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Broader Perspectives

EVENT REPORT

Sunrayce 97

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Thirty-five university teams from Canada and the USA raced their solar-powered cars 2000 km from Indiana to Colorado over a 10-day period during June 1997. The event, called Sunrayce 97, was designed to provide a stimulating educational opportunity for students of science and engineering, while educating the public about the exciting prospect of environmentally clean photovoltaic energy. Favourable weather produced a very fast race, with the winner, Cal State LA, averaging 70 km h^{-1} and with the top four teams separated by only 66 min. © 1998 John Wiley & Sons, Ltd.

THE EVENT

In the biennial Sunrayce programme, sponsored primarily by General Motors Corporation, the US Department of Energy and Electronic Data Systems (EDS), university teams from throughout North America design and build solar-powered single-passenger cars and compete against each other in a cross-country race through the USA. While the regulations governing Sunrayce include extensive provisions to ensure the safety of the participants, the spirit of the race is defined by just a few simple rules. The cars must be powered solely by solar energy. The solar array is limited in size to a projected area of 8 m^2 and a height of 1·6 m. The solar cars may run directly from the power supplied by their solar array or from solar energy previously stored in an on-board battery, which may not weigh more than 140 kg. Each car must carry a single driver ballasted to weigh 80 kg. Teams must not exceed the posted speed limit and must obey traffic signals. If photovoltaic cells are used, as they were for every entry in this year's event, they must be commercially available terrestrial-grade cells manufactured in North America. The storage battery must be commercially available lead–acid technology. These technology restrictions are intended to limit the cost of entering a competitive solar car. Despite these limitations, a dozen of the cars in Sunrayce 97 were capable of running at the posted speed limit throughout the race. The winning cars among these were the ones that were the most reliable.

Sixty post-secondary educational institutions from the USA and Canada registered for Sunrayce 97. Fifty-five of these teams built cars for the race, hoping to qualify for one of 40 available positions. Thirty-six of these solar cars qualified for the race by demonstrating their ability to run at least 160 km on a closed-loop course in less than 4 h. Had more than 40 cars met this minimum requirement, the field would have been filled with the 40 cars that travelled the furthest during their time on the qualifying track. One team subsequently withdrew during the race, leaving 35 teams who successfully completed the cross-country event.

THE RACE

This year's race spanned 2000 km from Indianapolis in Indiana to Colorado Springs in Colorado.

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The 10-day race was divided into nine race segments plus a rest day after the fourth day. The winner was defined as the team with the lowest total cumulative time for the nine segments combined. Because most teams finished each segment in much less than the 8 h allowed, there was ample time after crossing the finish line each day to point the solar array at the sun and charge the car's battery for the next day's journey.

Photographs of the two winning cars with the lowest cumulative time are shown in Figure 1. Table I lists the statistics for the top ten teams. The remaining teams completing the race are, in order: University of Minnesota, Messiah College, University of Western Ontario, University of Illinois, University of Pennsylvania, Western Michigan University, University of Missouri — Rolla, Ohio State University, University of North Dakota,

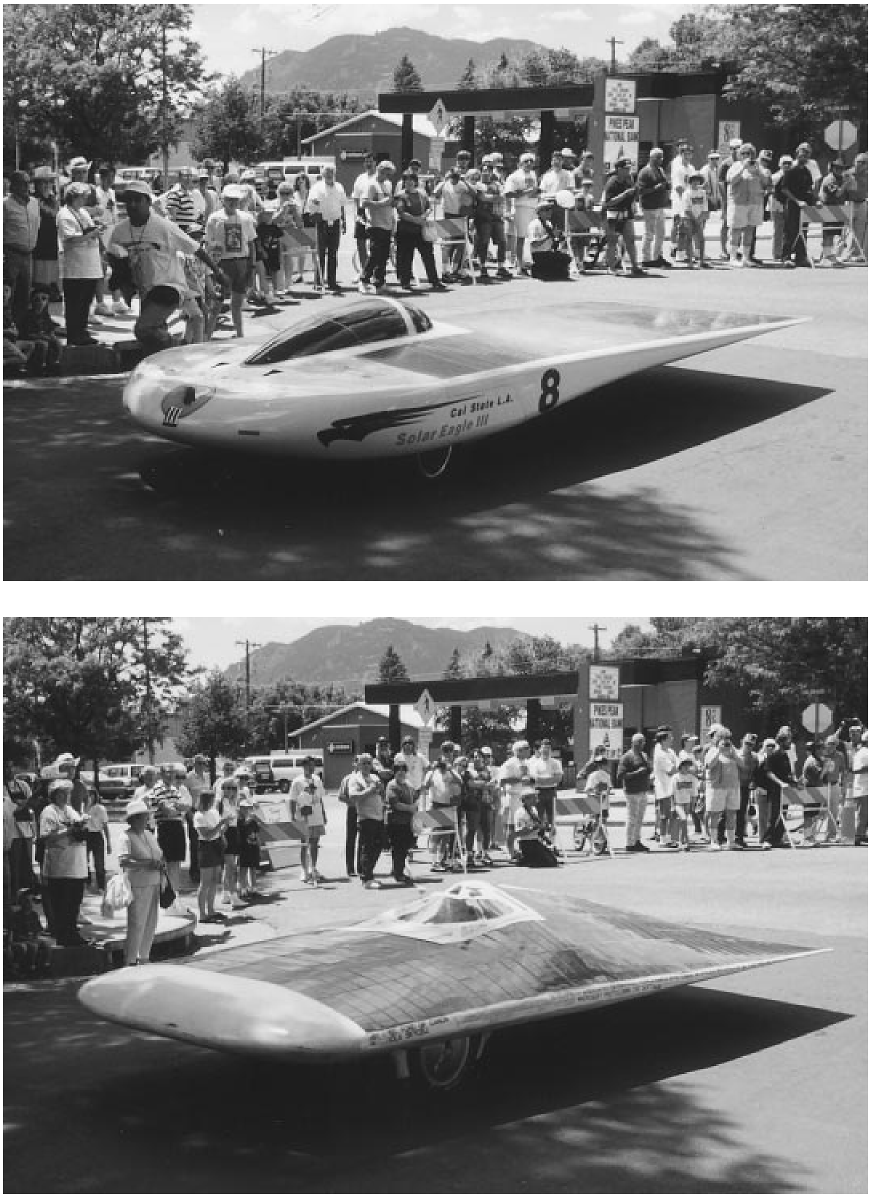

Figure 1. Top two finishers in Sunrayce 97 in Colorado Springs, Colorado. First place: California State University — Los Angeles. Second place: Massachusetts Institute of Technology

Table I. Top teams for Sunrayce 97

Place	Car no.	Team	Time (h: min: s)	Average speed (km h^{-1})
1	8	California State University — Los Angles	28:41:34	69·7
2	1	Massachusetts Institute of Technology	29:00:20	68·9
3	16	Stanford University/UC-Berkeley	29:33:15	67·6
4	12	Texas A & M University	29:47:21	67·1
5	74	Rose-Hulman Institute of Technology	31:37:54	63·2
6	111	University of Michigan	32:14:01	62·0
7	24	University of Waterloo	32:22:04	61·8
8	43	University of Missouri — Columbia	32:25:38	61·7
9	480	Yale University	35:09:59	56·8
10	100	Queen's University	35:11:14	56·8

Mankato & Winona State Universities, New Mexico Institute of Mining and Technology, United States Military Academy, McGill University, Kansas State University, Columbus State Community College, Iowa State University, California State University — Long Beach, Drexel University, École de Technologie Supérieure, Virginia Polytechnic Institute and State University, Principia College, South Dakota School of Mines and Technology, Auburn University, Purdue University and University of New Orleans. George Washington University started the race and was a top contender until a suspension failure on day 5 caused structural damage, forcing them to withdraw from the race in the interest of safety.

This year's race was 150 km longer than Sunrayce 95, which followed a similar route.[1] But sunny weather and more efficient designs allowed the top teams to finish the race in 5 h less! The average speed for the winner increased from 60 to 70 km h^{-1}. Eight teams had a faster average speed in Sunrayce 97 than the previous Sunrayce record established in 1995.

The top dozen cars in Sunrayce 97 were able to run the race without regard to the amount of energy used. Traditionally, solar cars operate at a speed selected to make the most of their limited energy supply, but in this race teams found that they could run their cars as fast as traffic and the speed limit would permit and still finish the day with energy to spare. This mode of operation became known as 'no-budget racing'. The spread of many hours in cumulative elapsed time among these top cars was due entirely to a wide variation in reliability and not to major differences in energy efficiency. For example, University of Minnesota finished just a few minutes behind the fastest car for seven of the nine race days, running at the speed limit whenever traffic would permit. But they finished only in 11th place overall because on the other 2 days breakdowns kept them off the road for a total of 7 h.

With so many cars pushing the speed limit, enforcement of this limit became an important and determining factor in the outcome of the race. Experience in previous Sunrayce events showed that the speedometers in the support vehicles were only accurate to within 5%. Furthermore, teams could cause their speedometer to show a lower speed by overinflating their tyres. To overcome this problem, the official observer assigned to ride in the chase vehicle with each team in Sunrayce 97 was equipped with a Global Positioning System (GPS) receiver. When properly used and interpreted, these hand-held receivers provided an improved measurement of velocity. When travelling at steady highway speed, the GPS velocity readings at 1-s intervals would fluctuate randomly by up to 4%, but by mentally averaging these readings over a period of 30 s the speed could be determined to 1% accuracy. Note that a 1% difference in speed was all that separated the top two teams, so this technique was only barely adequate for this application.

The GPS system worked well for ensuring consistent speed determination for the chase vehicles, but what about the speed of the solar cars? Because each solar car stays a few seconds in front of its official chase vehicle at all times, the two vehicles must have nearly identical average speeds for the day. Discrepancies in instantaneous speed between the two vehicles were thus thought to be inconsequential. But several teams found that by allowing the separation between their solar car and their chase vehicle to expand and contract by a few seconds as they travelled up and down hills they could increase their average speed by up to 5%! This practice, dubbed the 'yo-yo' effect, was eventually determined to be a violation of the race rules and two teams, MIT and Minnesota, received significant penalties. Were it not for these penalties, both teams would have beaten the previous 1-day speed record of 80 km h^{-1} set by Minnesota in 1995.

To understand the yo-yo effect and its significance for the race requires an example. Consider a typical hilly terrain composed of a 1-km downhill stretch followed by a 1-km uphill stretch. Teams A and B both begin the descent running at the speed limit of 90 km h^{-1} with their solar cars 2 s in front of their chase vehicles. Team A allows their solar car to exceed the speed limit on the downhill stretch by 10 km h^{-1}, while Team B does not. At the bottom of the hill, the solar car for Team A would be leading its chase vehicle by 6 s compared to 2 s for Team B. Such a gradual change in separation would not normally be noticed by the official observer. On the uphill slope both solar cars can go no faster than 80 km h^{-1} because that is as much climbing power as their propulsion systems can provide. The chase vehicle for Team A continues at the speed limit and slowly narrows the gap with their solar car, closing back to within 2 s at the top of the hill. The chase vehicle for Team B has to slow down to 80 km h^{-1} to keep from hitting their solar car. Team A completes the 2-km stretch in 6% less time than Team B. A significant fraction of the race route in Kansas was composed of a seemingly endless procession of hills just like this. The teams that allowed their solar cars to yo-yo beyond the speed limit gained a significant advantage, but were penalized when caught.

In contrast to the previous Sunrayce event where tyre blowouts and mechanical failures led to many loss-of-control accidents,[2] the solar cars in Sunrayce 97 proved to be quite safe on the road. This can be largely attributed to new rules preventing overloading or overpressuring of tyres, and to the widespread availability of tyres premounted to rims designed specifically for solar racecars. The most serious accidents related to Sunrayce 97 occurred when solar cars were being trailered. Two solar cars were severely damaged, and several students sent to hospital, as the result of the drivers losing control of their passenger vehicle while towing their solar car in a trailer.

THE SOLAR ARRAYS

A rule for this year's Sunrayce was the requirement that the photovoltaic cells used be manufactured in North America. Only commercial technology widely available at less than US\$10 W^{-1} was permitted. With just a few exceptions, all of the teams used either single-crystal Czochralski-grown silicon cells from Siemens Solar Industries or multicrystalline silicon cells formed using edge-defined film-fed growth from ASE Americas. Both types have an efficiency at standard test conditions close to 14%. Although many of the better teams used ASE cells, the top two teams used cells manufactured by Siemens Solar.

Several teams, including race runner-up MIT, increased the output of their solar array by shingling their cells.[3] Full-size cells are cut so that one of the two busbars lies along one edge, and the other busbar is removed. This cutting is normally done by laser from the rear side of the cells. The edge busbar is then tucked under the next cell in the series string. This reduces metal obscuration by as much as 5% compared to conventional tabbing. It is important to put a stress-relief copper interconnect between the cells. Simply soldering each busbar to the back of the adjacent cell produces an overly rigid structure that is susceptible to thermal-expansion problems.

While racing, the car's solar array must remain in a fixed orientation relative to the vehicle chassis. However, when the solar car is stopped for battery charging, the array may be detached from the car and tilted to face the sun. Reconfiguration of the shape of the solar array during charging, which was permitted in previous Sunrayce[2,4,5] and World Solar Challenge[6,7] events, was not permitted in Sunrayce 97. Figure 2 shows cars with their arrays tilted for charging, both in the designated charging area at the end of the first day of racing on the campus of Rose-Hulman Institute of Technology and at a mandatory midday stop in a remote area of Kansas. Because significantly more energy can be collected when the array is tilted toward the sun, teams that finish a day's leg early gain the additional advantage of being able to capture more

Figure 2. Solar arrays tilted for charging at the end of a race day and at a midday stop. In the top photo, the car in the foreground is the third-place finisher, from Stanford University. In the bottom photo, the car in the foreground is the fourth-place finisher, from Texas A&M University

solar energy for the next day's race. Teams that are slow to finish one day thus enter a downward spiral and quickly drop out of contention.

THE MOTORS

Most teams used either a 6-kW brushless DC motor from Solectria or a 3-kW brushless DC motor from Unique Mobility. Brushless DC motors are really variable-frequency three-phase AC motors with permanent magnets on the rotor. They get their name from the fact that DC voltage is supplied to the motor controller, which inverts this DC to the necessary AC waveform. They are highly efficient because the permanent magnets eliminate losses on the rotor and no brushes are needed that introduce friction. Typically, these motors run at high rotational speed and require substantial gear-drive reduction when used to power a solar car. They are capable of regenerative braking, which permits about half of the car's kinetic energy to be returned to the battery when stopping.

Sixteen teams used 10-kW axial-flux hub motors from New Generation Motors. These 16-kg motors are mounted directly at the wheel and operate at the wheel rotation speed, and thus require no gears, belts or chains. A disadvantage of these motors is that they have low starting torque when adjusted for a maximum speed near the speed limit (90 km h^{-1}). The teams with these motors were unable to start under their own power from a full stop on steep hills and several were penalized for pushing their cars. The superior efficiency of these motors when running apparently made up for the limitations. The top teams used these motors for at least a portion of the race. Race winners Cal State LA switched between their hub motor and their conventional brushless DC motor from day to day, depending on expected road conditions. Hub motors are also capable of regenerative braking.

The technical innovation award for propulsion design went to Messiah College of Grantham, Pennsylvania. This team modified their hub motor so that they could adjust the air-gap spacing while they were running. A spline gear kept the rotor axially aligned with the stator while a servomotor connected to a worm screw provided continuous adjustment of the air gap between the rotor and stator. This has the same effect as a mechanical transmission in that it allows the driver to adjust the torque-speed characteristic of the motor to match the load. A small air gap is used at low speeds to provide high torque consistent with the current-carrying capacity of the windings. At higher speeds a wider air gap is used to keep the induced internal voltage of the motor below the voltage available from the motor controller. While other teams using hub motors adjusted their air gap on a daily basis to match the expected road conditions, Messiah College was able to optimize on the fly for every hill and stoplight.

FUTURE DIRECTIONS

Sunrayce must identify new sponsors for each race, and therefore re-invent itself for each event. The success of Sunrayce 97 virtually ensures that there will be a Sunrayce in 1999, but the specific rules and the route chosen may be quite different. Specifically, potential sponsors for Sunrayce 99 have indicated a preference for a race route through a more densely populated region, most likely either the east or west coast of the USA. As solar cars have become much safer on the road, the need to run the race far from major cities is less pronounced.

It is also very likely that rule changes will be introduced to restore the importance of energy budget to the outcome of the race. This may be accomplished in one of several ways. One of the simplest is to increase the daily route distance; another is to reduce the allowed battery weight. Both of these solutions make the race more susceptible to cloudy weather. Nobody wants a race where few of the teams make it to the finish line on cloudy days.[4] A different approach would be to arrange for teams to run laps in the vicinity of the finish line each day so that the race becomes a maximum-distance race instead of a minimum-time race. Most teams would make it to the finish line even on cloudy days, with only the lap-running susceptible to poor weather. Finally, there could be a return to a rule used in GM Sunrayce 1990, where teams were required to disconnect their solar arrays upon crossing the finish line and could only commence battery charging after 5 p.m.[5,8] The main advantage of this rule is that it levels the playing field by making less energy available to the faster cars. The disadvantages are that it reduces public visibility of the solar arrays and it increases the race's susceptibility to cloudy weather.

SUMMARY

Sunrayce 97 provided over a thousand university students with an exciting forum for developing real-world engineering skills while becoming familiar with photovoltaic energy technology. Thanks to sunny weather, the cross-country race was run at or near the posted speed limit, making it significantly faster than previous Sunrayce events.[9] Sunrayce 97 succeeded in educating the public as well, providing a vivid display of modern electric transportation and energy technologies, and of the enthusiasm of today's students to apply this technology in beneficial ways.

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