where η_B denotes the battery transaction efficiency, taken as the same constant for charge and discharge, F represents the fractional state of charge, and E_{B0} is the fully-charged energy of the battery.

Combining the foregoing with the drive work, Eq. (13.5), and the energy supply on the left and right, respectively, gives for day 1

$$(W_{12})_1 = \frac{\eta_A \eta_D (\overline{GR}_{12})_1 A_A}{\overline{V}_1} + \frac{\eta_B \eta_D (F_1 - F_2)_1 E_{B0}}{S_1}. \tag{13.9}$$

The time difference has been replaced by $S_1 / \overline{V}_1$. The energy equation for day 2 is similar.

The state of charge at the starting time, t_1, on day 2, depends on the state of charge at the finishing time, t_2, on day 1. This, in turn, depends on the average day-1 speed, $\overline{V}_1$.

Take the average values of E_{B0}, F_1 (day 1), η_A, $\eta_{B,}$ and η_D to be 5.0 kW·h, 1.0, 0.1, 0.9, and 0.85, respectively. Set the beginning-charge time, t_1, and the impound time to 6 a.m., to 10:15 a.m., and 8:45 p.m., respectively. The latter two times may of course vary, but this variance will not be significant for the purpose of the example. The average irradiance will be taken as 300 W/m^2 for both days as typical of high overcast conditions.

First, examine the solution to Eq. (13.9) as a function of the fractional state of charge at the finish line of day 1. Note that the equation is arranged so that the energy loss per mile must be balanced by the energy available per mile at the average speed. In Fig. 13.1, the energy loss and the energy supply per mile[1] for each of three values of the finishing charge fraction, F_2, are plotted separately as functions of the average speed. The intersections of the three energy supply curves with the energy loss curve give the average speed for each F_2.

The lowest value of F_2, 0.1, corresponds approximately to a bus voltage of 47 V, when C.U.'s motor controller will stop operating. The average speed could be

[1] Because it is presented on an energy per mile basis, the result in Fig. 13.1 is independent of the distance to be traveled.

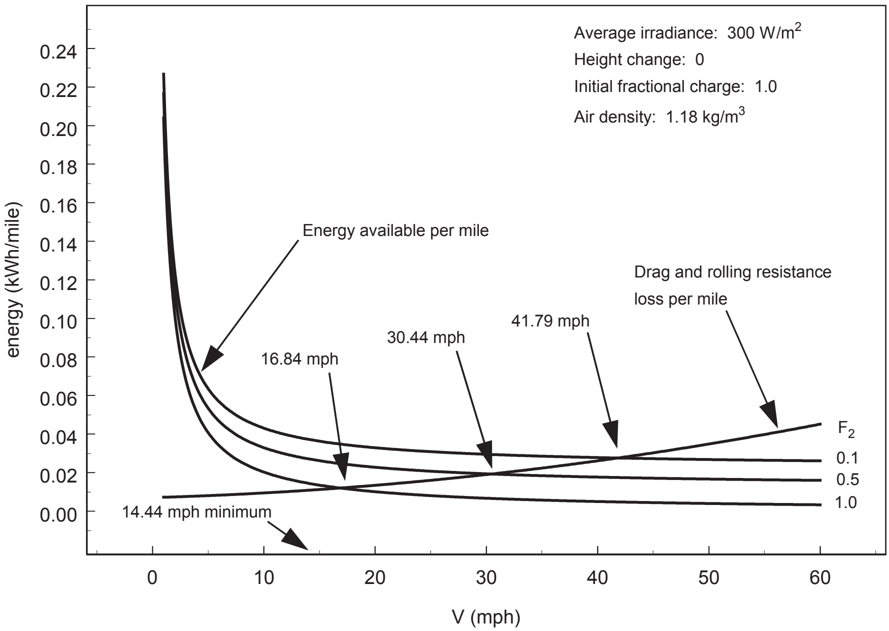

Fig. 13.1 Solution of Eq. (13.9)

nearly 42 mph if C.U. were willing to discharge to this level. This could place the team high in the day's standings and would maximize the time available for battery charging at the day 1 destination. But the next day's operation could be quite slow (recall that the irradiance will remain about 300 W/m^2) and might include trailering. At the other extreme, an F_2 of 1.0 corresponds to a net zero battery discharge. The speed indicated in the figure for this case (16.84 mph) is the speed attainable using direct solar energy alone. Fortunately for C.U., it is greater than the minimum speed (14.44 mph). This means that it would be possible to travel the entire distance of 115.5 miles without a net battery discharge. This would maximize the energy available to run the next day but could reduce the average speed for the 2-day period. Charging in the afternoon of day 1 and the morning of day 2 would not be necessary (or possible).

With other quantities regarded as constant, the optimum speed would be a function of the fractional state of charge at the finish lines of day 1 and day 2. We will search for the optimum speed for each day by a trial-and-error process. Successive values of $(F_2)_1$ between 0.1 and 1.0 will be set and $\overline{V}_1$, $(F_1)_2$, and $\overline{V}_2$ found by trial and error until the 2-day average speed is a maximum. The irradiance for day 2 will be the same as for day 1, and the other quantities used to develop Fig. 13.1 will also be the same. Because day 3 will be sunny, we will set $(F_2)_2$, the fractional state of charge at the finish line of day 2, at 0.1.

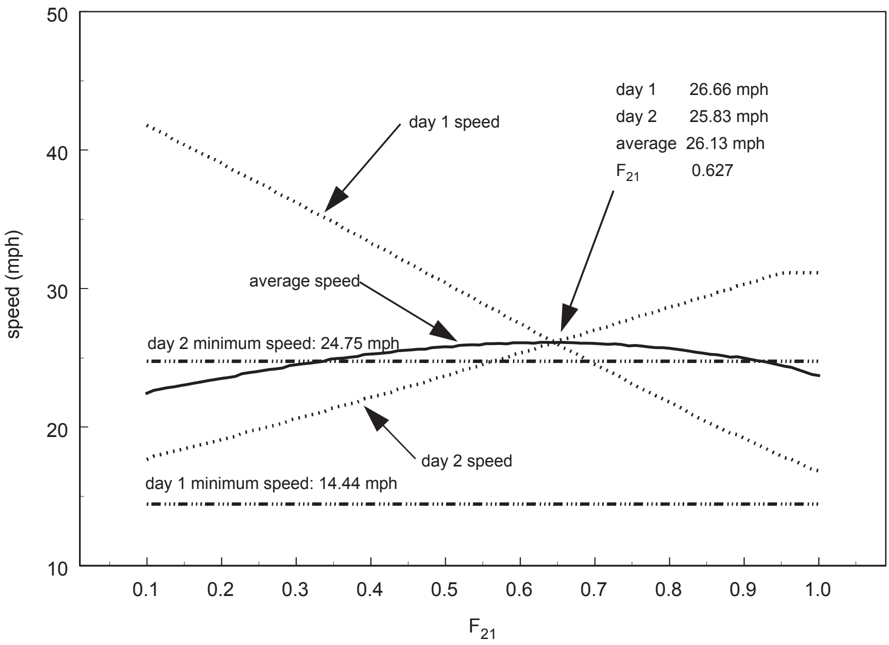

Fig. 13.2 Optimal vehicle speed

The results of the solution process are shown in Fig. 13.2. This figure shows the average speeds for day 1, day 2, and the 2-day average speed as functions of $(F_2)_1$. Also shown are the minimum speeds for each day.

The maximum average speed for the 2-day period was 26.13 mph, giving a total running time of 12 h (4.33 h on day 1 and 7.67 h on day 2). Note that the maximum is broad, and it would seem that C. U. has wide latitude in expending energy on day 1. However, the day-2 minimum speed line intersects the day-2 speed line at an $(F_2)_1$ of about 0.57. Thus, traveling at, or above, about 28 mph (estimated from Fig. 13.1) on day 1 will risk, or cause, trailering on day 2. However, the maximum is broad enough so that the team could hedge its bet a bit (in case the weather prediction for day 3 turns out to be optimistic) by keeping $(F_2)_1$ greater than 0.57 but less than perhaps 0.75. This would mean an average speed of less than about 28 mph and greater than about 22 mph during day 1.

The minimum speed for day 1 is so low that it does not intersect the day-1 speed curve over the range of fractional charge employed. Thus, as mentioned above, the team could run even more conservatively on day 1. However, the reader should keep in mind that the speed of the car is influenced by traffic and road conditions. In order to average about 17 mph (rounded from 16.84 mph), it might be necessary to travel much faster at times to make up for the instances when the car was stopped in traffic or slowly climbing a hill.

The greatest margin between the minimum speed for day 2 and the optimum speed for day 2 is just over 1 mph. In this situation the preparation of the team, especially the drivers, is critical. Energy wasted by poor driving technique or by unfamiliarity with the car could cause trailering on day 2.

The results above were predicated on a target $(F_2)_2$ of 0.1. If this were set at 0.2, to provide additional energy for day 3, what would the results be? The best average speed for the 2 days drops slightly to 25.06 mph. The total travel time consequently increases to 12.51 h, with 4.51 h expended in traveling on day 1 and just under 8 h on day 2.

With a detailed car, route, and weather simulation, the optimum speed could be found using the "little tap" method.

Attaining an average speed high enough to win does not necessarily mean that the team will finish first on any given day. If a given day is overcast and raining, the team must be disciplined and patient and keep its energy expenditure low, as shown in the example. This may mean squelching the desire to speed up if another team is closing; the team must be willing to finish low in the pack to conserve energy so that its average speed can be higher than those of its perhaps more aggressive competitors over the expected period of cloudy days.

The charging and discharging characteristics of the battery bank are vital parts of the energy management data base. The team must be able to estimate well the state of charge of the battery, the battery transaction efficiency, and must know the lower limit of the battery bus voltage. In the example, this limit was not set by the state of charge, as it might be with Pb-acid batteries, but by the motor controller shut-down voltage.

13.4 Micromanagement

Energy Dead Reckoning Ships navigate by "dead reckoning." The navigator predicts the next position by estimating the effects of weather and ocean currents. Micromanagement is energy dead reckoning, predicting the energy state from the current state and the predicted supply and use. Prior to the run, the average speed should be selected to leave the battery at a certain state of charge at the finish line. This speed would be the optimum vehicle speed (OVS), or possibly a more conservative speed. These choices were brought out in Example 13.1. During the day's run, the speed of the car is adjusted so that energy use remains in the proper relation to the energy supply to achieve these ends. Tools to assist in this are discussed in the section on the energy information system (EIS). Strategies for hills, cloud shadows, and the use of regeneration will now be suggested.

Hills Climbing a hill is analogous to acceleration. Each results in higher stored energy state: the higher potential energy at the top of the hill or the higher kinetic energy at the end of acceleration. The energy stored in either case is proportional to the vehicle's mass.

Climbing a hill usually costs additional battery energy depending on the climbing speed. Electrical losses proportional to the square of the current are part of this cost. Thus, climbing at low motor torque keeps the losses in the battery, power wiring, and motor smaller. A transmission, or an axial flux motor with an adjustable air gap, allows the drive to keep the shaft torque higher to lift the car up the hill, but at a lower motor current. This improves the car's efficiency while climbing, but the speed is necessarily less.

A low state of charge will dictate a low-speed climb. The additional current draw caused by higher speed could pull the battery voltage below an operational limit, such as the motor controller shut-down voltage. However, in other situations we may ask: Is there a climbing speed that minimizes the charge removed from the battery? Consider the following example:

13.5 Example 13.2

The car of Table 13.1 climbs a 1-mile-long hill at various steady speeds between 1 and 55 mph in still air under battery power only. Its battery consists of 60, 56-A h, SAFT STX600 Ni-Cd cells in series. The car is driven by an NGM-SC-M100 wheel motor (efficiency curves in Fig. 5.11) with its air gap set to 2.5 mm. The wheel radius is 0.241 m. The air temperature and pressure are as for Example 13.1. The car starts up the hill at the designated speed and fully charged (Fig. 13.3: H = 0), and thus its battery voltage is at a maximum.

Plot the charge removed from the battery and the final, that is, minimum battery bus voltage as functions of the climbing speed for grades of 1, 2, and 3° (1.75, 3.49, and 5.24 %, respectively). For comparison, show the charge removed for a horizontal run of 1 mile under the same conditions.

Solution Figure 13.3 shows the open circuit voltage and the effective internal resistance (mΩ) of the STX600 at 23 °C as a function of its fractional discharge, H (or $1-F$). A curve fit (solid lines) to each data set has also been plotted. The terminal voltage is given by Eq. (4.3), with the current positive for charge and negative for discharge.

Using the data of Table 13.1 and the atmospheric conditions and wheel radius specified above, Eqs. (2.15) and (2.17) were used to find the shaft torque and consequently the shaft power, P_S. The motor characteristics then gave the battery current, I_B, as

$$I_B = \frac{P_S}{V_B \eta_D}. \qquad (13.10)$$

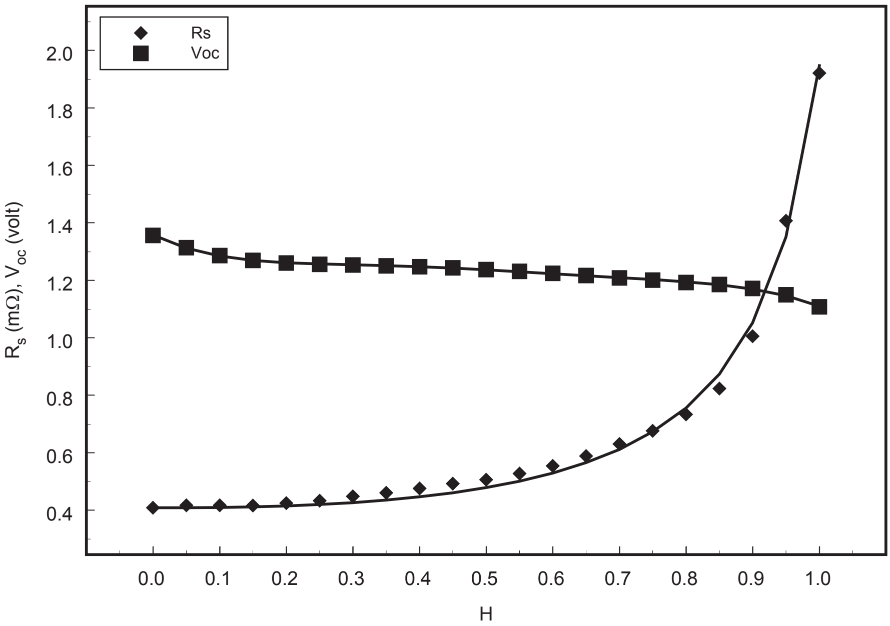

Fig. 13.3 SAFT STX600 characteristics. (Courtesy SAFT engineering)

The battery voltage was found from the curve fits of Fig. 13.3 by calculating the fractional state of discharge as

$$H = 1 - \frac{Q(t)}{Q(0)} = 1 - F(t), \tag{13.11}$$

where $Q(t)$ is the present state of charge and $Q(0)$ the initial charge. The "little tap" method was used: during each small time step Δt, the charge $I_B \Delta t$ was subtracted from the charge at the end of the previous step and the voltage of the battery calculated. The total charge removed and the final battery voltage were then plotted in Fig. 13.4 and 13.5, respectively.

Figure 13.4 shows that at each grade above zero there was a speed at which the charge removed was a minimum. The removed charge at first decreased as the speed increases because the time to reach the top of the hill rapidly decreased; therefore, the time to remove charge was less. However, this was eventually overcome by the increase in the current. The current increased both because the shaft power increased as a cubic function of the speed and because the battery bus voltage decreased as charge was removed from the battery.

Figure 13.5 shows that the minimum bus voltage, which occurred at the top of the hill, passes through a maximum at a particular speed. Following the removed charge, the fractional state of discharge, *H,* passed through a minimum.

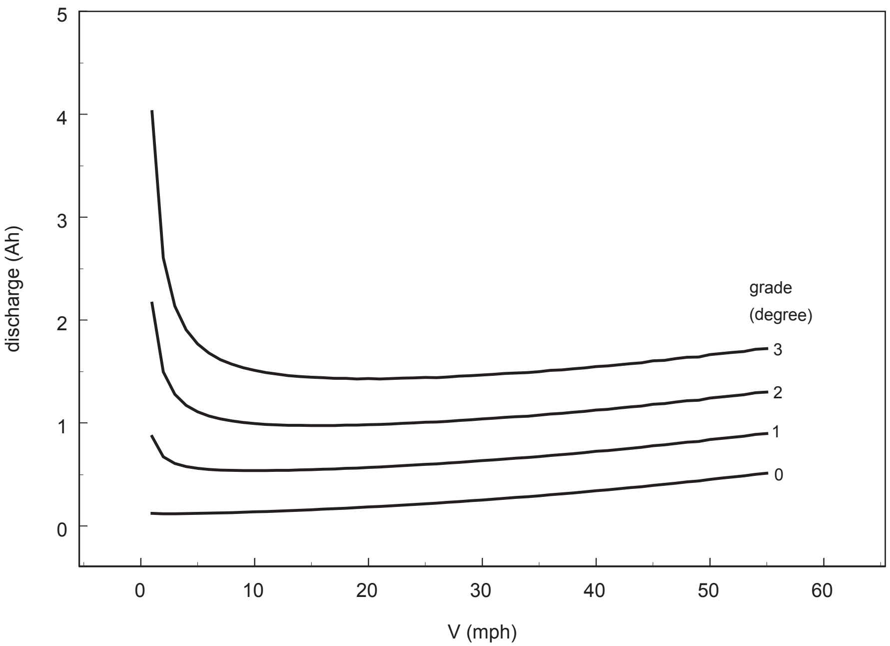

Fig. 13.4 Battery discharge vs. speed on four hills

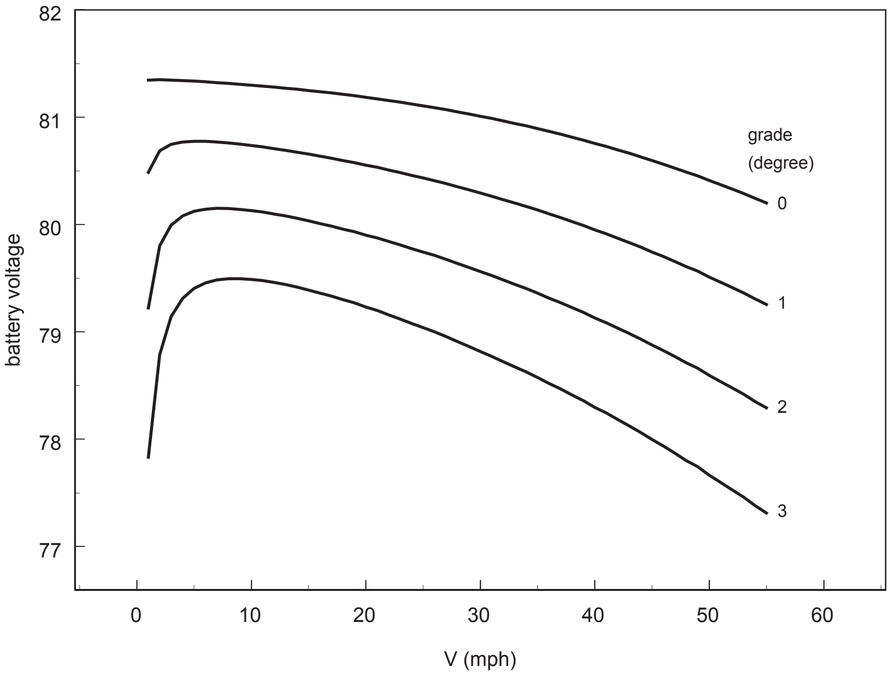

Fig. 13.5 Minimum battery voltage vs. speed on four hills

Consequently, so did the battery equivalent resistance, R_S. This caused the minimum battery voltage to be maximized, but at a lower speed because of the influence of the increasing current.

The climbing speed which minimizes the battery discharge is 10–20 mph, depending on the grade.

Rather than climbing at constant speed, the hill could be climbed at constant motor current. For example, suppose a motor current of 10 A is required when at cruising speed just before the hill. The car will slow to the climbing speed dictated by 10 A. Alternately, the battery current draw could be held constant. The car will then slow to a climbing speed that depends upon the array current available. The advantage of this latter method is that the battery current is directly controlled. This may be quite important when the remaining charge is low.

Regeneration A strategy for descending hills is to use the gravity assist to reach the local speed limit. The conversion of the potential energy to kinetic energy provided by gravity costs the vehicle no battery energy. Then regeneration should be used to maintain the local speed limit while descending. The kinetic energy thus attained is used to coast up the next hill until the car reaches its desired climbing speed; then the motor is used to climb the rest of the way. Regeneration should always be used for braking and for controlling the speed while descending hills in towns, where speed is restricted anyway. Then at least some of the car's precious kinetic energy will be recovered, rather than dissipated in heating the brakes.

Cloud Shadows Intermittent cloud shadows are best handled by keeping up speed and to move out of them as soon as possible.

13.6 Energy Information System

The term energy information system (EIS) refers to the equipment and information sources used to estimate the OVS for each day of the planning period and to select the highest, practical current speed considering the available solar radiation, the state of charge of the battery, and the projected energy requirement for the next hour needed to attain the OVS.

The EIS has six parts:

1. A weather and solar radiation forecasting facility
2. Present-time weather and solar radiation monitoring
3. Race vehicle telemetry
4. Energy management software
5. Road data
6. Global positioning information

13.7 Weather and Solar Radiation Forecasting

Equipment Radio, cellular telephone, and probably Internet communications are required in order to query various weather and solar energy prediction services.

From Weather Forecasts The hourly clearness index may be predicted using weather parameters that are given by readily available hourly forecasts (Accuweather 2013, for example). This avoids the uncertainties arising when attempting to predict hourly global radiation from the daily total. The hourly total extraterrestrial radiation, I_0, can be calculated by Eq. (3.8). Then the hourly total radiation on a horizontal surface may be calculated from Eq. (3.13).

Weather records going back several years for many locations can be obtained from the National Oceanic and Atmospheric Administration (NOAA). Free typical meteorological year (TMY) data (more than 200 locations are available, see Chap. 3) can be obtained from the Solar Energy Laboratory of the University of Wisconsin, Madison, and from the National Renewable Energy Laboratory (NREL). The following outlines the process of developing the clearness-index correlation for Atlanta, GA, for June and July.

13.8 Example 13.3

Outline the process of developing the clearness-index correlation for Atlanta, GA, for June and July.

Solution The set of weather parameters for the correlation will be based on those used by Jensinius (1983),[2] except that day length would have no bearing. And, although TMY files contain a large number of weather variables besides hourly total solar radiation, they do not contain the cloud probabilities used by Jensinius, but simply the total cloudiness in tenths. The work reported by Davies and McKay (1988, 1989) suggests that the clearness index is a nonlinear function of this cloud cover measure. Suppose we assume that the hourly clearness index, k_T, may be given by

$$k_T = f\left(\overline{c}^2, \overline{c}, \overline{T}_{db}, \overline{T}_{dp}, \overline{m}, I_0\right), \tag{13.12}$$

where f denotes an unknown formula using the variables in parentheses, c denotes cloud cover in tenths, T_{db} the dry bulb temperature (°C), T_{dp} the dew point temperature (°C), $$$$ the air mass, and I_0 the total, global, horizontal, extraterrestrial radiation (W h/m^2). The overbar denotes an average for the hour. We obtain the TMY2 data file for Atlanta (13874.tm2, 1,232 KB) and a copy of NREL (1999), a free handbook describing the TMY2 data files. The result, Eq. (13.13), may be

2 See also Jensinius in Hulstrom (1989), Chap. 7.

obtained by a specially written program or by using the built-in correlation facility invariably supplied with spreadsheet programs.

$$k_T = 0.09645 - 0.32143\bar{c}^2 + 0.11614\bar{c} + 0.01514\bar{T}_{\text{db}} - 0.007986\bar{T}_{\text{dp}} - 0.002056\bar{m} + 0.0004356 I_0. \quad (13.13)$$

Figure 13.6 shows the global radiation predicted by this correlation plotted against the corresponding TMY2 global radiation. The average root-mean-squared error was about 21 % with the least error evident at low irradiances.

Weather The energy management software must calculate the drag on the car. For this it requires the dry bulb temperature, the atmospheric pressure, and the wind speed and direction at the ground. These must be known at least hourly at the current location of the car. This information is available from sources such as Accuweather (2013). When it was not feasible to use such sources, teams have done their own forecasting using student meteorologists from their own or another school.

Satellite Images Solar radiation measurements derived from images received from earth-orbiting satellites can be used to predict the solar radiation by predicting the cloud cover motion from the images. Methods of predicting the cloud cover from satellite images were presented by Muench and Hawkins (1979) and Muench (1979). The methods used to measure solar radiation using geostationary satellite images were presented in the same papers. The methods used to measure solar radiation using geostationary satellite images were surveyed in Noia et al. (1993).

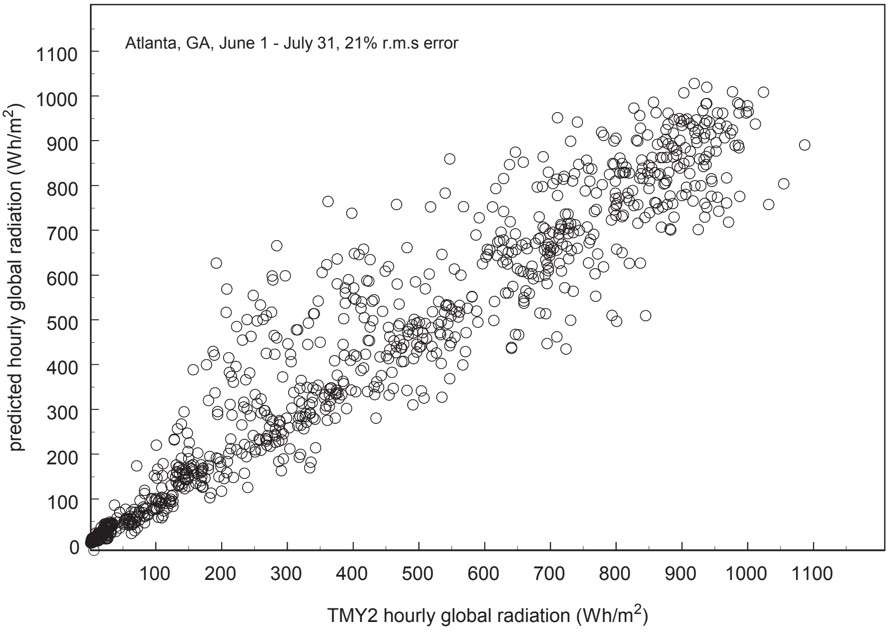

Fig. 13.6 Predicted hourly global irradiance

Justus, et al. (1986) presents results for the USA, Mexico, and South America. The statistical method discussed in Cano et al. (1986), Diabaté et al. (1989), and Perez et al. (1994) has been tested against ground measurements. Zalenka et al. (1992) reported a study of the error in extrapolating daily total radiation from a ground-based measurement compared to using satellite-derived radiation.

Satellite-based forecasting methods are complex and probably impractical for most solar racing teams. However, Kyle et al. (1994) report the superposition of the race route on satellite images, thus clearly showing the relation of the route to clouds and clear air.

13.9 Software

Components The software must accomplish two purposes: assist in estimating the OVS and assist in micromanaging the energy. A simulation code, if it is user-friendly and conveniently integrated into the EIS, could serve the first purpose. A spreadsheet program would probably be more convenient for micromanagement.

Simulation The operation of the simulation code must be convenient. Push button or point-and-click operations should be programmed to calculate a new solution from the current location and time, to edit the road data file (so "what if" can be played) or select a new one, to create or select new weather files, and to change the parameters of the car model.

The code should be configured to interpolate in space and time between the locations for which weather correlations have been prepared in order to estimate the solar and weather parameters at the current location of the simulated car. This was done by Craparo and Thacher (1995), for example.

The route information used by the simulation may be obtained by surveying the route, or it may be constructed by the use of commercial map software. Some commercial map codes can be used to find the grade and direction of segments of the day's race route as functions of the distance traveled. This method is easier and cheaper than traveling the route. But the resolution of the resulting topographical data will probably not be as good as that of a survey. Start several months before the race to allow time to garner the data and set it up to be read by the simulation code.

Surveying the route provides information about traffic conditions, road surfaces, stop lights, etc. This is not provided by the map software. The surveyors also become valuable guides to the team for navigating through unfamiliar cities and in choosing convenient hotels. A surveying trip would be done during the summer before the race or perhaps as late as the spring break before the summer of the race. The final route selected by the race organizers may deviate from that followed by the surveyors, requiring corrections to route data. By the time these are known, the only practical method of making these corrections is by map software.

Day's run	169.42	miles	
Minimum time	8	hours	
Minimum speed	21.178	mph	
Optimum speed	29.2	mph	
Start time	9	h	9 min
Current time	13	h	0 min
Elapsed time	3.85	h	
Odometer	111.86	miles	
Average speed	29.055	mph	
Distance to go	57.559	miles	
Arrival time	14	h	58.86 min
Current F	0.5256		
Predicted F2	0.4109		
Battery energy/mile	0.0204	kWh/mile	
Extrapolated F2	0.2815		

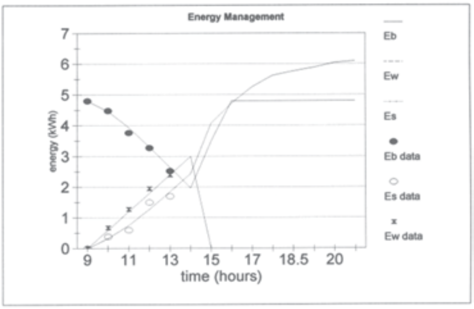

Fig. 13.7 Example of an energy display

Map software that can accept data from a Global Positioning System (GPS) receiver can be used to show the position of the car on the route and relative to upgrades and downgrades. This is valuable information for micromanagement.

Energy Display The spreadsheet program would receive the telemetry from the solar car, current solar irradiance measurements, and the predictions from the simulation. Figure 13.7 shows such a display as it might appear at 1 p.m. (13:00). The total solar energy received since starting the run, $E_S(t)$, the energy in the battery, $E_B(t)$, and the energy that has been expended to move the car, E_W(t), both actual (symbols) and those predicted by the simulation (lines) are shown. These are referenced to the driving wheel. The simulation should be set up to allow the operator can play “what if” by changing the speeds over the remaining course at any time. The actual values for E_S, E_W and E_B would be produced by the spreadsheet using telemetry data.

The energy manager can now estimate the effect of hills and speed changes and also see at a glance how the energy usage and predicted usage compare.

13.10 Preparations

Preparations should be carried out against the background of the realization that, from the racing system viewpoint, racing begins the moment the team decides to enter the race.

Preparations culminate in the testing of the racing system. This has two components: thorough car testing and thorough team training. The car testing, methods for which are discussed in detail in Chap. 12, has two objectives: to measure the drag area and rolling resistance coefficients of the car (on both wet and dry pavement) and to drive the car at least as many miles as the total length of the race and under various conditions—particularly over hilly terrain and in inclement weather. This driving tests the durability of the racing system and provides opportunities to train

Fig. 13.8 Racing in the rain

the team. The team must learn how to race the car when it is overcast and raining, as in Fig. 13.8, and in heavy traffic, as in Fig. 13.9. There must be strategies for every eventuality. There should be a mix of training and testing trips, some short and some long. Short trips focused on testing should be made over the same route

Fig. 13.9 Racing in heavy traffic

so that the route itself will be removed as a variable affecting the energy consumption of the car.

If the car has accumulated many hundreds of miles before the race, probably all the wheel bearings should be replaced. Leave enough time so that you can run 50–100 miles with the new bearings, then remeasure the rolling resistance coefficients. When racing, carefully inspect the car after each day's run, and especially during and after trailering, including all welds and suspension elements. Do not assume that such vital parts cannot fail, even if they have shown no wear during the training period. Come to the race with spare parts, such as shock absorbers. Bring welding equipment. *Take nothing for granted*.

13.11 Race Management

The average speed is influenced by the performance of the race team as race managers. Race management comprises solar car energy management and management of ancillary race activities. There are a multitude of these.

Flats Flat tires will result from improperly adjusted wheel spokes or poor matching of tires to rims as well as running over broken glass. Flats cause lost time. Rapid tire changes are a function of good wheel design, but they are also the result of having replacement wheels on hand, balanced and pressurized. This means that the wheels and tools must always be in a designated place in the chase or lead vehicle. Members of the team must be preassigned to do the change and should know exactly what to do so that no extra time is lost milling around. This means tire-change training must be accomplished during the prerace period.

Organizational Scope As the tire-changing example above shows, a racing team must be efficient. That is, every activity must be carried out in the smallest possible time. This implies rapid action but also minimum error; error requires repeated action. Rapid and error-free action requires organization, training, and reliable communications.

The race organization must account for both large and seemingly small activities. The large activities include feeding the team, sleeping accommodations, and fuel for the support vehicles. The seemingly small activities include awakening the team in sufficient time each morning so that all may be fed, the car removed from impound and put on charge, etc. This activity seems small, but it can loom large if time elapses and the team is not ready to start at its appointed time.

Communications Radio communications between the driver and the lead and chase vehicles must be available at all times when racing. Reliable communication is a function of proper equipment and propagation conditions, but also of making sure the batteries in the radio handsets are charged. Radio procedure must be disciplined. There must be no unnecessary chatter and only those designated to give information to the solar car driver should speak. This prevents confusion, which is unsafe.

Under the rules in Chap. 16, support vehicles must not travel on the race route. Therefore, at times during a race day, the suggested route for the off-route crew operating the vehicle towing the trailer may be separated by many miles from the race route. Therefore, communication with the off-route crew must be reliable over these distances. The personnel operating the towing vehicle must try to remain within the radio communication range, in case its services are needed.[3] This procedure is best worked out during the prerace period. However, remaining within the radio communication range is not always possible. Cell telephone communication is usually more reliable than radio communication over longer distances. Cell coverage during the 1999 race was excellent, but during earlier races there were regions with no cell coverage. Another drawback of this method of communications is that it is expensive.

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[3] The off-route team cannot delay because they leave later than the race car (because of packing up the trailer) and they may have to drive twice as far as the race team. And, if the day is sunny, they will be hard pressed to keep up.

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