Technical Report

Sunrayce 95

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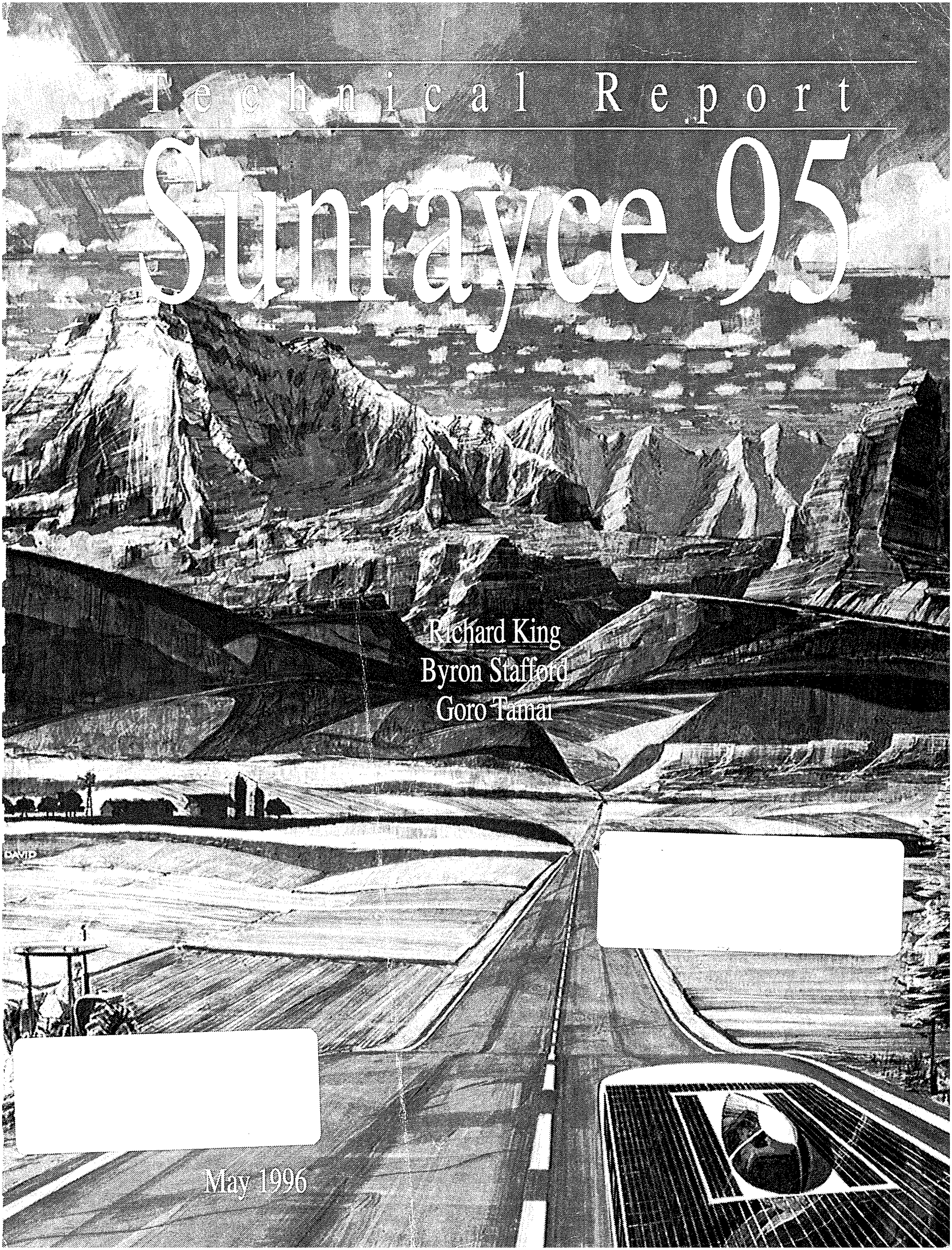
May 1996



Acknowledgements

Sunrayce 95

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Sunrayce
Introduction

From June 20-29, 1995, more than a thousand college and university students from across North America tested their solar cars and strategies against the environment in Sunrayce 95. The 1,250-mile race, from Indiana to Colorado, is the third in a series of collegiate solar-car races across the United States. The tradition began in 1990 with the GM Sunrayce USA from Florida to Michigan. In 1993, the tradition continued as 34 solar cars raced more than 1,100 miles from Texas to Minnesota in Sunrayce 93.

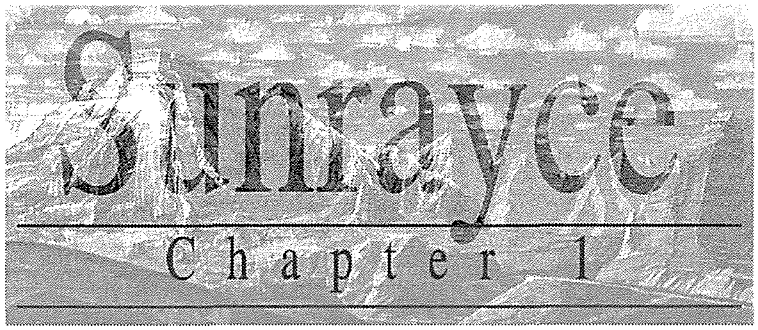
The U.S. Department of Energy, General Motors Corporation, and other organizations teamed together in a unique partnership between government and industry to sponsor Sunrayce 95. Their goal was to make learning exciting and relevant to today's concerns and to demonstrate that brain power is more important than horsepower.

This report details the excitement and enthusiasm—as well as the setbacks—of the students involved in Sunrayce 95. We have attempted to make this report as complete as possible. However, each person who participated has his or her own memories and experiences. The authors and event sponsors hope that this report will be used as both a documentary and a useful guide for teams involved in future races.

Sunrayce 95 is more than the race—it's an engineering and business challenge that starts almost 2 years before the race. Colleges, universities, community colleges, trade schools, and other post-secondary schools were invited to design, build, and race a solar-powered car. Designing and building a car requires applying classroom knowledge to real-world applications. Racing a solar car requires a strategy for energy management. Although the sun's energy is plentiful, it is often dispersed and may also be unpredictable, thus requiring cars to have a means of storing energy. Because only solar power is allowed, the cars must be energy efficient. And to finish the race, the cars must also be reliable.

The most powerful car did not win Sunrayce 95, nor did the lightest, nor did the car with the most battery energy, nor did the car with the greatest number of test miles. And for the first time in Sunrayce history, the winning team had far from the largest project budget. The top-2 finishers did not modify their solar cells, and the chassis construction techniques were vastly different among the top teams. However, there is one feature that four of the top-5 cars had in common—body style. MIT, Minnesota, Cal Poly Pomona, and Stanford all had central-canopy, "short-car" designs that evolved from the 1990 MIT and Waterloo concepts. Similar to the weight conclusion, the main reason for the short-car teams placing higher is probably because those teams did a better overall job of engineering and coordinating their entire solar-car project, including the choice of body shape.

The fact that no single vehicle or team statistic can overcome other deficiencies is a good sign that the Sunrayce title is truly up for grabs to any team that takes the time to think and create a well-balanced solar car and team.



Sunrayce 95—A Two-Year Endeavor

1.1 The First Year: Team- and Car-Building Begins

As soon as one race ends, planning for the next one begins. Barely 2 months after 34 solar-car teams crossed the Sunrayce 93 finish line, another group of solar-car teams were preparing to enter Sunrayce 95. On September 19, 1993, registration for Sunrayce 95 began. A request for proposals (RFP) was sent to every college and university in North America, with registration for Sunrayce requiring a written proposal describing a team's project. The school's proposal not only satisfies an important administrative function; it also asks students to conceptualize their whole project before beginning to build a vehicle.

Sixty-five schools submitted proposals on February 8, 1994, for registration. All teams that submitted proposals were officially registered. These 65 teams were later invited to attend the Sunrayce qualifier to secure starting positions in the race.

Any large project, such as building a solar car for Sunrayce, requires proper planning from start to finish. A schedule with milestones must be developed early and adhered to. The sooner teams begin their projects, the more successful they are likely to be. Figure 1.1.1 contains an example schedule for a Sunrayce project.

Many teams started working on their projects early. For example, Mankato State University, which had participated in the 1990 and 1993 Sunrayces and finished 16th in both, began work on their 1995 car in August 1993—before they even received the RFP. Faculty advisor Bruce Jones said they conceived the design on the flight home from the World Solar Car Rally in Ogata, Japan, where they received top honors for their class of vehicles and sixth place overall. Jones claims the students were inspired by some of the car designs they saw in Japan. Those ideas helped them conceptualize their next solar car.

For the 1995 race, Mankato decided to team up with Winona State University to double their efforts in building "Northern Light III." They

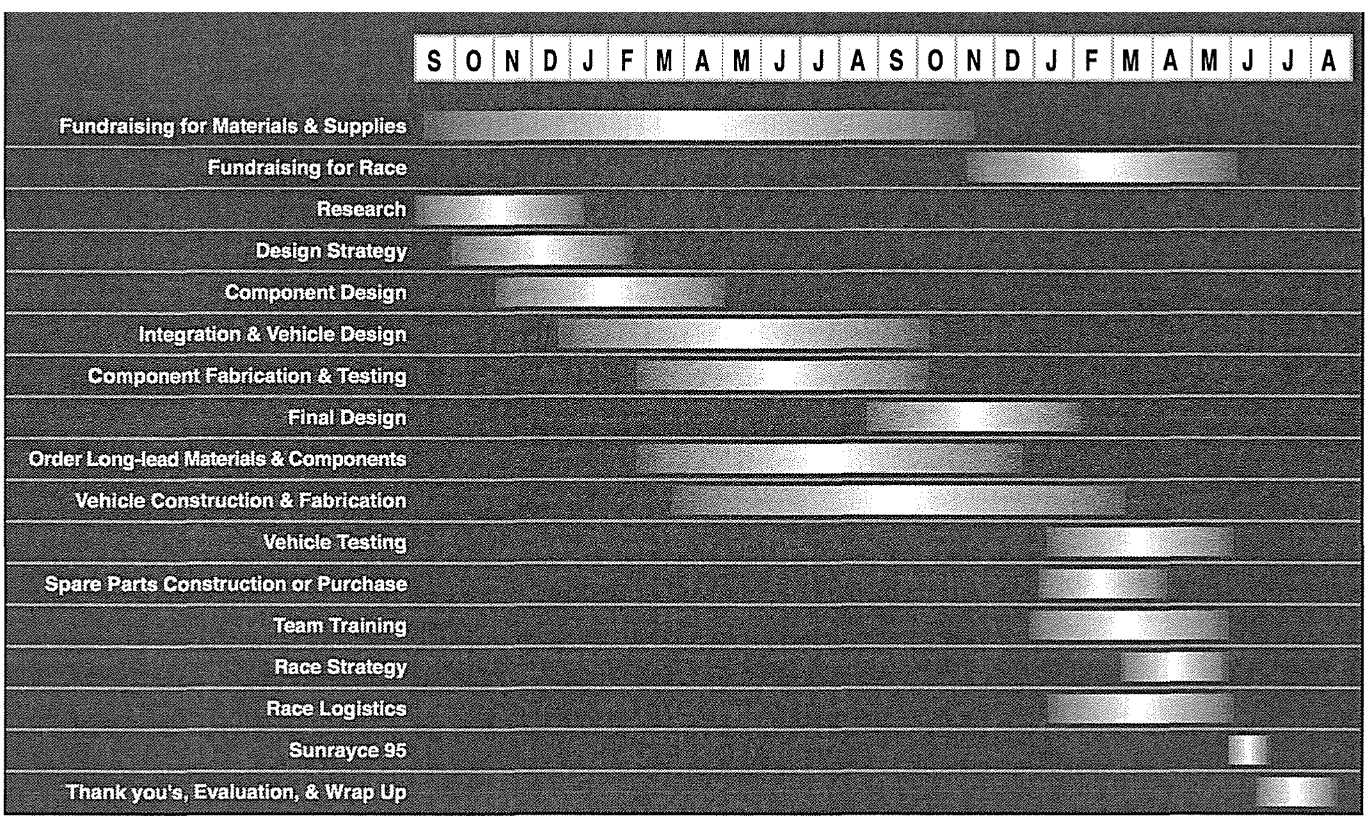


Figure 1.1.1: Sample milestone schedule.

divided tasks between the schools and used interactive television for group meetings. The Winona team took the lead on the car's frame, while Mankato focused on the composite shell. What they couldn't buy, extract from previous solar cars, or dredge up from dumpsters at high-tech companies, they built themselves. Team members remember salvaging scraps of expensive lightweight material being discarded by Northwest Airlines. "It's all part of being resourceful," they claim.

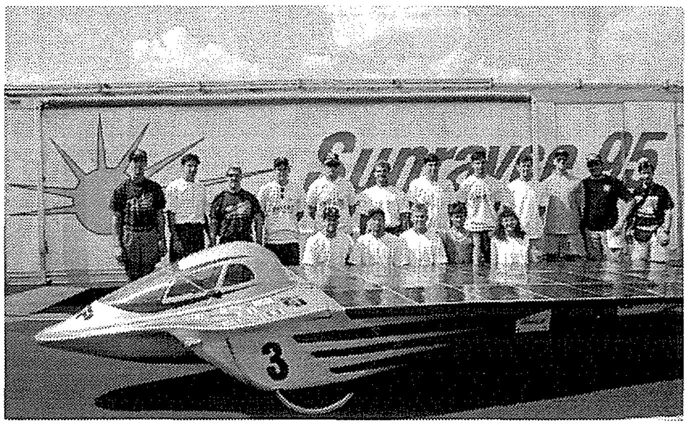


Figure 1.1.2: The Mankato and Winona State Universities team with their solar car "Northern Light III."

Throughout the first year, the Mankato and Winona team worked diligently on their car. There were constant revisions to the design. "We tried four or five different types of steering." said team member Angela Robin. "We had to scrap various versions because they were either too sloppy or too heavy. The chassis also went through various stages of assembly and disassembly. One day it's intact and the next day it's taken apart. Sometimes it was hard to gauge if we were on schedule."

Once all the bugs were worked out, students began making duplicate parts for back-ups during the race. All too often teams neglect this important step, and they are caught off guard when they have a breakdown during the race.

Hoping for a "three-peat"—having won both the 1990 and 1993 Sunrayces—the University of Michigan team began working on their Solar Vision in September 1993. The team spent months researching possible improvements over their last two cars and focused their efforts on building something better. As defending champions, they knew they were the team to beat.

The South Dakota School of Mines & Technology was another team that got off to an early start. Faculty advisor Dan Gerbec heard about Sunrayce in 1993 and wanted his school to participate in 1995. He started recruiting students and making plans before receiving the RFP, because he knew his rookie team would have a lot of catching up to do.

A key to South Dakota's fundraising effort was recruiting the local newspaper, The Rapid City Journal, as a sponsor. Besides contributing cash, the newspaper ran articles about the team's project, encouraging

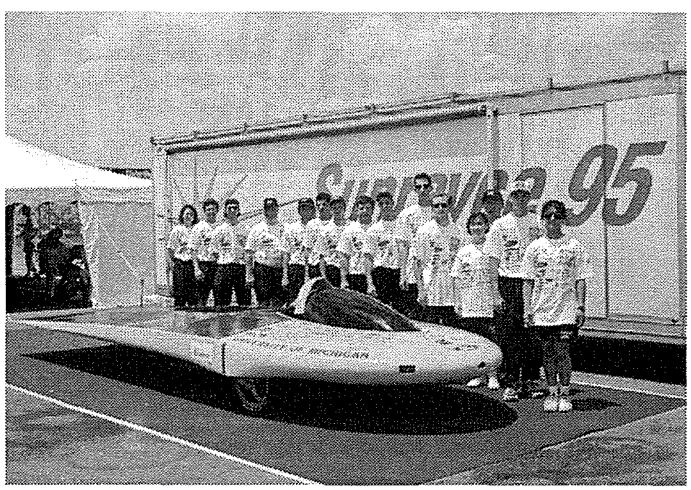


Figure 1.1.3: The University of Michigan solar-car team with their "Solar Vision."

the community to support the team. The newspaper even assigned a writer to follow the team's progress during the actual race. Articles about the solar car appeared in the Journal every day of the 9-day event.

The South Dakota team researched the first two Sunrayce competitions and decided to design for reliability. They recognized that cars with relatively few, if any, breakdowns were the top finishers in 1990 and 1993. They also realized that the chances for cloudy weather were high, so they chose a catamaran design to give them an advantage on diffuse, cloudy days.

When more students were needed to help build their car—the Solar Rolar—the team recruited people with a talent for getting things done. Zack Spencer, a freshman mechanical engineering student, chose to attend the Black Hills school because of the solar-car project. His assignment was to work on the car's body. The team planned to build a body composed of thin foam sandwiched between two micro-thin layers of carbon composite. Spencer had learned about composites from his father, who owns a business designing golf clubs and tennis rackets from lightweight materials. For Spencer, the challenge was working on something "so big."

One of the valuable lessons students are taught in the Sunrayce project is resourcefulness. As students begin to build their car, they must search for materials and learn how to fabricate parts. If their first choice is not readily available, they must find a comparable substitute. Throughout the whole project, they must learn how to deal promptly and effectively with problems, difficulties, and setbacks.

Resourcefulness was a daily necessity for the George Washington University (GWU) solar-car team. Because the university has a shortage of laboratory space, the students were relegated to the bottom floor of a parking garage under their Academic Center. There, in a small room created around a couple parking spaces illuminated with portable work lights, the students spent months sawing, soldering, and bolting together parts of their car. When it came time to build the solar array, drop cloths were used to make an improvised dust-free "clean room," where stu-

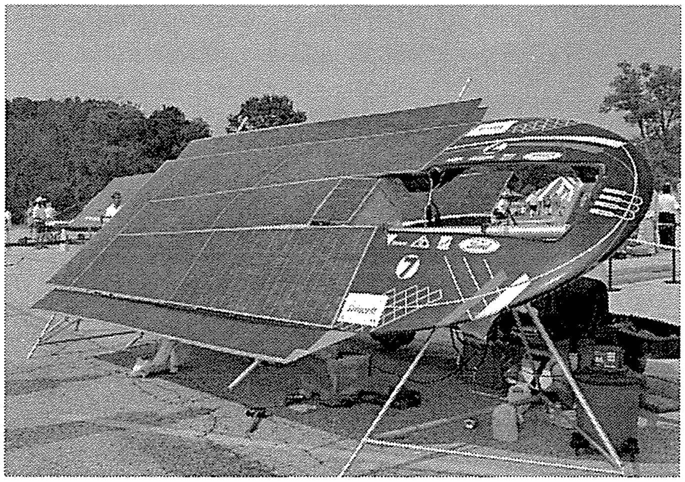


Figure 1.1.4: The George Washington University's solar car mounted in charging configuration.

dents hand-trimmed hundreds of solar cells used on the array.

If there were a grand prize for resourcefulness and innovative thinking, however, New Mexico Institute of Mining & Technology would have won. New Mexico Tech finished in last place in 1993, and they were determined to do better the next time around. The Zia Roadrunner II team designed and built the car's new frame. Before going further, they wanted to crash test it. The question was how to crash test without wheels. The answer they came up with was to drop it off a cliff! The team arranged to have a crane drop the body off an 80-foot cliff at a testing laboratory. When the time came, team members watched anxiously as the body was lifted into position. They were all wearing T-shirts with hearts on the front, symbolizing the theme of this year's project: "I hope this works II." The team figured that when the body hit bottom from a height of 80 feet, it would simulate hitting a brick wall at 40 mph. Team leader Casey Caddell said they determined mathematically that it would work. Theoretically, the battery box would remain intact so as not to crush the driver on impact. Cement bags were used to simulate the batteries.

Both the backdrop used and the shell itself were painted in a grid design. High-speed photography enabled the team to study what happened and to analyze those findings and improve the vehicle design.

The chassis dropped with a rather unspectacular "thud." According to team members, the crash test was successful. The battery box stayed where it was supposed to, and although the bulkheads failed in places, none appeared to have been structurally damaged. The design would require some modification, but the team found out what it wanted to know about the basic structure.

At Ohio State University, it was local sponsors that provided the resources necessary for their solar car called the "Red Shift." The Red Shift team was looking for materials that were lightweight, strong, and durable. They found one in Owens-Corning's "Hollex," a hollow glass fiber that provides a 30% weight savings compared to solid fibers. Much of the car's body parts ended up being made from Owens-Corning's new fiberglass.

Sometimes teams and sponsors benefit each other, a good example being Ohio State's project. Owens-Corning was looking for ways to showcase "Hollex." They were targeting the aerospace industry because they believed it had numerous applications. When Ohio State approached them, they saw a good fit to tie into Sunrayce and the automotive industry. Owens-Corning benefited from the project and said it was interesting to see how the students found different ways to use their product.

By the time the first year came to an end, most teams were actively building their cars. The planning and design phases were completed, and it was time to focus on machining parts and assembling the car. The next critical stage in the 2-year project was to complete the car and begin training.

1.2 The Second Year: Race Preparations Begin

The activity level picks up dramatically in the second year. Team meetings are more frequent and take on a sense of urgency. Anything causing a delay receives major attention. As team uniforms arrive and the car takes shape, the excitement builds as teams realize the race is getting close.

By April of 1995, two months before the race, almost all of the teams had their car built. Training a team to successfully race a solar-powered car takes at least 2 months, so the final weeks are reserved for practicing. Many teams practiced driving under simulated race conditions, navigating in and around their campus. Others drove the actual race route in early June.

For a few teams, though, work on building the car continued right up to the time they had to report to Indianapolis. For them, the hardest knack to learn was when to stop designing and start building. Some teams find it difficult to move from the drawing board to the drill press and soldering gun. They were convinced that if they fine-tuned the design one more time to eke out a little more energy gain, they would win the race. What they didn't realize was that without enough time to fully test the car, it would break down during the race.

There were 48 teams that we know of that were busy preparing for the race in those final months. We wish we had the space to fully document all their efforts. MIT tested their "Manta" in and around Boston. Goro Tamai says the driving was "grueling," but it sure made the car's weaknesses show up fast. The University of Minnesota's "Aurora II" was unveiled on their campus on May 2nd. Cal Poly Pomona's team had the toughest obstacles to overcome. They flipped their car during testing, and it took the team weeks to recover. Queens University entered their "QUEST" in the Canadian Solar Challenge in May and drove half of the Sunrayce route in June to prepare. Rose-Hulman Institute of Technology said they drove their car up and down the first leg of the race several times to practice. Drexel's "Sundragon" was often seen in and around Philadelphia.

Western Michigan University's (WMU) Sunseeker was one of the first cars to be complete—in the spring of 1995. WMU finished eighth in 1990, but dropped ten places to 18th in 1993. Determined to do better in 1995, they organized an energetic team that worked hard to finish early and begin training.

Figure 1.2.1: Western Michigan University's "Sunseeker."

Heather Ketchel, a junior in mechanical engineering, was one of three female drivers on the WMU team. Keri Lake, Cathy Prapotnik, and Rob Cavanagh were the other three drivers. Each had to score among the highest on a test containing oral, written, and practical areas to earn their positions. The next step was to start training out on the road.

Ketchel said she enjoyed being part of a predominantly female team. "Not only does it draw attention to the car, but we gain a little respect." She said respect is important, especially when you are in a male-dominated field.

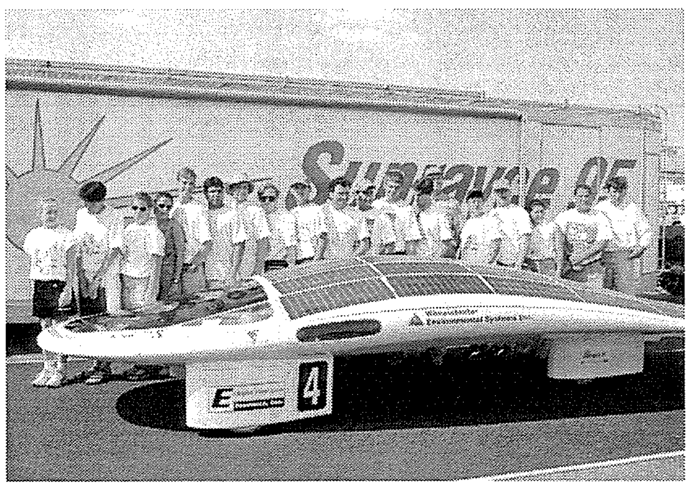


Figure 1.2.2: The Clarkson University solar car team with their "Helios."

Keri Lake, a graduate student in mechanical engineering, joined the Sunseeker team in May of 1994. She had always been interested in cars, but never had a chance to learn much about them. When she signed up, she just hoped to learn a little bit—then she became the leader of the chassis team and then a driver. "I've learned so much," Lake said. "It definitely was a positive experience."

Besides training on open roads, the Sunseeker team arranged to do some controlled testing on an airstrip in Paw Paw, Michigan, over Memorial Day weekend. The team had a relentless pursuit for perfection, along with high expectations. "Our minimum goal was the top-10." Lake said. "We all felt if we could just continue to work hard the last few weeks we could do well. We had a really good car. Everybody just had to learn their responsibilities and stick to them."

That same weekend you could see one of the most unique solar cars ever fabricated driving around Potsdam, New York. The team from Clarkson University was giving their "Helios" test runs in preparation for an unveiling ceremony in Peekskill, New York, on June 1st. Clarkson finished 28th in Sunrayce 93, but the scope of this year's effort was much larger compared to the past. They had more team members working longer hours, and they raised four times more money.

Unveiling ceremonies are beneficial because they involve the local community and give teams the opportunity to properly thank their sponsors.

Many teams planned elaborate unveiling ceremonies, and Clarkson had one of the best. The ceremony was conducted at the Alternative Energy Environmental Fair held on the site of one of their sponsors, Wheelabrator Environmental Systems—a trash-to-energy plant that donated about $15,000 to their project. Many VIPs were invited, including the state Environmental Conservation Commissioner, who had the honor of unveiling the car. Hundreds of people were there to cheer the team and wish them well.

During spring break, the South Dakota team took their newly completed car, the "Solar Rolar," to Bonneville Raceway Park in Salt Lake City, Utah, for its initial shakedown. Dan Gerbec, Solar Rolar's faculty advisor, believes it was at the Bonneville track that the team started to really show its fortitude. After testing for about 185 miles around the track, the bearings went out in one wheel, tearing up the bushings and wheel. Gerbec wanted to shut the testing down and pack up to fix the car back on campus. The team, led by Chris Scolton, had set a goal to test at least 200 miles. They wanted to fix the wheel and do more. After a lengthy discussion, Scolton and Gerbec reached a compromise. Half the crew would pack up equipment, while three determined students continued to repair the damage. Gerbec gave them 3 hours. In two-and-a-half hours, Solar Rolar was back on the track.

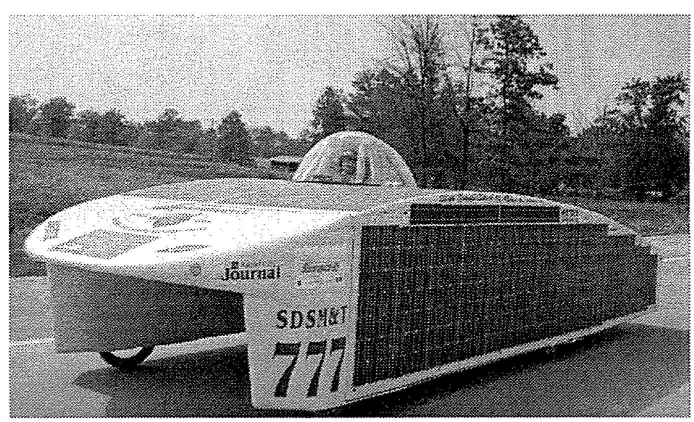


Figure 1.2.3: The South Dakota School of Mines & Technology's "Solar Rolar" out on the highway.

A few weeks later, Solar Rolar's final cross-state road test provided the team an opportunity to simulate the stress and pressure of actual racing conditions. The team's four drivers—Tim Gross, Chris Hinders, Mike James, and Chris Scolton—all agreed that learning to drive the car was more demanding than first expected.

"At the beginning it was extremely nerve-racking," said Scolton. "We weren't used to driving as a team." That came with practice. "Everybody had to get used to the car," he said, "not just the driver."

Inside the car, the driver couldn't see his hands or feet when driving. He half reclined in a seat made of thin metal, which was enclosed by a sturdy roll cage. Each had to wear a bicycle helmet and radio headphones.

"It's very demanding driving because you are trying to watch so many things at once and get it right," said Hinders, referring to speed, battery current, traffic, and the road. Following directions wasn't always easy either. Sometimes, Hinders said, it was hard to keep speed and amps at levels the chase wanted. Drivers don't always agree with directions they receive, and some have more patience than others.

During the run from Huron to Wall, South Dakota, the Solar Rolar reached 66 mph. That was an exciting moment for the team. Most of the time they averaged 25 mph. "The team learned how to conserve energy," said Gerbec. "They started the run with a 17-mph average and consuming 45 watt-hours per mile. By the end of the run, they were averaging 25 mph and consuming 30 watt-hours per mile."

Their run through the Badlands also gave the drivers experience driving some steep slopes that they would face during the race. By the time they reached home, they had run a 500-mile shakedown with relatively few problems. It left the team feeling confident and eager to get to Indianapolis.

The Sunrayce student participants were not the only ones who were busy making preparations. Many of the towns along the route were also making plans. In the town of Louisiana, Missouri, the pit stop for Day 3, the Chamber of Commerce wanted to put on a big show for the Sunraycers. They were encouraging local businesses to hold special promotions, sidewalk sales, and entertainment. They were also planning a science fair.

In Smith Center, Kansas, a special committee of the Chamber of Commerce was working with two Sunrayce teams that the town had "adopted," Mercer University and Clarkson University. Videos showing Smith Center and the county were mailed to both schools. Mercer sent a video of their car named "SunScream II," and team members from Clarkson visited in early June and showed photographs of their car.

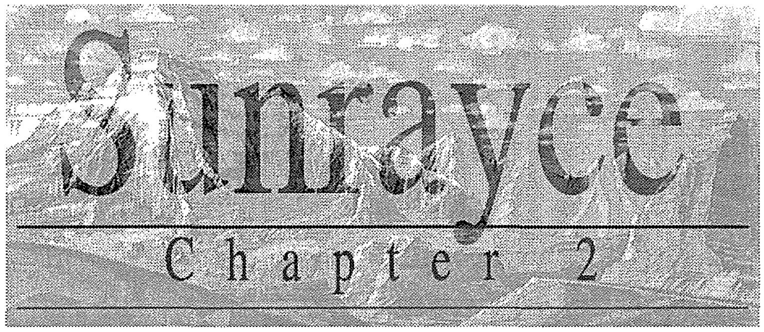
To show their adopted teams some real mid-western hospitality once they arrived, the Smith Center committee arranged to have Peterson Industries donate the use of eight campers for the students to sleep in. They also found enough families to take 200 students into their homes and arranged to have the Xi Zeta Mu sorority provide welcome baskets filled with fresh fruit and food. The local fourth graders were also planning to sing "Home on the Range" during a special presentation at the finish line.

In Oberlin, just down the road from Smith Center, townspeople were painting parking spaces on Main Street where the solar cars were to stop for their pit stop on Day 7. Crews were also hanging banners, and Town Superintendent Gary Shike was encouraging civic groups to set up food booths.

In St. Francis, the overnight stop for Day 7, the newspaper was urging people to start preparing for the solar cars to arrive. "Bring your lawn chairs and line the route through town and enjoy the afternoon," Gloria Bracelin from the Chamber of Commerce was quoted as saying. The Chamber was arranging to have food booths, concessions to sell soft drinks in Sunrayce cups sponsored by their local TV Channel 29 and First National Bank, and a raffle to give away two model solar cars.

At the Smithsonian Institution in Washington, D.C., and the Henry Ford Museum in Detroit, Michigan, a group from EDS was busy installing exhibits to show minute-by-minute progress of the race. The exhibits explored the role of alternative energy vehicles, traced the history of the Sunrayce, and provided details of this year's race. With the push of a button, visitors were able to tap into the satellite Location Communication System (LCS) using GPS sensors to track the precise location of the solar cars as they raced through America's heartland. "One of the major goals of EDS, Delphi, Delco Electronics and Hughes was to generate more enthusiasm and public awareness of the Sunrayce event. Both the Henry Ford Museum and Smithsolian Institution acted as a perfect forum, reaching thousands of people throughout the event," said Bill Dye, EDS Sunrayce Project Manager.

With all the plans taking shape, Sunrayce 95 was sure to have one of the largest audiences ever to watch a solar-car race.



Scrutineering

Before the solar cars were allowed to race on the Indianapolis Raceway Park (IRP) road course, they all had to pass visual and dynamic scrutineering. The visual scrutineering consisted of experienced Sunrayce officials inspecting the solar cars for solar array size, battery and electrical system specification and isolation, and mechanical soundness. Ergonomic requirements such as driver seating position, roll bar clearance, and road visibility were also checked. In addition to simple visual inspections, some quasi-static tests were also conducted such as the minimum-turning-radius test and the seven-second exit.

Once all the first-round requirements were met, the solar cars were led to a 5/8-mile oval track where they had to pass three dynamic tests: acceleration, slalom, and braking. The cars entered the oval at the base of the main grandstands and were allowed to make one trial lap around the track to inspect the slalom course and get accustomed to the twelve degree banked turns. After the trial runs, the cars were waved into pit lane where the dynamic scrutineering events would commence. The first event was a 120-meter (400-ft) acceleration test that was to be used for starting grid positioning for the following day's road-course qualifier race. Following the sprint, the solar cars curved around the banked turn and swooped back down on to the straightaway where a series of eight cones, spaced 15 meters apart, awaited. All solar cars were required to navigate through the 120-meter slalom course without displacing any cones in 21.6 seconds (12.4 mph) or less.

Drivers who thought they were home free having just completed two of the three events were in for a surprise. After swinging through the cones, the solar cars had to accelerate around the other banked turn and back on to the slightly inclined (3-degree) straightaway at the foot of the main grandstands. The final test was the braking test in which the driver had to bring the solar car to a complete stop at a minimum deceleration rate of 17 km/hr per second ((0.5 g') from a minimum speed of 50 km/hr (31 mph). A set of cones was arranged in a funnel pattern to help steer the solar cars in a straight line for the braking attempt. Similar to the slalom test, displacing cones would nullify the brake attempt. A Sunrayce official with a stopwatch stood a comfortable distance away from the cones and flashed a red light if the proper funnel entry speed was reached. The track was hot and gummy from all the rubber laid down by IRP's non-solar-powered race cars, which made the track almost as slick as a wet road.

Only two teams successfully passed all three tests on the first attempt: MIT and Texas A&M. Purdue University's only fumble was jumping the gun at the acceleration start, and Prairie View A&M did not see the red light on their first brake attempt.

The average elapsed time for the acceleration run was 21.8 seconds. The king of the drag strip was the entry from the University of Pennsylvania with a sizzling time of just 13.09 seconds. Other sprinters were Drexel at 15.55 seconds, and Virginia Tech at 15.68 seconds. The acceleration times for all qualifying teams are shown in Figure 2.2.

The average slalom course time was 17.7 seconds. This event was problematic for only a few teams. Twenty-nine teams passed on their first attempt, and only two teams required more than two attempts. The best time was again posted by UPenn with a time of 14.05 seconds. Other notables, as

Figure 2.1: University of Illinois's Sunchief undergoes scrutineering inspection. Note the sliding hatch assembly and the streamlined side/rear view mirrors.

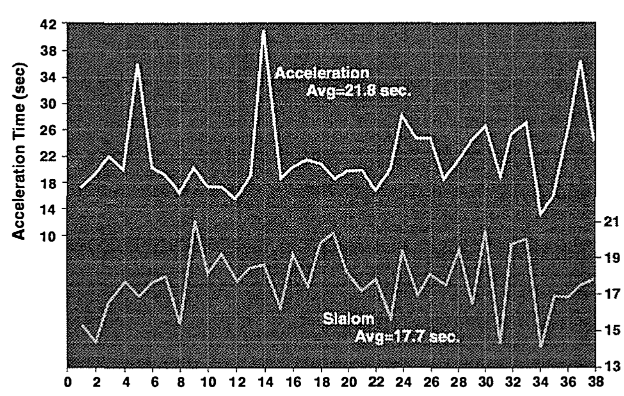


Figure 2.2: Acceleration and slalom times during scrutineering.

shown in Figure 2.2, were Columbus State Community College (14.24 seconds) and University of Minnesota (14.43 seconds).

The average number of brake-test attempts was a disappointing four tries. As shown in Figure 2.4, only four (or five including Prairie View) of the 38 qualifying teams passed the brake test on their first attempt: MIT, Purdue, Waterloo, and Texas A&M. Unfortunately, the deceleration times were recorded for only a few teams, so deceleration rates could not be plotted.

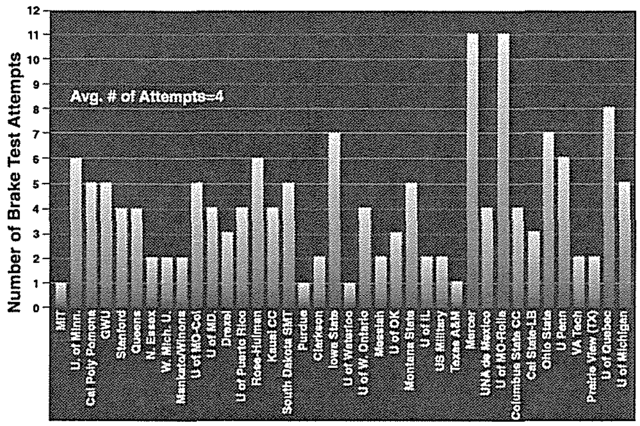


Figure 2.3: Number of brake-test attempts plotted against overall finish position.

Each team was allowed three tries before they had to go back to the pits to make brake system changes. Some alterations made in the pits include: changing tire pressures, changing the tires themselves, shimming the brake pads, altering the front/rear brake bias, and even replacing broken brake and suspension components.

All the solar cars that successfully passed the brake test on the first attempt were equipped with hydraulically actuated disk brakes. The Purdue Heliophile, being a four-wheeled vehicle with disc brakes at each corner, had a distinct advantage.

Failing the brake test kept a few competitors from ever leaving the IRP oval as Sunraycers. Some of the problems experienced by those teams included: brake-line leaking, failure to reach the required speed, aluminum brake discs being eaten up by the pads, and simply undersized brakes.

Some teams complained that the brake test was too demanding for solar cars. However, because Sunrayce is held on public roads with pedestrians and regular traffic, adequate brakes are a must.

All teams were required to qualify and start Sunrayce 95 with their vehicle in the configuration that it was scrutineered. However, once the race started, changes to some components could be made. Some teams made engineering changes in adjustment or hardware after the race start in areas such as tires, wheels, transmission components, and motors. Therefore, the scrutineering results presented are only an inkling of how responsive the solar cars were on the road.

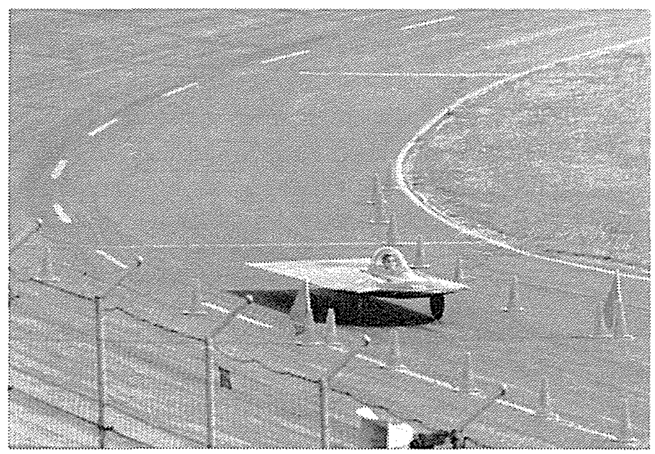
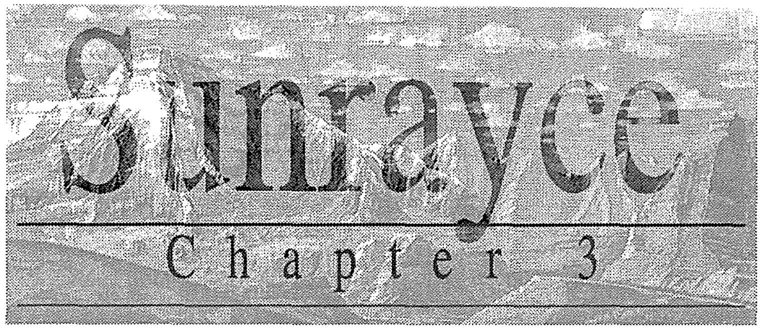


Figure 2.4: George Washington University driver David Lieberman readies for a brake-test attempt.



Qualifying

Forty-six teams reported to the Indianapolis Raceway Park for scrutineering and qualifying the week before the race. Of those teams, 38 passed the rigorous process. The eight teams that either failed to pass scrutineering or didn't complete the required 50-mile qualifier were Principia College, Southeastern Oklahoma University, Auburn University, AzTech College, the University of Massachusetts at Lowell, Middle Tennessee State University, Northern New Mexico Community College, and New Mexico Institute of Mining & Technology.

Two teams worked right up to the last minute but were unable to make it to Indianapolis. Arizona State University could not raise the funds they needed and withdrew about a week before the race. In spite of the setback, four team members traveled to Indianapolis to help the Northern Essex Community College team. Howard University also worked up to the last minute, but the team could not complete their car in time.

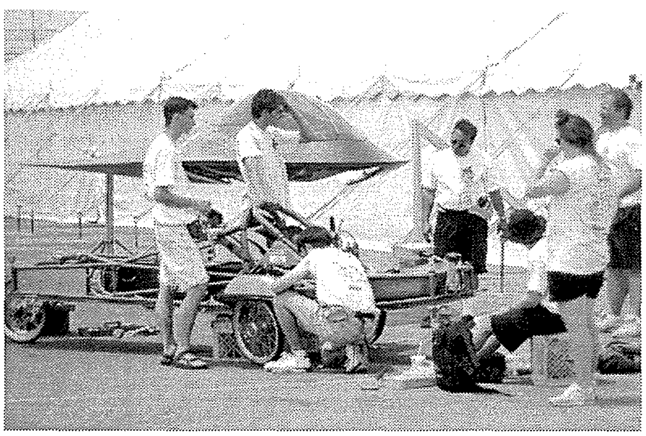


Figure 3.1.1: The Iowa State University solar-car team working on their "PrISUm Cynergy" prior to scrutineering and qualifying at Indianapolis Raceway Park.

New Mexico Tech was forced to pull out because their Zia Roadrunner II was damaged in a minor accident during a test run in Indianapolis just before the qualifier. This vehicle was designed as a two-wheel car, but it fell on its side during the 20-mph practice run.

The first day of qualifying was for seeded teams. There were only 21 teams that had passed scrutineering and began driving laps. Queens' "QUEST" completed the most laps of the 1.8-mile road course—91 laps in all—in an attempt to gain pole position. The "Pride of Maryland II.1" completed 90 laps, and the University of Minnesota completed 88. Qualifying results for the seeded teams are contained in Table 3.1.

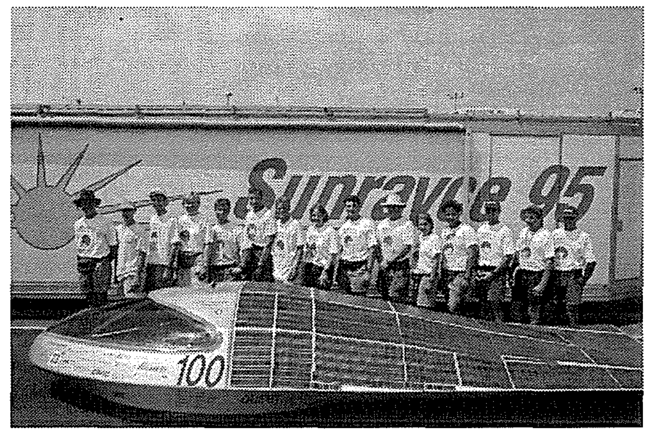


Figure 3.1.2: The Queens University solar-car team with their "QUEST" just after passing scrutineering.

Nineteen of the 21 teams qualified. Michigan completed only ten laps, because a hub failure caused considerable damage and the team couldn't make repairs in time to finish. In similar fashion, Clarkson suffered mechanical woes and couldn't finish. What was agonizing for Clarkson was that they had completed 25 laps and needed to complete only two more to qualify. They had to make repairs and try again on another day.

The second day of qualifying was for the challengers. There were 14 teams that passed scrutineering that were vying for 13 slots. The challengers capitalized on what turned out to be a strategically advantageous second day of qualifying. They had a target: pole position was only 92 laps away.

California Polytechnic University-Pomona's Intrepid Too successfully completed 117 laps, just edging ahead of MIT in a dramatic lap-by-lap contest of speed and strategy. MIT's Manta finished with 115 laps. Results are contained in Table 3.2.

Eleven of the 14 challengers qualified. Together with the 19 seeded teams, there were 30 teams ready to start. On Sunday, there was a third and final Last Chance Qualifier for all the remaining teams to try again. There were 12 teams that passed scrutineering that were competing for the ten remaining slots. Excitement filled the air as they lined up to start qualifying. As it turned out though, only eight of the teams completed the required 27 laps, as shown in Table 3.3. The closest to making the field was Principia College,

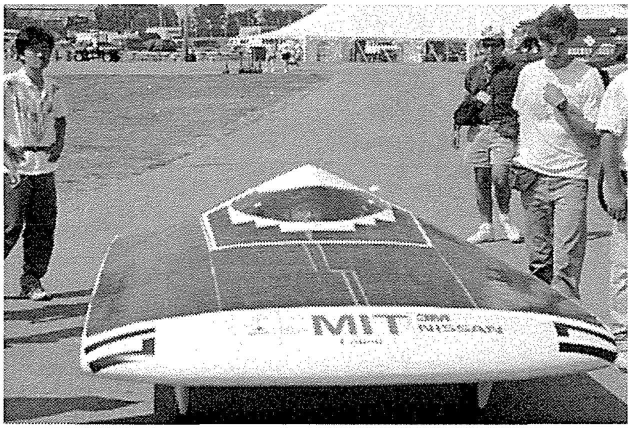


Figure 3.1.3: The Massachusetts Institute of Technology's "Manta" entering the track for qualifying at the Indianapolis Raceway Park.

who burned out several motors, including one given to them by Iowa State, and was finally forced to retire. Principia's team handled it well and continued to participate by trailering their car to the overnights to put on local demonstrations.

With the starting line-up of 38 teams all set—as summarized in Table 3.4—the teams had a day off on Monday to make final preparations. Pleased with their performance during the Last Chance Qualifier, the Michigan team decided to take a test run of the first day's leg from Indianapolis to Terre Haute. The car performed flawlessly. On the return trip from Terre Haute, the team wanted to re-run a hill on the route that had given them trouble during the test run. When the trailer was opened, they were greeted by a terrible problem.

The car's rear trailing arm had snapped, bringing the back of Solar Vision down and onto its rear wheel, which had crashed up through the solar array. It was the night before the start and they had just found out that the rear suspension was destroyed, the array had a module missing, and they were stuck 50 miles from Indianapolis at a truck stop!

They stayed up all night to rebuild the rear suspension and rewired a new module into the array. Carefully, they put the car back in their trailer as the sun was rising and reached Monument Circle 15 minutes before the start!

While Michigan worked all night, most of the other teams were enjoying themselves at a kick-off banquet held Monday night as a pep rally. Secretary of Energy Hazel R. O'Leary spoke at the banquet. She said the technology the students were working on would help drive the country into the 21st century. "We had better get there quickly or we will be following in somebody else's dust," she said. Ken Baker, General Motor's vice president for R&D, also spoke. He hailed the Clarkson team to do well because he had graduated from that institution.

Awards were given out at the banquet, and the highlight was the University of Mexico winning the $5,000 Dupont award for "Best Use of Composites." When the announcement was made, team members leaped to their feet and cheered wildly. Up on the stage, the team launched into a rah-rah cheer in Spanish that delighted the audience. The award was much deserved—and monetarily, much needed. They struggled to get to the Sunrayce, including being delayed by custom officials for 2 days while trying to cross the border from Mexico.

Table 3.1. Seeded Qualifiers Results for Sunrayce 95.

Position	**Car #**	**Team**	**Total # of Laps Completed**	**Qualifying Elapsed Time**	**Qualifying Speed**
1	100	Queens University	91	1:40:01	31.25
2	2	University of Maryland	90	1:28:22	34.14
3	35	University of Minnesota	88	1:34:23	31.98
4	371	Purdue University	85	1:28:00	34.22
5	22	University of Illinois	84	1:26:14	34.90
6	76	Drexel University	83	1:43:55	32.77
7	95	Western Michigan University	79	1:29:46	34.06
8	777	South Dakota School of Mining & Technology	73	1:40:55	29.74
9	43	University of Missouri, Columbia	65	1:40:32	29.95
10	3	Mankato and Winona State University	55	1:36:01	31.51
11	74	Rose-Hulman Institute of Technology	51	1:40:24	30.09
12	9	Iowa State University	42	1:46:18	30.66
13	500	University of Puerto Rico, Mayaguez	40	1:40:57	29.70
14	16	Stanford University	34	1:42:17	29.51
15	33	Ohio State University	32	1:37:48	30.66
16	619	Prairie View A & M University	31	1:59:53	25.47
17	8	Kauai Community College	29	1:24:34	35.61
18	7	George Washington University	29	1:40:59	29.91
19	6	Virginia Polytechnic Institute & State University	28	1:45:03	29.05
DNQ	4	Clarkson University	25	1:18:26	33.11
DNQ	1	University of Michigan	10	0:32:20	33.73

Table 3.2. Challengers Qualifier Results for Sunrayce 95.

Position	Car #	Team	Total # of Laps Completed	Qualifying Elapsed Time	Qualifying Speed
1	25	California Polytechnic University, Pomona	117	1:18:35	38.21
2	17	Massachusetts Institute of Technology	115	1:23:36	36.26
3	31	University of Oklahoma	71	1:43:18	29.46
4	24	University of Waterloo	71	1:43:59	28.89
5	96	University of Western Ontario	69	1:36:26	31.24
6	12	Texas A & M University	66	1:42:11	29.51
7	92	Columbus State Community College	42	1:57:26	25.55
8	406	Montana State University	37	1:35:12	31.58
9	101	University of Quebec	36	1:56:58	27.55
10	28	Northern Essex Community College	34	1:30:48	36.33
11	27	United States Military Academy	28	1:48:35	27.89
DNQ	195	California State University, Long Beach	9	0:28:10	11.84
DNQ	32	Principia College	6	1:11:05	3.71
DNQ	67	University of Pennsylvania	2	0:25:36	0.64

Table 3.3. Last Chance Qualifier Results for Sunrayce 95.

Position	Car #	Team	Total # of Laps Completed	Qualifying Elapsed Time	Qualifying Speed
1	4	Clarkson University	61	1:35:52	31.40
2	77	Messiah College	31	1:56:35	26.34
3	109	Universidad Nacional Autonoma de Mexico	30	1:45:46	28.38
4	1	University of Michigan	29	1:40:28	29.98
5	195	California State University, Long Beach	29	1:46:49	28.31
6	67	University of Pennsylvania	29	1:54:44	26.61
7	90	Mercer University	28	1:39:00	30.96
8	42	University of Missouri, Rolla	27	1:47:05	28.08
DNQ	32	Principia College	10	0:43:46	25.36
DNQ	50	University of Massachusetts, Lowell	7	0:38:07	20.38
DNQ	713	AzTech College	5	1:34:31	5.87
DNQ	111	Middle Tennessee State University	1	0:04:18	25.81

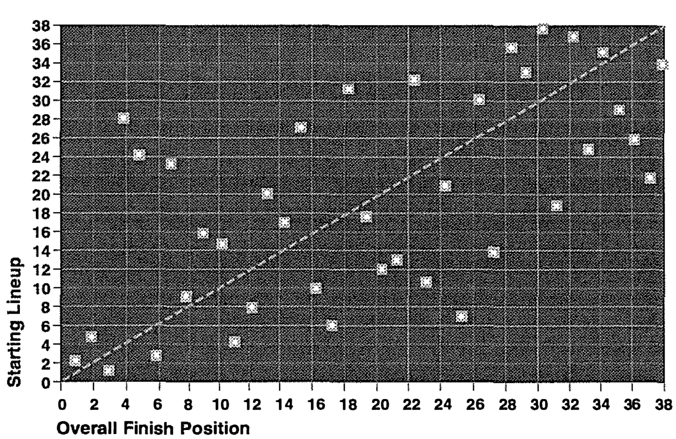
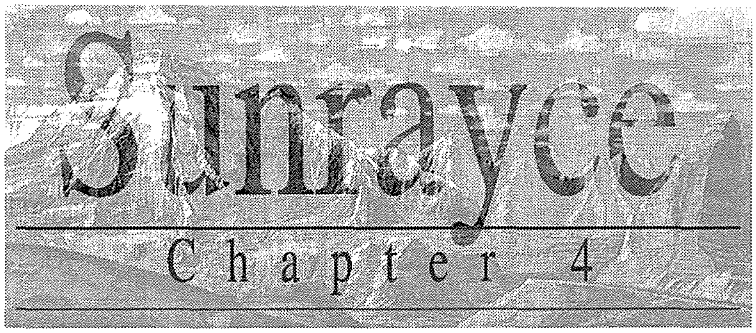


Figure 3.1.4: Starting line-up versus overall race finish shows a weak but positive correlation.

Table 3.4. Starting Lineup for Sunrayce 95

Position	Car #	Team	Total # of Laps Completed	Qualifying Elapsed Time	Qualifying Speed	Start Time
1	25	California Polytechnic University, Pomona	117	1:18:35	38.21	10:00
2	17	Massachusetts Institute of Technology	115	1:23:36	36.26	10.01
3	100	Queens University	91	1:40:01	31.25	10:02
4	2	University of Maryland	90	1:28:22	34.14	10:03
5	35	University of Minnesota	88	1:34:23	31.98	10:04
6	371	Purdue University	85	1:28:00	34.22	10:05
7	22	University of Illinois	84	1:26:14	34.90	10:06
8	76	Drexel University	83	1:43:55	32.77	10:07
9	95	Western Michigan Univ	79	1:29:46	34.06	10:08
10	777	South Dakota School of Mines & Technology	73	1:40:55	29.74	10:09
11	31	University of Oklahoma	71	1:43:18	29.46	10:10
12	24	University of Waterloo	71	1:43:59	28.89	10:11
13	96	University of Western Ontario	69	1:36:26	31.24	10:12
14	12	Texas A&M University	66	1:42:11	29.51	10:13
15	43	University of Missouri, Columbia	65	1:40:32	29.95	10:14
16	3	Mankato and Winona State Universities	55	1:36:01	31:51	10:15
17	74	Rose-Hulman Institute of Technology	51	1:40:24	30.09	10:16
18	9	Iowa State University	42	1:46:18	30.66	10:17
19	92	Columbus State Community College	42	1:57:26	25.55	10:18
20	500	University of Puerto Rico, Mayaguez	40	1:40:57	29.70	10:19
21	406	Montana State University	37	1:35:12	31.58	10:20
22	101	University of Quebec	36	1:56:58	27.55	10:21
23	28	Northern Essex Community College	34	1:30:48	36.33	10:22
24	16	Stanford University	34	1:42:17	29.51	10:23
25	33	Ohio State University	32	1:37:48	30.66	10:24
26	619	Prairie View A&M University	31	1:59:53	25.47	10:25
27	8	Kauai Community College	29	1:24:34	35.61	10:26
28	7	George Washington Univ	29	1:40:59	29.91	10:27
29	6	Virginia Polytechnic Institute & State University	28	1:45:03	29.05	10:28
30	27	United States Military Academy	28	1:48:35	27.89	10:29
31	4	Clarkson University	61	1:35:52	31.40	10:30
32	77	Messiah College	31	1:56:35	26.34	10:31
33	109	Universidad Nacional Autonoma de Mexico	30	1:45:46	28.38	10:32
34	1	University of Michigan	29	1:40:28	29.98	10:33
35	195	California State University, Long Beach	29	1:46:49	28.31	10:34
36	67	University of Pennsylvania	29	1:54:44	26.61	10:35
37	90	Mercer University	28	1:39:00	30.96	10:36
38	42	University of Missouri, Rolla	27	1:47:05	28.08	10:37



The Race

4.1 The Route

The race began in Indianapolis, Indiana, skirted the metropolitan areas of St. Louis, Missouri, and Kansas City, Missouri, and finished in the Denver metropolitan area (Table 4.1). The race, which covered 1246 miles (2007 km), was run mostly on U.S. highways. The maximum speed limit was 55 mph, except for about 18 miles of highways on Days 5 and 9 that had a 65-mph speed limit. About 80% of the roads had two lanes, with the remainder being 4-lane road. The road surfaces varied: about 80% were asphalt, some 10% were chip-and-seal, and the remaining 10% were concrete.

The route was from east to west, generally between 39- and 40-degree north latitudes. The elevation increased from about 300 m in Indianapolis, Indiana, to almost 1700 m in Golden, Colorado. Most of the elevation gain occurred on Day 6 (200 m), Day 7 (500 m), and Day 8 (600 m). Although the overall change in elevation is gradual from Manhattan, Kansas, to Golden, Colorado, the localized variations—the hills and grades—along the complete route challenged all solar cars.

4.2 Day One

The morning of Tuesday, June 20th, was sunny and bright. Teams had to arrive at Monument Circle in downtown Indianapolis by 6:00 a.m. to assemble for a group photo. The solar cars were then put on display around the Circle until the starting ceremonies began at 9:00 a.m. After national anthems, speeches, and introductions of all 38 teams, the cars were paraded down Market Street. The starting line was located directly in front of the Capitol building. At 10:00 a.m. sharp, teams were given the green flag at 1-minute intervals. The race was on!

The first leg to the Rose-Hulman Institute of Technology campus in Terre Haute was 65 miles of mostly four-lane roads. The Intrepid finished first, with the Manta just 5 seconds behind. They both averaged 36 mph.

Table 4.1. Route Summary of Locations and Distances.

Date	Start	Midday	Finish	Distance
Day 1 (6/20/95)	Indianapolis, IN Monument Circle	none	Terre Haute, IN Rose-Hulman Institute of Technology	65 miles (105 km)
Day 2 (6/21/95)	Terre Haute, IN Rose-Hulman Institute of Technology	Effingham, IL Sacred Heart Catholic Church	Godfrey (Alton), IL Lewis & Clark Community College	169 miles (272 km)
Day 3 (6/22/95)	Godfrey (Alton), IL Lewis & Clark Community College	Louisiana, MO downtown	Fulton, MO Fulton High School	165 miles (266 km)
Day 4 (6/23/95)	Fulton, MO Fulton High School	California, MO downtown	Lee's Summit, MO Longview Community College	156 miles (251 km)
Rest Day (6/24/95)				
Day 5 (6/25/95)	Lee's Summit, MO Longview Community College	Topeka, KS downtown	Manhattan, KS Kansas State University	152 miles (245 km)
Day 6 (6/26/95)	Manhattan, KS Kansas State University	Glasco, KS downtown	Smith Center, KS Smith Center High School	150 miles (242 km)
Day 7 (6/27/95)	Smith Center, KS Smith Center High School	Oberlin, KS downtown	St. Francis, KS St. Francis High School	166 miles (267 km)
Day 8 (6/28/95)	St. Francis, KS St. Francis High School	Anton, CO downtown	Aurora, CO Hinkley High School	171 miles (275 km)
Day 9 (6/29/95)	Aurora, CO Hinkley High School	none	Golden, CO National Renewable Energy Laboratory	52 miles (84 km)

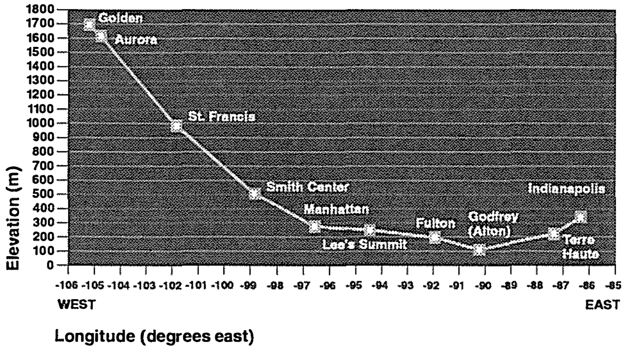


Figure 4.1.1: Profile of elevation gain, as the solar cars traveled from east to west.

With just four teams failing to complete the leg because of mechanical difficulties, it was an exciting day for almost everyone.

The University of Missouri-Columbia's "SunTiger II" started in 15th position and passed eleven cars to finish third. The team was ecstatic about their performance. Most of the time, the SunTiger traveled the speed limit—except when it was 55 mph. In those areas, the team averaged 45-47 mph. They used up about 66 percent of their battery, but were able to fully recharge the batteries in 3 to 4 hours that afternoon.

The University of Mexico passed 11 cars. They started in 33rd position and finished in 23rd. However, they had difficulty with our red lights and ran a

Figure 4.2.1: The line-up for the start of Sunrayce 95 in downtown Indianapolis.

couple unintentionally. The resulting 35 minutes of penalties dropped them to 28th position. Don Hudson, an observer in the chase van following the Mexican team, said they also had problems with their communication system and the car's brakes. Even with all the problems, Hudson said he was impressed with the enthusiasm of the team. "When I observed in 1993, very few teams showed the same enthusiasm as that team," Hudson said.

Rose-Hulman's Solar Phantom III started in 17th position and was the 14th to arrive at campus. The partisan crowd waited patiently for the team to

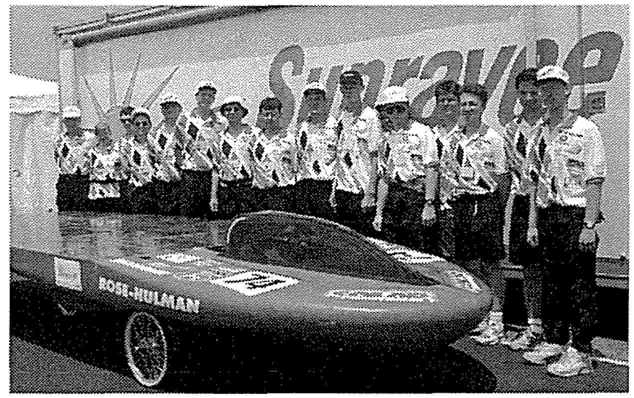


Figure 4.2.2: The Rose-Hulman Institute of Technology solar-car team with their "Solar Phantom."

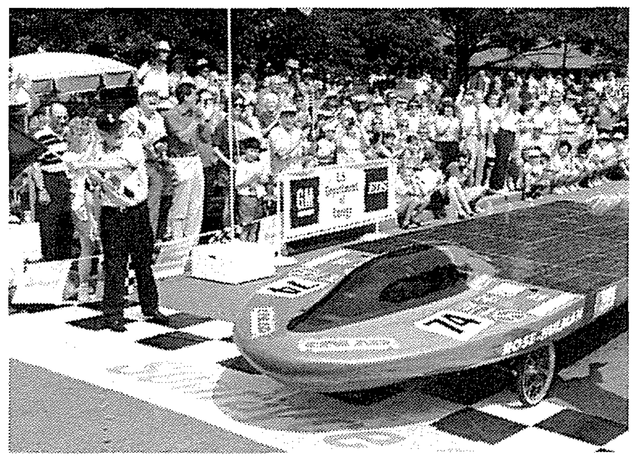


Figure 4.2.3: Rose-Hulman's "Solar Phantom" was the crowd's favorite on the first day.

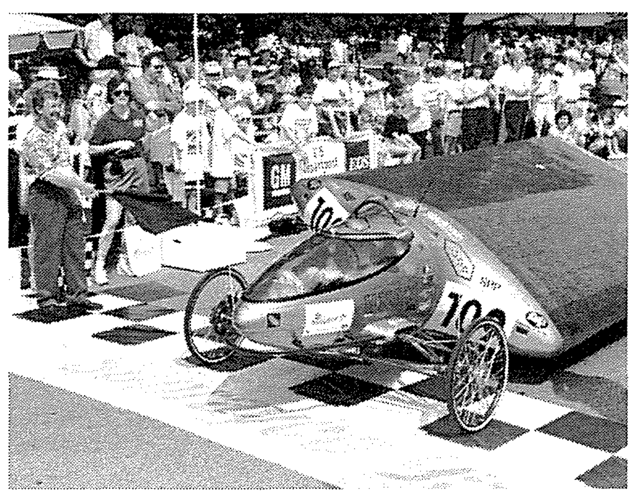


Figure 4.2.4: The University of Mexico finished 23rd on Day One.

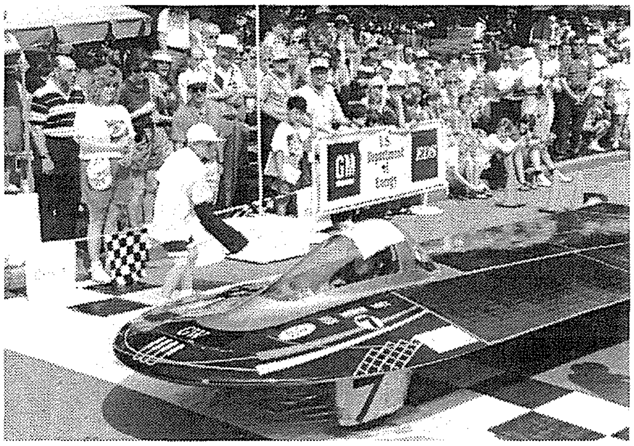


Figure 4.2.5: The George Washington University finished 17th after the first day.

arrive and then let everyone know who their favorite was. Cheers, applause, and signs reading "Go Rose" were abundant everywhere. Rose-Hulman has long been an important institution in the Wabash Valley, and it was heartening to see so many people come out to acknowledge the school's participation in Sunrayce 95.

4.3 Day Two

Day Two was a 170-mile trek across Illinois with the pit stop in Effingham, about 72 miles from the start. A large crowd cheered as the day's home team, the University of Illinois, entered the pit stop with their "Sunchief." Radio station WCRC 95.7 was broadcasting live, as well as several TV stations. The Illinois team was engulfed with reporters snapping pictures and trying to get interviews as team members scurried to change drivers and ready their car in 15 minutes.

The Sunchief started the day in 13th place, but was the 21st car at the pit stop. That was of little concern to Dan Wright, who drove the first half. "We're running the pace we want to run right now," said Wright. Their main goal was to finish each day's leg, and at their current pace they would finish with time to spare. And they did just that, crossing the finish line at Lewis & Clark Community College in Godfrey, Illinois, with an elapsed time of 7 hours and 52 minutes, leaving 38 minutes to spare.

A few more minutes is just what the Texas A&M Aggie Beamer crew wished they had. They came up 2 miles short—10 minutes from the finish line with spent batteries. Texas A&M faculty advisor Tom Talley said that at that point the team was either going to fall apart or come together and pull through. The team had been frustrated all day. With only a six-member crew having to coordinate four vehicles, they had to work harder than most of the other teams with 10-20 members.

Like good Aggies, they didn't quit. They planned a strategy to get their car recharged the next morning so they could continue on. Their dedication and hard work impressed everyone. By the time they reached the finish in Colorado, they were the unanimous choice for winning the overall teamwork award.

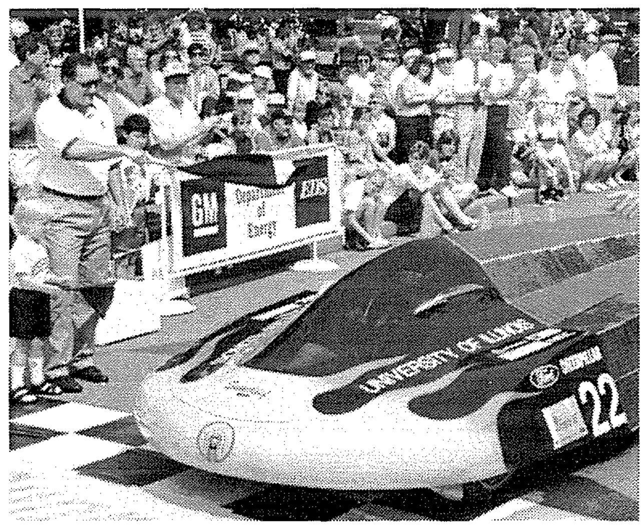


Figure 4.3.1: The University of Illinois' "Sunchief."

MIT's Manta was the first to cross the finish line, but MIT was assessed a 15-minute penalty for getting lost and driving without a chase vehicle. As Goro Tamai explains it, he was driving the Manta in the afternoon. The lead vehicle was usually some distance ahead, and sometimes it was actually out of sight for awhile. He came up over the crest of a hill with a fork in the road. His lead vehicle was nowhere in sight, so he had to make a decision, but he made the wrong one. Within seconds, he discovered his mistake, hit the brakes, and turned around. He got back on the route and looked in his mirror and saw a white Chevy van in his mirror and thought everything was fine. After about 20 minutes, he tried to radio his team but no one answered! He looked more carefully in his mirror and discovered Art Boyt, a Sunrayce official, was driving. Tamai thought everything was fine because a Sunrayce official was observing him. The chase vehicle eventually caught up. Later that evening, he found out that he was assessed a 10-minute penalty for driving without a chase vehicle and a 5-minute penalty for exceeding 55 mph!

Cal Poly Pomona, which started in first place, came in 6 minutes behind the Manta, but retained their position thanks to MIT's penalty. The Intrepid Too did not go unscathed, though. Cal Poly Pomona also received a 5 minute for driving over the 55 mph limit. They finished the day averaging 38 mph.

Third into Lewis & Clark Community College was Northern Essex. After blowing out a motor controller minutes after the start, they sped to the finish to recharge. Unfortunately, they too received a five-minute penalty for exceeding 55 mph. To make matters worse, it took the team nearly 45 minutes to unload and erect the car's solar array—a costly mistake because they needed every minute to recharge.

The Northern Essex bullet-shaped car was a unique design tied to a bold strategy. The car's solar array was disconnected and folded up within the car's body during racing. Without the drag and structural weight of a large array, the "TNE-3" could race with less energy than any of its competitors. However, the streak-and-recharge strategy would require adequate recharge time in the mornings and afternoons to be successful.

The Michigan team was doing well. They had moved up 12 places on Day One and were about 40 miles from the finish when one of their cast magnesium wheels broke again, similar to what had happened during the qualifier. That evening, they decided to replace the car's flawed magnesium wheels with newly machined aluminum wheels.

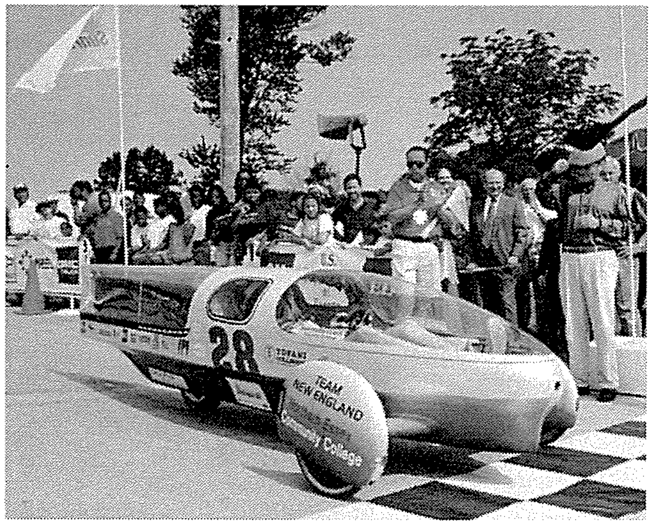


Figure 4.4.2: Northern Essex Community College's "TNE3."

4.4 Day Three

The race route in the morning of Day Three followed Illinois Route 100 north along the banks of the Mississippi and Illinois rivers. Two weeks earlier, the road was under water in places as a result of the heavy spring rains. Although it was sunny, the trees along the road created shade that hindered the racers. In Kampsville, the route turned west on Illinois Route 96 and continued through Atlas before crossing the Mississippi River at the Champ Clark Bridge into Missouri. The town of Louisiana is located there, and just about everyone in town was waiting to watch the cars pull into the pit stop.

The sidewalks were crowded with people, and it was clear from the bustling atmosphere and smiling faces that everyone was excited to have the 15-minute pit stop in their town. At noon, Northern Essex pulled into town seconds before MIT and Minnesota, making the crowd cheer with delight.

Radio station KJFM 102 was broadcasting live from the pit stop, airing interviews with various team members and race officials. No doubt hundreds of rolls of film were shot and hours of videos taken during the day.

The town's anticipation of the solar cars' arrival was best illustrated by a fence that had a "Sunrayce 95" mural painted in bright yellow, blue, and orange. Posters with all 38 schools' names were posted up along the street as well, giving all the teams a nice, warm welcome.

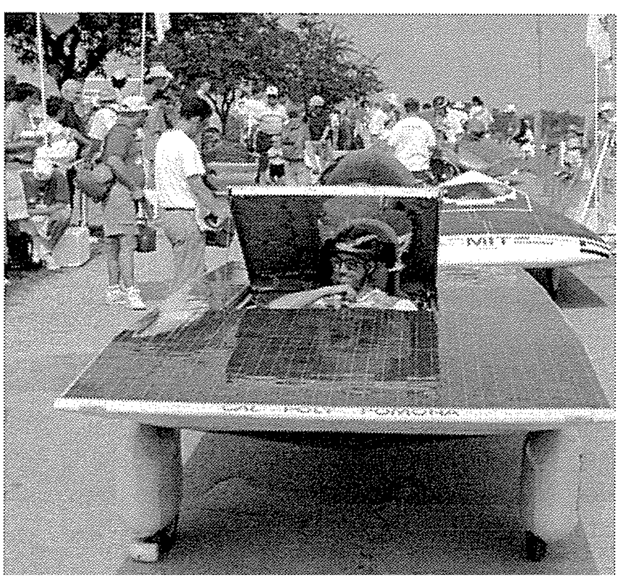


Figure 4.4.1: .Cal Poly Pomona's "Intrepid Too" was the first to start from the Lewis & Clark Community College on Day Three.

The noon sun had now turned a sunburned-flesh red and was heating the pavement to grill-like temperatures. With temperatures in the high 90s and cockpits well over the 100-degree mark, drivers always looked as though they had just stepped from the sauna. Crew members sprayed water onto the solar cells. On more than one occasion, the drivers directed the spray onto themselves.

It was nearing mid-afternoon when the University of Western Ontario's "SunStang" rolled into Louisiana. Team captain Rasha Al-Naji was the second driver of the day. She said they changed drivers at about half way because of the extreme heat inside the vehicle. A spectator asked just how hot it was inside the car, but before she could answer, a crew member offered, with a smile, "We don't want them to know."

The Ontario team had "adopted" Louisiana, and they had been brainstorming all day in an effort to find something special to do to impress the town when they arrived. Since they were from Canada, they wanted to have a friendly game of street hockey, but no one brought their sticks. What they did bring was a special plate from the Mayor of London, Ontario, the team's hometown, that Al-Naji presented to the town. She and her crew also helped place a plaque on the Lewis Building to commemorate the historic occasion.

Days One and Two were a warm-up (no pun intended) to Days Three and Four, considered by the officials as the two most difficult legs because of the traffic congestion and more challenging terrain. As it turned out, some of the teams did encounter more difficulties as the race moved into Missouri.

Northern Essex experienced a setback when a tire blew that caused another failure. Sliding sideways across the road subsequently pulled the tire off another wheel. Within 12 minutes they had the tires changed and back on the road, thanks in part to the Minnesota scout vehicle that stopped to help direct traffic.

Kauai Community College had a similar accident. They had a great first half and were keeping up with the leaders as they pulled into the pit stop in Louisiana, Missouri. Christy Kajiwara started driving the second half and was averaging about 45 mph about 3 miles outside of Louisiana when a rear tire blew. The car skidded around and went over the right shoulder, down a small hill, and landed softly in a grassy area. Unfortunately, the rear titanium swingarm broke, which ended their racing for the day.

A passerby stopped to offer help and directed the Kauai team to a welder's shop. Owner Marvin

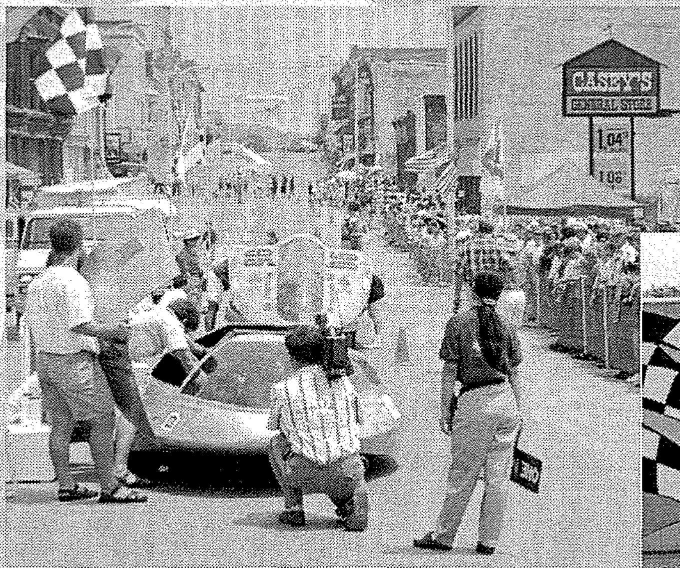


Figure 4.4.3: The pit stop in Louisiana, Missouri, on Day Three.

Figure 4.4.4: Residents from the town of Louisiana, Missouri, had painted a mural in the middle of town.

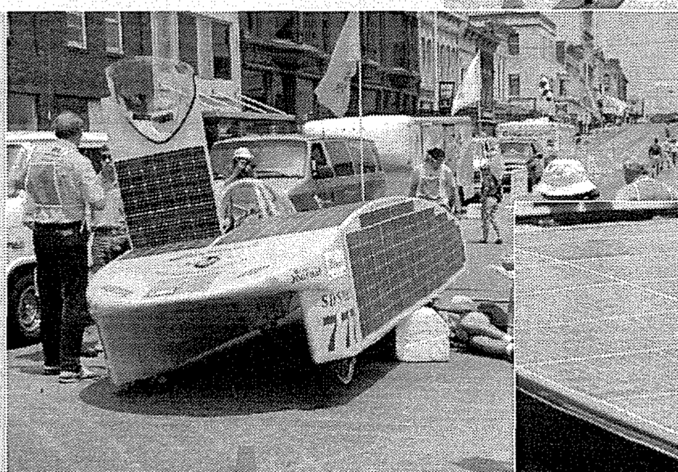


Figure 4.4.5: South Dakota's "Solar Rolar" at the pit stop on Day Three.

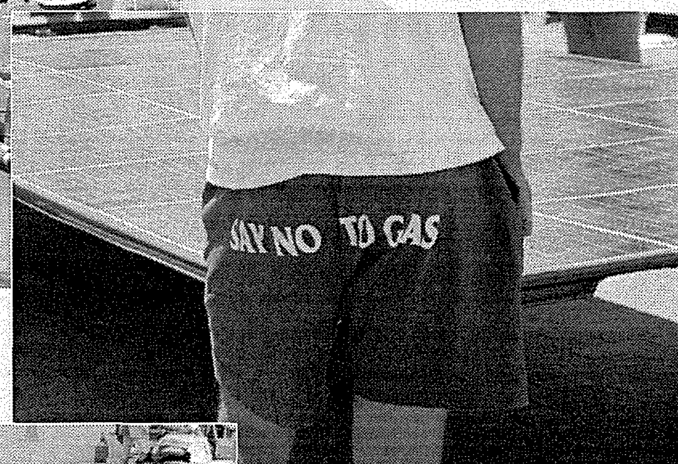


Figure 4.4.6: A not-so-subtle message on one of the Mankato/Winona team members.

Figure 4.4.7: Driver Christy Kajiwara, with the Kauai Community College, readies herself for a big day of racing.

Darnell at Marv's Garage had never welded titanium before, but he gave it his best effort. Titanium is a difficult metal to weld, and the team was very grateful for the help. They trailered the repaired car to the finish line to recharge later that evening. When it was time for impound, the car suffered another break in the swingarm, as it was being pushed over the lawn to the impound tent.

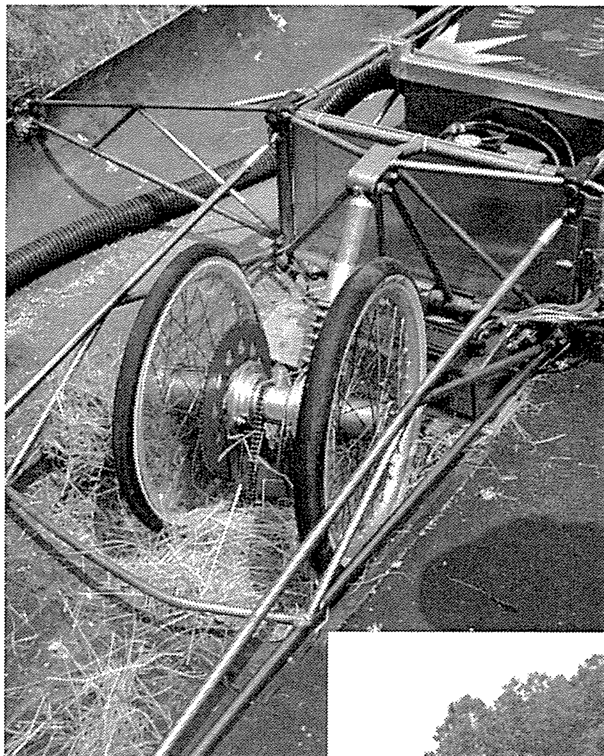
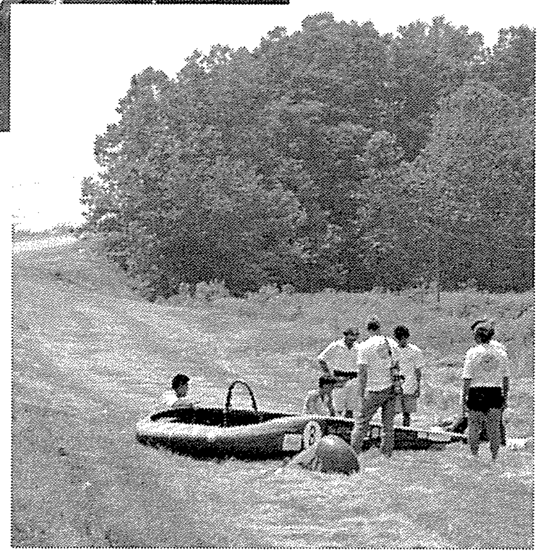


Figure 4.4.8: Just outside Louisiana, Missouri, on Day Three, Kauai's rear tire blew, sending the car off the road and breaking the swingarm.



The Kauai Community College was awarded the teamwork award that evening for demonstrating team effort throughout their hectic day of racing. Team member spirits were holding up, although all admitted it was a difficult day. Now they had to focus on getting the swingarm fixed one more time.

The Michigan team spent most of the day at the starting line, replacing a shattered magnesium wheel and rebuilding a right front brake that was torn apart in the mishap on Day 3. It took longer than they thought, but they were still confident they could climb back into the top-10. Overall, their spirits were good, probably because they were refreshed after sleeping all afternoon while the car was being fixed. At the end of the day, they put the car on the course for about 5 miles, then trailered to the finish line in Fulton.

MIT was again the first to reach the finish line in Fulton, Missouri, on Day Three. They cruised the 140-mile leg at an average speed of 43 mph. However, they were again assessed a 5-minute penalty for speeding. Twenty-five seconds behind was Minnesota. Continuing to cash in with its "sprint-and-charge" strategy, Northern Essex came in third about 15 minutes later.

4.5 Day Four

Friday, June 22nd, was the summer solstice—the longest day of the year. As the sun began to rise over Fulton High School, teams positioned their cars to soak up as much of the plentiful sunlight as possible. Most teams were preparing to go all out today because tomorrow was a rest day (no racing), which, weather permitting, would allow everyone to fully recharge their batteries. Because every day for the past week was sunny, few gave much thought to the weather changing.

With the sun high and hot, and everyone sprinting to Lee's Summit, Day Four recorded the fastest speeds of the race so far. The top five teams all averaged over 40 mph, with the University of Minnesota posting a remarkable 48 mph. The fast speeds also made the pit stop in California, Missouri, an exciting place to be. Thirty-three of the cars came racing through the pit stop, the most since the race began.

Minnesota's Aurora II was the first car to excite the crowd waiting at the California, Missouri, pit stop. MIT, Cal Poly Pomona, and Northern Essex were close behind. These top teams were providing some heated action, but the best was yet to come. The open, predominantly four-lane roads the rest of the way to the finish in Lee's Summit allowed the teams to easily overtake one another. By the time they reached the finish line, the lead had changed several times, and all four were within minutes of each other.

Northern Essex crossed the finish line first, just 37 seconds in front of Minnesota and 5 minutes in front of MIT. Northern Essex, however, had incurred 25 penalty minutes and was not able to improve their overall standing. Minnesota continued to surprise everyone by finishing first, officially, which moved them into second place overall. MIT provided another flawless race day, increasing their first-place lead by 3 minutes. But the race was far from over, and the leaders were still incredibly close. After 4 days, MIT had only built a 10-minute lead.

Other teams that improved their standing on Day Four were the George Washington University, which moved into fifth place ahead of Queens; Stanford, which moved into 11th place; the University of Maryland, which moved up from 16th to 12th; and the United States Military Academy, which edged out the University of Missouri-Rolla by 18 seconds to take 28th place overall.

Others were not so fortunate. The University of Michigan experienced another tire failure. After experiencing the same failure three times in a row, the team felt they had pushed their margin of safety far enough. They didn't

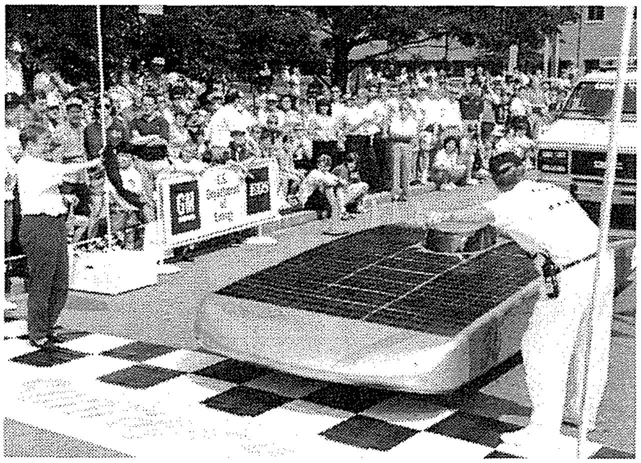


Figure 4.5.1: The University of Minnesota's "Aurora II."

Figure 4.5.2: The action was fast and furious when the leaders reached the pit stop. MIT, Minnesota, Northern Essex, and Cal Poly Pomona were all within minutes of each other.

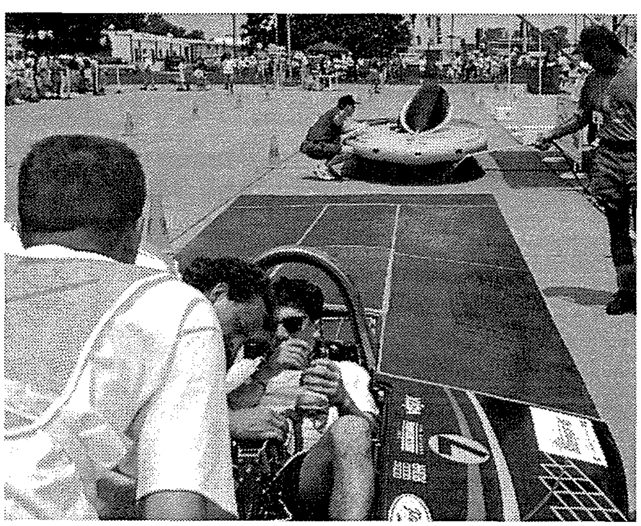


Figure 4.5.3: The George Washington University with the University of Michigan in a pit stop. The Michigan team was giving a gallant effort, but would soon have to retire from the race because of mechanical failures.

take long after assessing the damage to withdraw from the race. The whole team gave it their best shot, but no one wanted to risk the safety of the driver.

The Michigan team was magnanimous in defeat. After winning the first two Sunrayces, withdrawing was not easy. But they loaned spare parts and equipment to many of the remaining teams, and some team members stayed until the end, helping wherever they could.

Kauai Community College spent the whole day Friday in Fulton trying to repair their cracked swingarm. They took the swingarm to a welder's shop, and in a couple hours, they had the repair completed. Then it took another couple hours to put the car back together. By the time Sunrayce officials inspected and approved the repair, it was 4 p.m. They put the car back on the track and raced until time ran out, averaging close to 50 mph. And when they reached Lee's Summit, the team's spirits were back to normal. They had a day of rest ahead of them and near full batteries, because the car had sat recharging all day while it was being repaired. They all felt the second half of the race would bring them better luck.

4.6 The Rest Day

The route in 1990 ran from Florida to Michigan, and in 1993, it ran from Texas to Minnesota. Both times, the racers encountered several consecutive days of rain and clouds. Race officials looked for a sunnier route and decided to start Sunrayce 95 in Indiana and end in Colorado. There were two reasons for the selection. The Plains states have statistically less rainfall in June, and by running east-to-west—counter to prevailing weather patterns—racers would drive through storms faster.

Relatedly, a rest day was inserted into the middle of the race to help cars recharge their batteries after a tough first half. Rainfall in the month of June in Indiana, Illinois and Missouri is four times that of Kansas and Colorado. Because the chance for rain and clouds was high, the rest day would provide the opportunity to regroup and recharge, making a safer and more competitive second half.

Figure 4.6.1: Team members catching some much needed sleep on the rest day at Longview Community College in Lee's Summit, Missouri.

Just when you think you have the weather outsmarted, it does the unexpected. Instead of rain, the first 4 days were clear and sunny. And instead of a clear rest day, it rained, so no one was able to recharge their batteries!

Everyone did have a relaxing day, however. Longview Community College, the site of the overnight and rest day, has a beautiful campus with open fields, a lake, and excellent recreational facilities. Teams were able to catch up on some very necessary sleep, make repairs, and even do laundry chores.

That evening, there was a barbecue for everyone. As the night wore on, some of the officials and teams put on skits for entertainment. General "Can Do" revved up the crowd with a rousing speech, and the University of Mexico team got everyone dancing.

4.7 Day Five

The fifth day of racing would take the teams through Topeka, Kansas, to Kansas State University in Manhattan, a total of 152 miles. The official battery sponsor of Sunrayce 95—Delphi Automotive Systems—provided free batteries to teams. Most of the batteries were manufactured at Delphi's plant in Olathe, Kansas, about 30 miles west of Kansas City. When the plant manager found out that the Sunrayce route was passing so close to their plant, he offered the facility for a pit stop. Unfortunately, the pit stop was already arranged in Topeka, but Sunrayce officials jumped at the idea to use the facility to conduct a surprise inspection for the cars. Plans were made without the teams' knowledge to have the cars drive through the plant parking lot. A course was devised to test the car's height, turning radius, horn, and lights. As expected, most passed without incident. Only a few penalties were assessed for inoperative horns or turn signals.

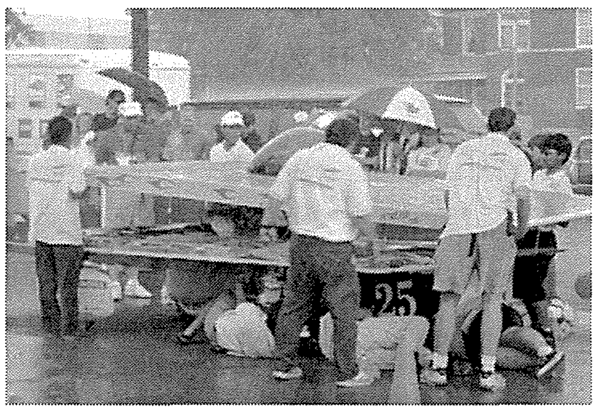


Figure 4.7.1: Just as Cal Poly Pomona's "Intrepid Too" entered the pit stop in Topeka on Day Five, it started to pour, and the team had to change drivers in the rain.

As GWU pulled their car across the parking lot to the starting line, one of the car's tires began to go flat. The team quickly fixed it, but they wondered if it was a bad omen. They soon discovered it wasn't. With probably the most efficient car, they soon outpaced everyone in the cloudy weather. Before they were halfway to the pit stop, they had passed everyone in front of them!

Passing MIT that morning wasn't easy, however. It was raining, and visibility was poor. GWU couldn't pass MIT for some time because they were both doing the speed limit. Finally, the opportunity came. A section of the route that was posted at 65 mph was just ahead. Once on it, MIT sped up to 62 mph, but GWU was able to get by them by accelerating to 65 mph!

The State Capitol's parking lot in Topeka was filled with anxious locals waiting for the cars to race in for their 15-minute pit stop. Although it was raining off and on, the crowd was not deterred. GWU was the first to arrive, followed by MIT and Northern Essex. Cal Poly Pomona pulled in next, just as a dark rain cloud approached. As soon as Pomona's team members started to lift off the canopy to change drivers, it started to pour very hard. Everyone was soaked to the bone!

GWU was the first to reach the finish line, 47 minutes ahead of Northern Essex, their nearest competitor. Their great run had moved them from fifth overall up to second overall. Northern Essex managed to overcome several obstacles to finish second for the day, including a motor-controller failure, a flat tire, and having to stop to recharge because of dead batteries less than a mile from the finish line! They waited for about 30 minutes to recharge enough to get up the steep hill just before entering the KSU campus, but without full sunlight, their hopes of getting a substantial recharge for tomorrow's run looked grim.

Other teams were driving more conservatively because of the cloudy weather. MIT was third to finish, with an average speed of 29 mph—well off the blistering speed of 47 mph they achieved on Day 4. Cal Poly Pomona finished fourth, 12 minutes behind MIT, despite two flats and stopping to change from slicks to treaded tires. Cal Poly Pomona's good finish moved them into third place, ahead of Minnesota. Minnesota finished fifth, and Western Michigan made a surprising 6th place finish to greatly improve their standing.

Two days of rain and clouds took its toll. Only ten cars made it to the pit stop in Topeka, and only nine were able to complete the leg. With their car repaired and batteries recharged, Kauai did well by finishing 7th. With just 27 minutes before time ran out, Stanford and Queens came racing across the finish line, just 11 seconds apart!

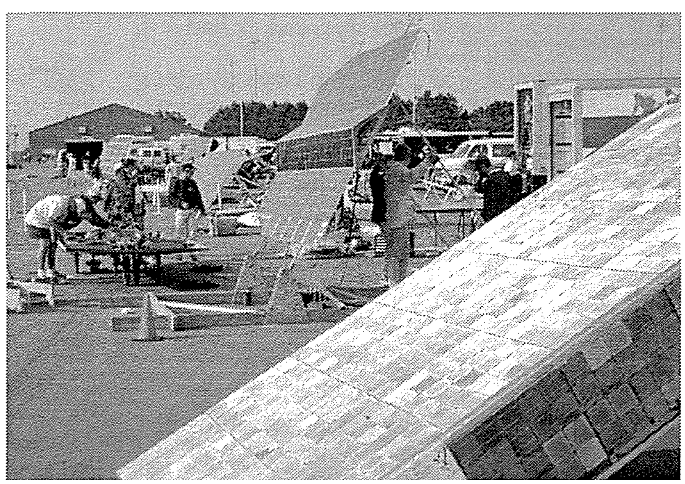


Figure 4.7.2: Teams recharging their solar cars at Kansas State University. Columbus State Community College is in the foreground.

For the Maryland team, everything that could go wrong did. But despite a disappointing day that included a motor breakdown, a rear tire blowout, and a front wheel coming off, the team was still in good spirits at 6:40 p.m., when they finally ran out of battery power just 14 miles from the finish line.

Similarly, Purdue University hit a large pot hole just before the Topeka pit stop that broke a motor mount. The team stayed and warned other teams of the hazard and kept the area safe. They were awarded the Teamwork award that evening for looking out for the others.

Rose-Hulman started Day 5 by taking a gamble. They decided to go faster than normal to get ahead of the clouds and hopefully find some sun. But the weather didn't cooperate. They completed 87 miles of the 152-mile leg and then called it quits for the day.

One bright spot in the day was stopping at Kansas State University, which hosted the overnight. They had set up tables in Bramlage Hall and prepared a steak dinner for everyone. Local and state dignitaries, including Lt. Governor Sheila Frahm, Manhattan Mayor Edith Stunkel, and KSU President Jon Wefald, welcomed the Sunraycers during the evening daily awards ceremony.

4.8 Day Six

The George Washington University team surprised everyone by jumping into second place on Day Five. The team was in high spirits when they left the starting line to lead the pack to Smith Center, Kansas. They hit the road and never looked back. By midday, they were 22 minutes in front of MIT and running hard. Overall, they were less than 15 minutes behind MIT, and the team was beginning the believe they might pull into first by the time they reached Smith Center. Unfortunately, the car's motor controller began to fail, and the car came to a crawl just outside Smith Center. Still, they crossed the finish line 14 minutes ahead of MIT and were now only 12 minutes behind in the overall standings!

Because of the rain during the previous 2 days, the cars had depleted batteries and were running conservatively even though the sun was shining bright. GWU and MIT averaged 37 mph. Minnesota and Cal Poly Pomona were close behind and continued their dog fight for third place. When the day started, Pomona was in third place overall by 3 minutes. By the end of the day, Minnesota had pulled ahead by 5 minutes.

Northern Essex started the day with low batteries. They tried gallantly to keep up with the leaders, but by the time they reached the pit stop in Glasco, the batteries were just about dead. Without a deployed array, they couldn't even take advantage of the 15-minute pit stop. Just outside Glasco, Northern Essex realized they couldn't go on, and they pulled into a parking area to recharge.

Northern Essex charged for several hours before heading for the finish line. By the time they reached Smith Center, they had 15 minutes to spare and had finished in 14th place for the day. They had started the day in 3rd place overall, just 30 minutes behind first-place MIT. Now they were in 5th place overall and more than 4 hours behind MIT.

Stanford University finished fifth for the day and continued to improve during the second half of the race. Montana State University finished sixth and moved up in the overall standings from 26th to 22nd. Mankato-Winona State Universities finished seventh and moved up from 11th to 9th place overall.

Several teams, such as Ohio State, South Dakota, and Pennsylvania, decided to trailer from Manhattan to Smith Center first thing in the morning so they could charge their batteries. The South Dakota team hadn't finished Day 5 because their batteries were drained. The team felt that the final 2 days of the race would be the toughest, and trailering would give them a full day to recharge the batteries. The decision dropped the South Dakota team from 13th place overall to 18th, but the team felt they would make up the time the last 3 days.

Most of the teams tried to race as far as they could, even though they had low batteries. Only 19 teams reached the pit stop in Glasco, and of those, only 14 were able to reach the finish in Smith Center. Clarkson tried very hard, but came up just a few miles short. They did not want to disappoint their adopted hometown crowd in Smith Center. But depleting the car's batteries too much could cause damage to the car's 40 six-volt batteries. The Clarkson team crept along at an average speed of 19 mph, trying to conserve energy.

Over a year ago, after the race course had been determined, the team from Clarkson University in Potsdam, New York, was looking for a place to stay in Smith Center, a town of 1,800 people, and was having trouble finding rooms. At about that same time, the adopt-a-town program was started, which linked towns along the race route with teams. Clarkson's team decided that Smith Center sounded like "a cool town, and it's been golden ever since," said the team's administrator, Leslie Anne Hummel, a human dynamo known to team members simply as "Holmes."

The town of Smith Center sent Clarkson a box of T-shirts. "Clarkson is in upstate New York," Hummel said. "People would see the T-shirts and ask, 'Smith Center? Where is that?' I would reply by saying it is located in the geographical center of the U.S. and is the birth place of "Home on the Range."

By 7:00 p.m. the whole town was waiting at the finish line to greet their adopted teams. A special ceremony was planned, highlighted by the fourth graders singing "Home on the Range" to the teams. Everybody had been waiting for 3 hours, but still there was no word of the Clarkson team.

Out on the route, the Clarkson team kept creeping along. "We were begging for juice," said Hummel. "As the afternoon wore on, I had no fingernails left," she said.

About 3 miles south of town, the Clarkson team came to a hill by the Smith Center Country Club. It proved too much, and the team had to load

Figure 4.8.5: Hundreds crowd around Clarkson's "Helios" when it finally arrived at Smith Center.

Figure 4.8.1 and Figure 4.8.2: The George Washington University was first to start on Day Six from KSU in Manhattan, Kansas. Cal Poly Pomona and Minnesota ready their cars to give chase.

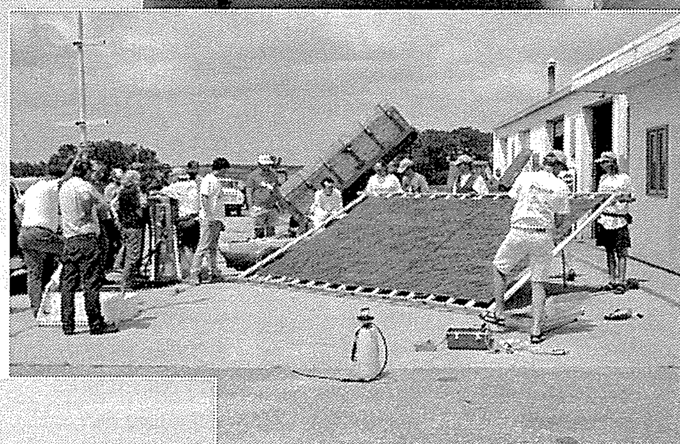


Figure 4.8.3: Northern Essex had to pull over to recharge on Day Six.

Figure 4.8.4: Solar cars charging at the high school in Smith Center, Kansas.

"Helios" onto its trailer. As they pulled into town, they noticed it was deserted and wondered if they were going the right way. Everybody was waiting at the high school. When they saw the crowd waiting for them "we couldn't just not come in," said Hummel.

Determined not to disappoint residents of their hometown for a day, they unloaded their sleek car a short distance before the finish line and drove Helios across at roughly 7:30 p.m., honking the car's horn for the hundreds of fans. The cheering crowd swarmed around the car, trying to get a closer look.

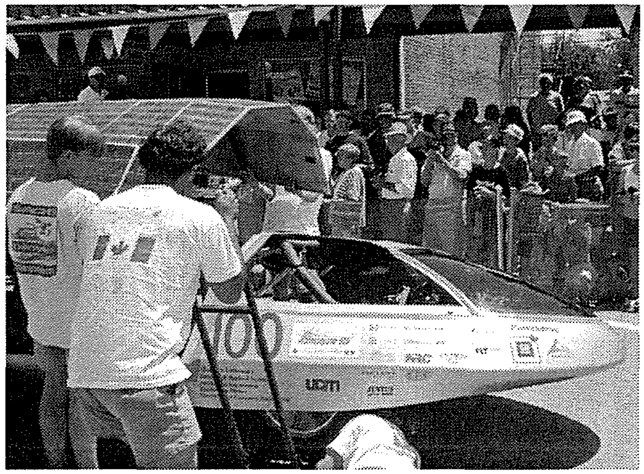


Figure 4.9.2: Queens University at the pit stop in Oberlin, Kansas.

The Mercer University team from Macon, Georgia, also adopted Smith Center. The town donated trailers for both teams to spend the night in, as well as arranging families to have team members to stay with. Over 30 families opened their homes to these and other teams.

An evening ceremony was begun as a tribute to all the Sunrayce teams. Mayor Gary Gardner welcomed the teams on behalf of Smith Center. The ceremony was highlighted by two songs, one written in 1995 by a local resident about driving a solar car across the prairie, the other by a resident in 1873 about life on the prairie. As the fourth graders sang "Home on the Range," everyone realized how special this part of the world is.

Smith Center may only be a small town, but it has big ideas and people with giant-size hearts.

4.9 Day Seven

Day Seven belonged to Minnesota's "Aurora II" from start to finish. The Aurora II had finished in the top-5 every day since the race began, but never in first place. On a perfect, sunny racing day, the Minnesota team decided it was their turn to lead the pack for a day. They bolted from the start in third place and by mid-morning had passed GWU and MIT to take the lead into the pit stop in Oberlin, Kansas.

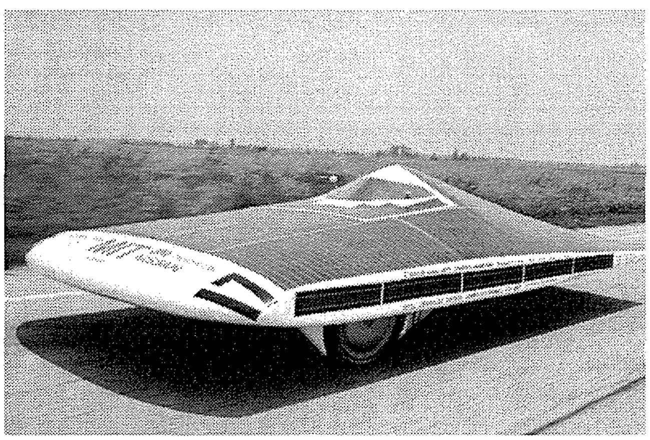


Figure 4.9.1: MIT's Manta in hot pursuit of Minnesota's "Aurora II" on Day Seven from Smith Center to St. Francis, Kansas.

MIT made a race of it, staying within minutes of Minnesota all the way to the finish in St. Francis. Both teams ran strong, but the Aurora II seemed to have a little more power to climb the hills that marked the journey across western Kansas.

The Minnesota team reached St. Francis just 4 minutes ahead of MIT to win the daily crown for the first time. The team was ecstatic. Furthermore, because MIT was "pushing" them all afternoon, they ran faster than ever before and broke the Sunrayce average speed record. When the results were officially calculated, the Aurora II had run the 166-mile leg in 3 hours and 33 minutes for an average speed of 50.42 mph!

Simplicity and reliability were working for the Aurora II. When the Minnesota team began their project, they wanted to keep things simple. Six of the nine team leaders were on the Sunrayce '93 team, and they realized that a car can't win the race if it spends time on the side of the road or in a trailer. Thus far, the car had suffered only one flat, which was caused by a poorly installed inner tube.

Minnesota started the day in third place, 30 minutes behind GWU. Their strong first-place finish moved them into second place overall. MIT continued to be unshakable and held a 45-minute overall lead with only 2 days left. Cal Poly Pomona finished a consistent third, losing some ground to MIT and Minnesota in the overall standings, but also gaining ground on GWU, who finished 6th. Stanford again finished strong, this time in fourth place for the day, further solidifying the team's position in the top-10. Queens University continued its persistent bid for the top by taking fifth for the day, 8 minutes ahead of GWU. Western Michigan,

Figure 4.9.3: Teams charging at the high school in St. Francis, Kansas.

Northern Essex, Mankato-Winona, and Kauai rounded out the top-10.

Kauai Community College had a terrific day of racing and was given a special "Advancement Award" that evening. The recognition was for advancing the furthest in the standings in the past 3 days of racing. Kauai went from 27th position to 19th in that period.

For the first time since the very short first day, the University of Mexico finished the day's leg under its own power. The Mexican team finished the 166-mile leg with less than 2 minutes to spare. The team had pushed hard all day. When they didn't reach the pit stop by the 3:00 p.m. cutoff, their chances looked grim. But the team and car performed well all afternoon, and they accomplished their goal. The team was so happy you would think they had won the race.

The warm Kansas hospitality was evident again throughout the day. In Oberlin, the site of the mid-day pit stop, flags lined the streets as hundreds of well wishers cheered the teams. Shops opened their doors for sidewalk sales, and locals provided food, drinks, and ice cream for everyone. Queens University had adopted Oberlin, and when they pulled up in sixth place the town went wild. Mayor Charles Frickey presented the team keys to the city before they left.

In St. Francis, the locals prepared a barbecue for everyone as part of the meal plan, and Bank West served free ice cream for the teams. They also had two local disk jockeys, Elrod and King, play music later that evening, which seemed to put everyone in a relaxed mood. With the final stretch ahead, it was time to kick back a little. The weather had turned cooler and more comfortable, so several teams started playing football on the athletic field. The music and play went on long into the night, as if it were everyone's last chance to really be together.

The status of the weather over the last couple of days was the topic of conversation by day's end, and it depended on who you talked to. Some said it would be cloudy, others said it would be sunny the rest of the way.

4.10 Day Eight

The distance from St. Francis, Kansas, to Aurora, Colorado, was 171 miles, which made Day Eight the longest leg of the race. The route stretched across open prairie in eastern Colorado with few stops and little traffic, which would benefit the racers. However, clouds started to thicken as the day progressed, and there was a steady climb in elevation to get to the "Mile High" city.

MIT's speed, averaged over the first 7 days, was 39 mph. If they could maintain an average of at least 43 mph over the last 2 days, they would average over 40 mph for the entire 1,246-mile race and establish an impressive record for future teams to try and beat. Early in the day it seemed possible, but as they approached Denver the clouds thickened, which slowed their pace. MIT finished the day in second place, with an average speed of 41 mph.

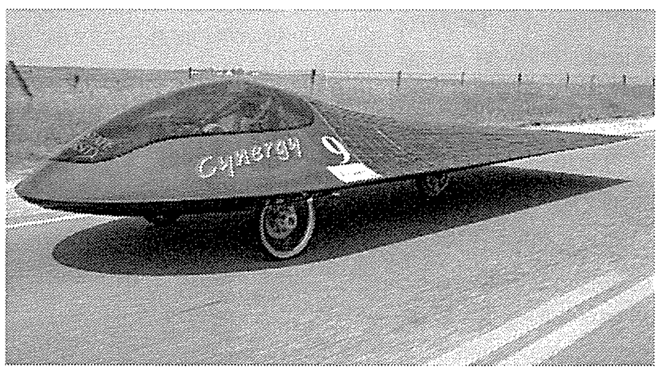


Figure 4.10.1: Iowa State University's "Cynergy" racing across Kansas.

Cal Poly Pomona reached the finish line in Aurora first, about a minute and a half ahead of MIT, at 2:13 p.m. They ran a flawless day, but had drained their batteries very low. As the clouds thickened and it began raining about 4:30 p.m., the team wondered if they had miscalculated and not left enough battery reserve to finish the last 51 miles to Golden on the next day. Their attitude remained optimistic, as most believed there would be some sun on the last day.

Only the top-10 leaders were able to reach the finish before the rain began. Everyone else got caught in the approaching storm and had to trailer to the finish. The University of Mexico stayed at St. Francis after the scheduled start to recharge their batteries, which they had drained the previous day to complete the leg. They ended up driving about 87 miles before trailering to Aurora.

South Dakota's Solar Rolar left St. Francis at 10:11 a.m. and made the pit stop at 1:15 p.m. By mid-afternoon, it had reached the toughest stretch of the 10-day, 1,246-mile race: a series of long hills, including one three-quarter-mile, 8-percent grade. The car's speed slowed to 15 mph, then to 10 mph. About that time, trucks pulling three modular homes came up behind the Solar Rolar. Team members agreed that three houses made a neighborhood, and it was time to pull over to let them by. You know you're traveling slowly when a house passes you. Someone commented over the team's radio "there goes the neighborhood" as they passed by.

At 4:21 p.m., 30 miles from the finish line, South Dakota's team leaders called it quits. The car had been creeping along at 2 mph for some time. Crew members loaded the car and hauled it the rest of the way into Aurora, right into a torrential downpour!

When the South Dakota team pulled into the Hinkley High School parking lot, they found all the teams huddled with their cars under the stadium bleachers. It was pouring very hard by then, and the bleachers provided some protection. The teams stayed there for several hours until it stopped raining about 8:00 p.m. Some teams moved their cars out to try and get a little more charge, but by then the sun was setting over the mountains and there was nothing to be gained.

The rain really put a damper on what would have been a festive evening. Everyone was wet and cold. As soon as the cars were impounded, most left to find a warm place to sleep for the night. The weather reports were saying there was a chance for rain again, but no one believed it could get any worse.

4.11 Day Nine

It isn't over until it's over. That's an old cliché that rang true on the morning of the last day. Teams that thought their position in the standings was secure because the last day was so short were very nervous. Rain and dense fog greeted the racers on Thursday morning. The clouds were so thick no one could get any power from their solar arrays. The last leg to the finish line at the National Renewable Energy Laboratory in Golden would have to be driven entirely on what the cars had left in their batteries. Those who hadn't left any reserve were in serious trouble.

MIT held a 47-minute lead over Minnesota, which seemed like a comfortable margin, but the team wasn't sure they could drive the 52 miles on what was left in their battery. MIT started driving conservatively about 15-20 mph. Of the leaders, Cal Poly Pomona felt the most secure about how much battery reserve they had left. They were only 47 minutes behind Minnesota in third and wanted to make a run for it. Pomona's Intrepid Too started in hopes of moving into second place, maybe even first, depending on what happened to MIT. About half way to the finish line, the Intrepid Too came to a crawl as it started to climb a long hill. MIT passed them, and then Minnesota, and the team started to wonder if they would be able to hold onto third place.

The rain and fog made visibility poor. MIT, which hadn't had a breakdown the whole way, was moving along steadily. Suddenly, the Manta lost power. Water had gotten into the controller and created a short. The team started to make repairs, which wasn't easy in the rain along the side of a busy highway. While they were working, Minnesota's Aurora II drove by. The team kept working nervously, knowing their lead was slipping away. Twenty minutes went by before they had a new controller installed and power restored. They quickly buttoned up the car and got under way. By this time, Goro Tamai was wet and shivering. The temperature was about 50 degrees, the coldest day in June in history! As they crept along at 10 mph, no one could believe what was happening.

At the finish line, a large crowd was braving the rain and cold to watch the end of the race. Kauai Community College was the first across the finish line at 11:45 a.m., but they had installed a new set of batteries. The penalty for changing batteries on the last day was five and a half hours, which dropped them officially to 17th for the day. Kauai ended up 15th overall, which was terrific considering all their difficulties. Seven other teams swapped batteries on the last day, including the University of Illinois and the University of Oklahoma, who crossed the line shortly after noon.

The first team to reach the finish under their own power without changing batteries was the University of Minnesota at 12:45 p.m. The team was jubilant, knowing they had clinched second place overall. Now the waiting game started. They had begun the day 47 minutes behind MIT. When Minnesota passed MIT's broken-down Manta on the side of the road several miles back, no one knew how severe their problem was. Fifteen, 20 minutes went by, and still there was no sign of MIT. Finally—at 1:12 p.m.—the gallant MIT team crossed the finish line to win Sunrayce 95. They had beaten Minnesota by 19 minutes.

4.12 Daily Summary

The Massachusetts Institute of Technology team never won a daily finish, but they won the race because of their consistent performance every day. Table 4.12.1 shows the daily finish order—but it is the total elapsed time that determines the overall winner. The team's daily finish is determined by the team's daily driving time plus any time penalties.

Table 4.12.2 shows the teams' overall finish order at the end of each day. By Day 3, Massachusetts Institute of Technology took over first place and never relinquished the lead.

4.13 Final Results

Table 4.13.1 shows the final results of Sunrayce 95. Any time penalties are included in the elapsed time and are reflected in the average speed. The significant range of average speed is generally attributed to the variation in efficiency and reliability of the solar cars.

4.14 Awards

Special awards and recognitions were made at the Kick-off Banquet on June 19, during the race, and at the Victory Banquet on June 30, 1995. Table 4.14.1 lists these awards.

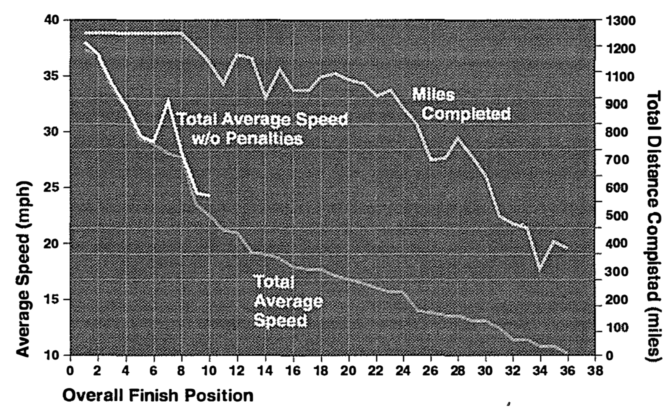


Figure 4.13.1 Eight cars officially completed all of the mileage.

Table 4.12.1. Teams' Daily Finish Order and Overall Finish, Listed by Overall Finish.

Car #	Team	Day # Finishes versus Overall Finish 1	2	3	4	5	6	7	8	9	F
17	Massachusetts Institute of Technology	2	2	2	2	3	2	2	2	3	1
35	University of Minnesota	5	4	1	1	5	3	1	3	2	2
25	California Polytechnic University, Pomona	1	1	3	3	4	4	3	1	7	3
7	George Washington University	17	5	4	5	1	1	6	8	9	4
16	Stanford University	9	9	16	12	8	5	4	5	4	5
100	Queens University	6	6	6	6	9	9	5	4	12	6
28	Northern Essex Community College	8	3	5	4	2	14	8	6	23	7
95	Western Michigan University	23	7	7	7	6	8	7	7	8	8
3	Mankato and Winona State Universities	4	15	8	9	17	7	9	10	15	9
43	University of Missouri, Columbia	3	8	11	8	10	13	16	30	1	10
2	University of Maryland	12	20	14	11	11	10	13	32	28	11
76	Drexel University	10	10	9	10	12	18	14	12	19	12
500	University of Puerto Rico, Mayaguez	20	21	12	13	13	17	18	17	26	13
74	Rose-Hulman Institute of Technology	14	14	10	17	23	16	17	31	18	14
8	Kauai Community College	33	19	26	31	7	12	10	9	17	15
777	South Dakota School of Mines & Technology	11	16	13	15	14	35	12	14	30	16
371	Purdue University	7	11	17	14	20	20	25	27	14	17
4	Clarkson University	16	13	18	19	19	19	19	25	10	18
9	Iowa State University	15	12	15	16	18	15	21	20	36	19
24	University of Waterloo	19	24	21	24	16	21	24	18	12	20
96	University of Western Ontario	18	18	22	18	21	22	23	23	6	21
77	Messiah College	21	23	24	23	22	30	15	16	21	22
31	University of Oklahoma	38	17	20	21	15	27	11	13	22	23
406	Montana State University	26	28	19	28	33	6	20	19	34	24
22	University of Illinois	13	25	33	22	33	11	26	15	20	25
27	United States Military Academy	30	26	34	25	25	26	30	21	5	26
12	Texas A&M University	27	27	28	26	29	23	31	26	27	27
90	Mercer University	29	22	23	20	27	34	28	24	35	28
109	Universidad Nacional Autonoma de Mexico	28	33	31	27	24	28	22	28	32	29
42	University of Missouri, Rolla	24	31	28	29	32	25	27	22	25	30
92	Columbus State Community College	32	34	27	33	28	32	36	33	16	31
195	California State University, Long Beach	35	36	25	35	31	31	34	29	29	32
33	Ohio State University	22	29	37	38	33	35	33	11	33	33
67	University of Pennsylvania	31	35	37	32	26	37	29	36	31	34
6	Virginia Polytechnic Institute & State University	36	37	28	30	33	29	31	34	11	35
619	Prairie View A&M University	34	38	31	34	30	33	35	35	24	36
101	University of Quebec	37	32	36	37	37	24	*	*	*	*
1	University of Michigan	25	30	35	36	*	*	*	*	*	*

Table 4.12.2. Teams' Starting Order and Overall Finish After Each Day.

		Starting Lineup and Overall Finish After Day #									
Car #	**Team**	**S**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
17	Massachusetts Institute of Technology	2	2	2	1	1	1	1	1	1	1
35	University of Minnesota	5	5	4	3	2	4	3	2	2	2
25	California Polytechnic University, Pomona	1	1	1	2	3	3	4	4	3	3
7	George Washington University	28	17	6	6	5	2	2	3	4	4
16	Stanford University	24	9	8	12	11	8	8	8	8	5
100	Queens University	3	6	5	5	6	6	6	6	5	6
28	Northern Essex Community College	23	8	3	4	4	5	5	5	6	7
95	Western Michigan University	9	23	14	8	8	7	7	7	7	8
3	Mankato and Winona State Universities	16	4	11	7	7	11	9	9	9	9
43	University of Missouri, Columbia	15	3	7	10	10	9	10	10	11	10
2	University of Maryland	4	12	17	16	12	12	11	11	12	11
76	Drexel University	8	10	10	9	9	10	12	12	10	12
500	University of Puerto Rico, Mayaguez	20	20	19	18	17	14	13	13	13	13
74	Rose-Hulman Institute of Technology	17	14	15	11	15	17	16	15	18	14
8	Kauai Community College	27	33	24	24	27	22	21	19	14	15
777	South Dakota School of Mines & Technology	10	11	13	14	14	13	18	18	16	16
371	Purdue University	6	7	9	13	13	15	15	16	17	17
4	Clarkson University	31	16	16	17	18	18	17	17	19	18
9	Iowa State University	18	15	12	15	16	16	14	14	15	19
24	University of Waterloo	12	19	21	20	20	20	20	21	21	20
96	University of Western Ontario	13	18	18	19	19	19	19	20	20	21
77	Messiah College	32	21	20	21	22	21	23	23	22	22
31	University of Oklahoma	11	38	33	26	24	24	25	24	24	23
406	Montana State University	21	26	26	22	23	25	22	22	23	24
22	University of Illinois	7	13	22	27	26	27	24	25	25	25
27	United States Military Academy	30	30	28	29	28	28	28	29	29	26
12	Texas A&M University	14	27	27	25	25	26	27	27	27	27
90	Mercer University	36	29	23	23	21	23	26	26	26	28
109	Universidad Nacional Autonoma de Mexico	33	28	31	30	30	29	30	28	28	29
42	University of Missouri, Rolla	38	24	30	28	29	30	29	30	30	30
92	Columbus State Community College	19	32	32	32	31	31	31	31	32	31
195	California State University, Long Beach	37	35	36	34	34	34	33	34	33	32
33	Ohio State University	25	22	25	31	32	32	32	32	31	33
67	University of Pennsylvania	35	31	34	35	35	33	34	33	34	34
6	Virginia Polytechnic Institute & State University	29	36	37	37	36	35	35	35	35	35
619	Prairie View A&M University	26	34	38	38	38	36	36	36	36	36
101	University of Quebec	22	37	35	36	37	37	*	*	*	*
1	University of Michigan	34	25	29	33	33	*	*	*	*	*

Table 4.13.1 Final Results of Sunrayce 95.

Finish Place	Car #	Team	Elapsed Time (HH:MM:SS)	Ave. Speed (mph)
1	17	Massachusetts Institute of Technology	33:37:11	37.23
2	35	University of Minnesota	33:56:00	36.88
3	25	California State Polytechnic University, Pomona	37:03:43	33.77
4	7	George Washington University	38:55:29	32.15
5	16	Stanford University	42:47:12	29.25
6	100	Queens University	43:23:25	28.84
7	28	Northern Essex Community College	44:39:42	28.02
8	95	Western Michigan University	45:17:49	27.63
9	3	Mankato and Winona State Universities	53:29:33	23.40
10	43	University of Missouri, Columbia	55:47:05	22.44
11	2	University of Maryland	59:11:47	21.14
12	76	Drexel University	59:34:22	21.01
13	500	University of Puerto Rico, Mayaguez	65:27:22	19.12
14	74	Rose-Hulman Institute of Technology	65:50:24	19.01
15	8	Kauai Community College	66:54:00	18.71
16	777	South Dakota School of Mines & Technology	69:53:18	17.91
17	371	Purdue University	70:19:28	17.80
18	4	Clarkson University	70:45:04	17.69
19	9	Iowa State University	73:02:53	17.13
20	24	University of Waterloo	74:16:04	16.85
21	96	University of Western Ontario	75:37:03	16.55
22	77	Messiah College	77:51:10	16.08
23	31	University of Oklahoma	79:20:42	15.77
24	406	Montana State University	79:50:41	15.67
25	22	University of Illinois	89:38:00	13.96
26	27	United States Military Academy	90:42:11	13.80
27	12	Texas A&M University	91:36:38	13.66
28	90	Mercer University	91:43:20	13.65
29	109	Universidad Nacional Autonoma de Mexico	95:09:00	13.15
30	42	University of Missouri, Rolla	95:09:58	13.15
31	92	Columbus State Community College	99:59:25	12.52
32	195	California State University, Long Beach	107:20:06	11.66
33	33	Ohio State University	108:28:45	11.54
34	67	University of Pennsylvania	114:32:42	10.93
35	6	Virginia Polytechnic Institute & State University	115:02:06	10.88
36	619	Prairie View A&M University	121:34:58	10.29

Note: University of Quebec withdrew from competition after Day 6.

Note: University of Michigan withdrew from competition after Day 4.

Table. 4.14.1. Sunrayce 95 Awards

Overall Finish:
1st: Massachusetts Institute of Technology
2nd: University of Minnesota
3rd: California State Polytechnic University, Pomona

Max J. King Award:
Universidad Nacional Autonoma de Mexico

Stars of Sunrayce:
Male: Jeff Etringer, Iowa State University
Female: Kate von Reis, Stanford University

Sportsmanship:
1st: Kauai Community College
2nd: Prairie View A&M University
3rd: University of Western Ontario

Teamwork:
1st: Texas A&M University
2nd: Messiah College
3rd: Queens University

Cost Effectiveness:
Northern Essex Community College

Technical Innovation:
Solar Array: Messiah College
Chassis/Suspension: California State Polytechnic University, Pomona
Propulsion/Electronics: George Washington University

ALEM Safety Award:
Western Michigan University

Sprint Rally:
Mankato and Winona State Universities
Principia College

Top Qualifier:
1st: California State Polytechnic University, Pomona
2nd: Massachusetts Institute of Technology
3rd: Queens University

Artistic Design:
1st: George Washington University
2nd: Clarkson University
3rd: University of Oklahoma

Delphi Best Battery:
University of Waterloo

DuPont Best Use of Composites:
Universidad Nacional Autonoma de Mexico

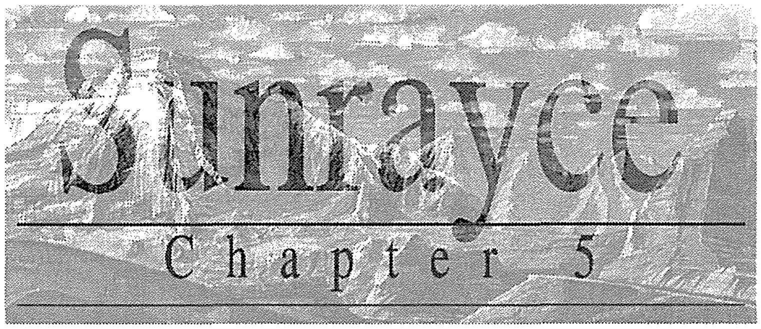
Best Video:
1st: Columbus State Community College
2nd: Kauai Community College
3rd: Principia College

Table 4.14.2. Daily Awards

Day	Teamwork	Sportsmanship
1	University of Oklahoma	U.S. Military Academy
2	Western Michigan University	Rose-Hulman Institute of Technology
3	Kauai Community College	University of Pennsylvania
4	Mankato/Winona State University	California State Polytechnic University, Pomona
5	Purdue University	University of Minnesota
6	Stanford University	Queens University
7	Prairie View A&M University	Montana State University
8	Everyone	George Washington University
9	Columbus State Community College	University of Missouri, Rolla

Table 4.14.3. EDS Awards

Best Use of Aerodynamics in Design	University of Minnesota
First to Start Area on Day 1	University of Oklahoma
Overcame Most to Qualify	University of Missouri, Rolla
Overall Spirit as Team	Western Michigan University
Royal Effort to Keep Vehicle in Rayce	Prairie View A&M University
Best Effort Helping Another Team	University of Maryland
Most Improved Over Period of Rayce	Kauai Community College
Team Working Together After Accident	California State Polytechnic University, Pomona
Treated Observers Best During Rayce	California State University, Long Beach
Best Use of All Technologies	South Dakota School of Mines & Technology



The Teams and Their Solar Cars

5.1: The Pre-Race Favorites

There was no secret as to which teams were expected to dominate Sunrayce 95. The top-3 pre-race favorites were: University of Michigan, Cal Poly Pomona, and George Washington University, because they had finished first, second, and fourth, respectively, in Sunrayce 93. California State University at Los Angeles finished 3rd in Sunrayce 93, but did not race in Sunrayce 95.

After two Sunrayces, Michigan was the only team to have any wins under their belt. The Michigan team was known not only for building reliable and fast solar cars, but for their top-notch team organization skills and their very successful fundraising abilities. Also, with a World Wide Web page designed to scare off the likes of Honda and Biel, and rumors circulating that they had a helicopter as their scout vehicle, many teams had given up all hope of beating the two-time national champions.

Cal Poly Pomona also has a strong solar-powered resume. Cal Poly Pomona placed 2nd in Sunrayce 93 and went on to be the top-finishing American team at the 1993 World Solar Challenge. The Intrepid Too Team, however, suffered a testing accident just 3 weeks before the qualifiers. This left the team rushing to rebuild a heavily damaged solar array and some vital mechanical components. Many were skeptical to whether Cal Poly Pomona would show up at all.

The George Washington University team had built a very fast car for Sunrayce 93. In the World Solar Challenge that year, they finished just behind American rival Cal Poly Pomona in ninth place. GWU's new car was rumored to be an improved version of the 1993 car, with the latest in solar-array fabrication techniques and maybe even an in-hub motor.

Other pre-race hopefuls were the teams from MIT, Stanford, University of Illinois, and Purdue. MIT had been out of Sunraycing since their sixth-place finish at GM Sunrayce USA in 1990. Several teams recalled MIT's 1990 performance in which a lack of spare parts most probably cost the team a spot in the top-3. Stanford had placed in the top-10 at both previous Sunrayces. Purdue University, was returning to Sunrayce 95 with a vengeance having not qualified their 1993 car due to vehicle instabilities. Finally, the University of Illinois was completely new to Sunrayce, but because of their fine reputation as an engineering school, they were expected to run well.

Another team that many competitors had their eyes on was the University of Maryland because of their long successful experience in solar racing and the fact that they were bringing back their 1993 car—thoroughly tested and developed. Yet another team that piqued the interest of competitors was Ohio State because of their historical rivalry with the University of Michigan Wolverines. Rumors abounded that Ohio State's mission was simple: beat Michigan.

Figure 5.1.1: University of Maryland team co-captain Melissa Judd gets ready for the big start at Indianapolis Monument Circle.

5.2: The Sunrayce Learning Curve

Does it help to come from a previously successful Sunrayce team? How well do Sunrayce teams transfer knowledge? After three generations of Sunrayce, we can now start answering those questions by observing trends of how teams learn the art of Sunraycing and improve their status in the Sunrayce hierarchy.

Figure 5.2.2 shows the Sunrayce overall finish position history of all the Sunrayce 95 teams. Clearly, prior Sunrayce experience helps a team race more successfully. Notice that all of the top-15 finishers were participants in Sunrayce 93, or had members with Sunrayce experience. Of the bottom-18 finishers, only a third had had any Sunrayce experience.

Figure 5.2.1: The SolarRolar from the South Dakota School of Mines & Technology cruises across the finish line at the NREL in the pouring rain.

The rookie-of-Sunrayce 95 award goes to the team from the South Dakota School of Mines and Technology, who placed 16th out of the field of 38 teams. There is one team that finished higher than SDSM&T that could be classified as a rookie team: Northern Essex Community College. However, NECC team co-captain Olaf Bleck was co-captain of the 1990 MIT team, and the other NECC co-captain, James Nelson, was the captain of the Sunrayce 93 eighth-place finishing University of Massachusetts-Lowell team. Needless to say, this was no rookie team.

There were only two teams at Sunrayce 95 that were absent from Sunrayce 93, but present at the 1990 GM Sunrayce USA: MIT and University of Pennsylvania. It is easy to assume that all the members of 1995 MIT and UPenn teams were new to Sunrayce and to classify these teams as rookies. But, because having faculty or upperclassmen with Sunrayce experience—or even an old solar car on campus—is a great advantage, these two teams were not considered to be rookies. In MIT's case, the only person with Sunrayce experience left on the team was their chief engineer, Goro Tamai, who was a freshman on the 1990 MIT Galaxy team.

This brings us to another interesting topic. Over half of the top-10 teams in Sunrayce 95 were either led or advised by students (mostly graduate students) who were at one or more Sunrayces. For example, second-place University of Minnesota's co-advisor, Scott Grabow, was a member on the 1990 Mankato team and has been active at Minnesota for the past two Sunrayces.

The third-place Cal Poly Pomona team was loaded with Sunrayce 93 veterans and even a few from the 1990 event, including co-advisor Tina Shelton. Fourth-place George Washington University also had many Sunrayce 93 veterans, including team captain Cory Knudtson and co-advisors Joel Jermakian and Robert Piacesi, who were also members of the 1990 University of Maryland team. Finally, fifth-place Stanford University's team captain Kate Von Reis and chief engineer Chris Shaw both raced Stanford's Sunrayce 93 solar car.

The most improved team of 1995 is no secret; the University of Minnesota finished a midpack 21st place in Sunrayce 1993, but stormed back in Sunrayce 95 with a stunning second-place finish. The Aurora II was truly a 2-year project. The team started designing their car during the 1993 race, studying the competition's solar cars and noting improvements that would lead to a faster car.

Other notable teams on a steep learning curve include Queens University, Western Michigan University, Mankato and Winona State Universities, and University of Missouri-Columbia. All four of these teams moved into the top-10 from their mid- to upper-teens finishes in 1993. The Queens team from Canada beat out all seeded teams on the first day of qualifying at IRP and started Sunrayce 95 third on the grid. The Queens Quest finished every day except the last and hung on to finish the race just 36 minutes behind Stanford in sixth place, barely missing a place in the top-5.

Western Michigan University finished comfortably in eighth place with more than an 8-hour margin over ninth-place Mankato/Winona State. The WMU team gained attention during the race for being the fastest wide-track four-wheeled solar car and for having three female drivers.

The light-weight Mankato and Winona State Universities car finally unhooked itself from the 16th-place Sunrayce finish by cruising into the ninth-place spot. As discussed in Section 6.4, the Mankato and Winona team successfully gambled on battery capacity, carrying only 77 kg of batteries, to keep vehicle weight and loads to a minimum.

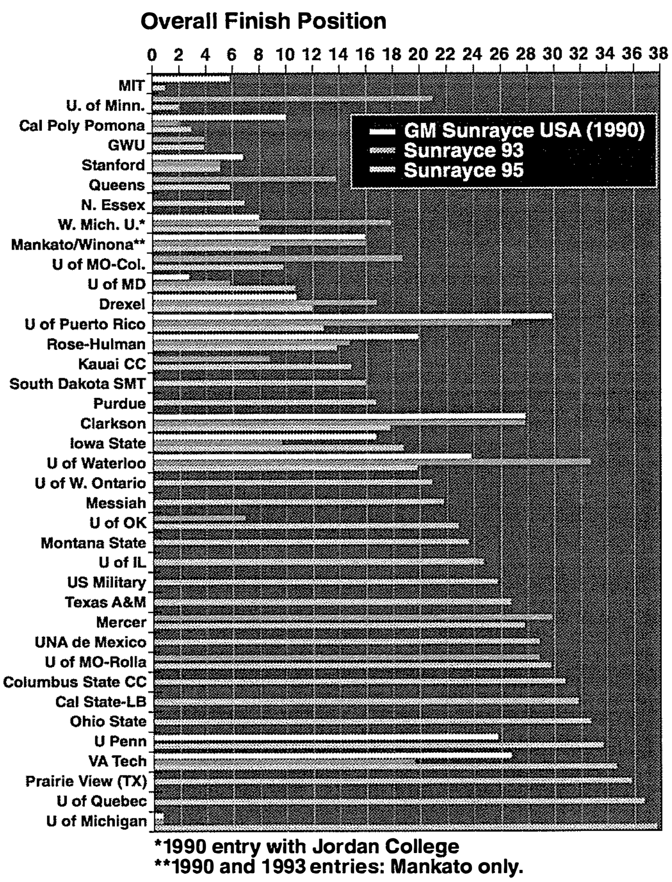


Figure 5.2.2: Overall finish position history of all Sunrayce 95 teams from the 1990 GM Sunrayce USA to Sunrayce 95.

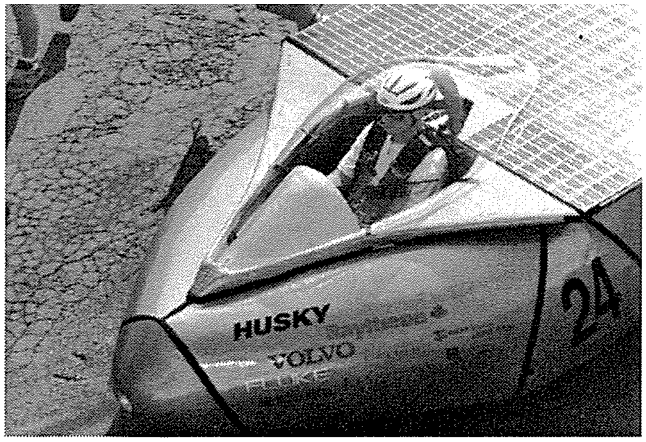


Figure 5.2.3: A bird's eye view of the University of Waterloo's Midnight Sun III.

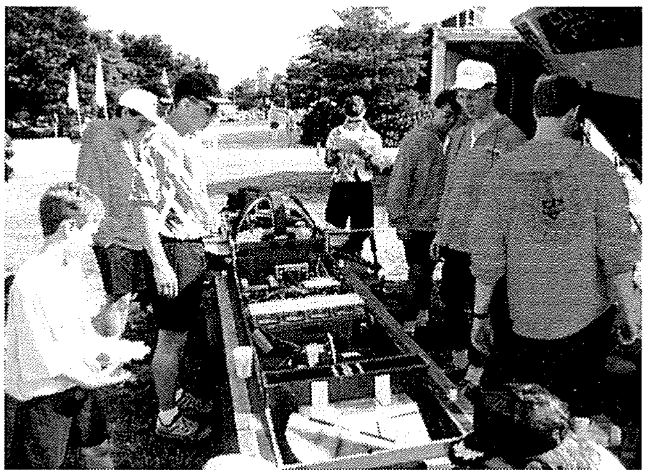


Figure 5.2.4: Members of the Rose-Hulman team inspect their composite-beam-framed car during charging hours.

The Sun Tiger II team from University of Missouri-Columbia returned to Sunrayce 95 with a new car after finishing in 19th place in the previous race. UMO-Columbia finished an impressive third on Day 1 and briefly fell out of the top-10 in the overall standings on Day 8. By outrunning all others on the final day, the Sun Tiger II secured the last of the coveted top-10 spots in Sunrayce 95.

Other teams that also deserve mention in this section for continuously improving their finish positions over the three Sunrayces, or improving dramatically since Sunrayce 93, include: Rose-Hulman Institute of Technology, University of Puerto Rico, Clarkson University, and the University of Waterloo. The Rose-Hulman Institute of Technology, the host of the first overnight stop of Sunrayce 95, has been steadily improving their finish position over the past three Sunrayces. They started in 1990 with a 20th place finish. Then, in 1993, with a modified version of their 1990 car, they finished a respectable 15th. In Sunrayce 95, the team in red improved their position another notch to 14th place with an entirely new car—the Solar Phantom III. This car was one of several cars that featured two rear wheels mounted close together for added safety while still maintaining the mechanical simplicity of a three wheeler.

The University of Puerto Rico's Shining Star II finished 13th with a body style similar to that of the 1993 Cal State LA car. The Shining Star II had an aluminum space frame, their trademark Soloflex exercise straps for suspension springs, and side-mounted solar panels for the cloudy days. Apart from the University of Minnesota, Puerto Rico made the biggest leap in finishing order since 1993—fourteen places.

Clarkson finished in the top half of the field at 18th with their new solar car, the Helios. The Helios' sleek body and fine craftsmanship netted them second-place honors in the "Artistic Design" contest. The Helios had a full composite structure, complete with full wheel skirts, custom machined aluminum mag wheels, and a multi-mirror rear-view mirror system where the line-of-sight exited from the bottom of the wheel skirt. The Helios was one of very few cars in Sunrayce 95 to be tested full-scale in a wind tunnel. The final drag area (CdA) was a respectable 0.139 m^2 (Section

University of Waterloo bounced back in Sunrayce 95 with a 20th place finish with the Midnight Sun III. According to Waterloo advisor Professor Gordon Savage, the design philosophy was to concentrate on function before form and be reliable. They also designed their solar car so that all the construction was within the capabilities of the students. The 1995 team was a group completely new to Sunrayce. In addition, the students were able to work on the project for only 4 months at a time due to the cooperative study/work program instituted at their university. To combat this potentially disarraying structure, the team established a small group to maintain communication among team members on and off campus. To help with fundraising and project promotion, an advisor board was formed that comprised team and university alumni as well as corporate sponsors. Along with their help, the Waterloo team managed to triple their cash income over their previous effort. Unfortunately, the Midnight Sun III did not get as many test miles as they had hoped: 150 test miles on the bare chassis and much fewer on the completed car.

5.3: The Front Pack

1st Place: Massachusetts Institute of Technology's Manta

How does a team that has not seen a Sunrayce since the 1990 GM Sunrayce USA win Sunrayce 95? Just make sure you never have to stop for repairs. In fact, the MIT Manta team almost accomplished the no-stop Sunrayce, making their first and only unscheduled pit stop about 30 miles from the finish line when rain seeped into their

Figure 5.3.1: The MIT Manta races across the finish line at the National Renewable Energy Laboratory, clinching the Sunrayce 95 championship.

motor controller (Section 6.9). Vehicle reliability was the number-one goal of Project Manta—for with reliability secured, safety and speed would surely follow. Though the Manta never officially finished a single day in first place, it won the race, which is based on the lowest cumulative time.

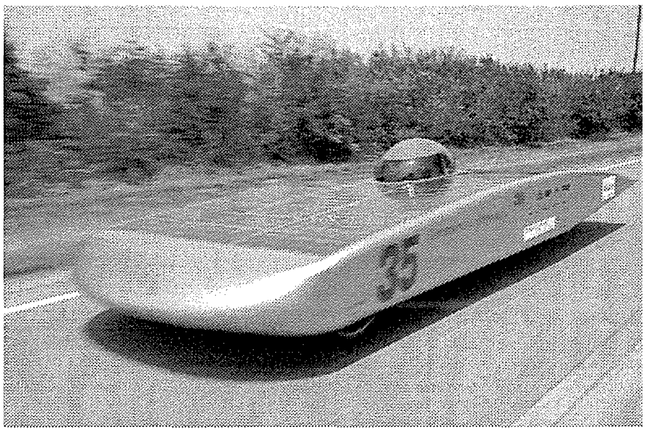


Figure 5.3.2: University of Minnesota's Aurora II on the road in Sunrayce 95.

Aside from reliability, other design features that gave the Manta an edge over the competition include its light weight of 370 kg (814 lbs) including driver and a dynamically fine-tuned chassis shod with Michelin's ultra-low rolling resistance tires. Rolling losses were further cut by spinning the wheels on Champion Teflon-sealed, solid-film lubricant ball bearings. Manta's solar array generated 850 watts on the road and almost 1300 watts during charging. This array, combined with a highly adjustable charging rig, channeled the sun's energy efficiently enough to top off the battery pack for the start of all but 3 days of the race. Manta's unique streamlined body shape, which had a low drag area (CdA) estimated at 0.134 m^2 (Section 6.5), probably had the highest solar-array-area vs. aerodynamic-drag ratio of any car in the race.

Manta's simplicity led to predictability in performance. The backbone of the car was a tubular steel frame with steel and aluminum suspension parts. The wheels were machined out of a solid billet of magnesium guaranteeing a solid, dependable ride. The array was made up of a string of carefully selected ASE Americas solar cells, straight out of the box. The drive system was a Solectria BRLS8 motor and matching controller used previously on another MIT project. The Manta body shell was a carbon-fiber and honeycomb composite structure ribbed in a closed-cell structure for maximum rigidity to prevent solar-array flex. The energy bank of the Manta was a set of nine pre-conditioned Trojan batteries that tipped the scales at just 1 kg shy of the maximum allowed 140 kg. MIT's Solectria motor was wound for 108 volts, leaving the team with a limited pack voltage range from which to choose. After extensive battery testing, MIT chose a Trojan 108-volt pack.

2nd Place: University of Minnesota's Aurora II

The team from University of Minnesota started designing its car during Sunrayce 93. With a very organized team of experienced Sunraycers and a beautifully fabricated car, Minnesota came within 19 minutes of winning the Sunrayce 95 crown. On Day 7, cruising through Kansas from Smith Center to Oberlin under sunny skies, the Aurora II shattered the Sunrayce single-day average-speed record by eclipsing the 50 mph barrier. The Minnesota team constructed a very reliable car, making only two unscheduled stops to replace flat tires.

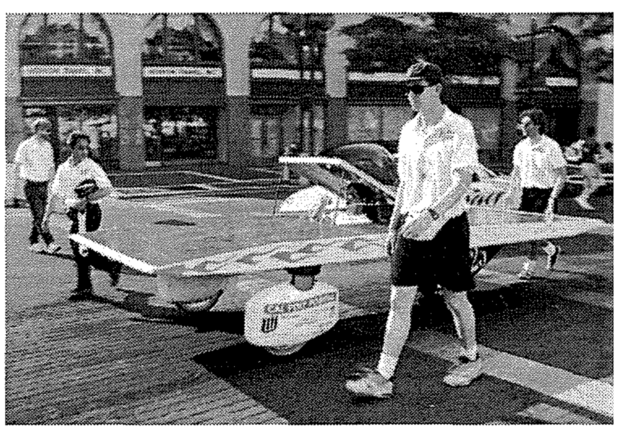


Figure 5.3.3: The Intrepid Too and Cal Poly Pomona team members ready themselves as pole sitters of the largest solar-car race ever held in North America.

The Aurora II had a unique composite flat panel chassis, reminiscent of vintage wooden-framed sports cars. Flat pre-fabricated fiberglass/Nomex panels, typically used in industry for aircraft and boats, were bonded together into a box-frame structure, neatly housing the driver, batteries, and the electronic components. According to co-advisor Scott Grabow, the primary concern of the team was safety, followed by reliability and weight reduction. To address these issues, the batteries were located in front of the driver to prevent the ramrod effect in event of a frontal collision. Also, the center-of-gravity of the vehicle was placed as close as possible to the driver position, and careful attention was paid to distribute the car's weight equally among the three tires. The team thoroughly bench-tested all components, practiced the dynamic scrutineering events, and even practiced caravan driving.

The body shape of the Aurora II is based on that of the Sunrayce 93 third-place finisher Cal State LA. The basic shape is a simple two-dimensional airfoil with a rounded leading edge. The driver was seated along the centerline of the vehicle, and a Plexiglas bubble canopy was located midway along the length of the vehicle. The team took great care in sculpting and polishing Aurora II's nose and even opted to keep decals off it. The team from the University of Minnesota was rewarded for their body design by winning the EDS "Best Use of Aerodynamics in Design" award.

3rd Place: California State Polytechnic University-Pomona's Intrepid Too

Despite a testing accident just weeks earlier, Intrepid Too arrived at IRP looking and hustling like new, winning the pole position by completing a whopping 117 laps around the IRP road course. The Intrepid Too, as the name suggests, is an improved version of their 1993 Intrepid. The new model resembles a flat three-legged table with a large tinted bubble in the middle of the solar array.

Some highlights of the Intrepid Too include an impressive aerodynamic drag area of 0.13 m^2 (estimated from power consumption data), a 90+ percent efficient custom-made Hathaway hub motor, and a meticulously constructed solar

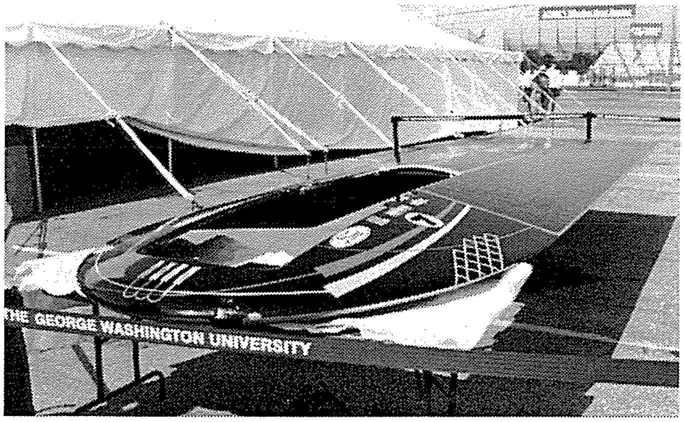


Figure 5.3.4: It is no surprise that the GW won the "Artistic Design" award.

array. The Intrepid Too, like several other cars at the race, had two rear wheels placed close together inside a single fairing. The rear wheels were directly mounted on either side of the double-shafted Hathaway hub motor, with the motor housing fixed to the rear suspension. To alter the "gear ratio" of the drive system, the team had a supply of three different-size wheel/tire combinations. To compensate for the change in the body's angle of attack, the rear suspension had a clever linkage that allowed the rear end to be lowered or raised. Intrepid Too's front suspension featured a telescoping motorcycle shock assembly that can virtually eliminate energy-robbing lateral scrub and bumpsteer. The Cal Poly Pomona team was awarded the Sunrayce "Chassis/Suspension Technical Innovation" award for their sophisticated suspension design and rugged composite work. The Cal Poly Pomona car had six flat tires and a few electrical glitches including an overheating motor controller; the car didn't have regenerative brakes.

Pomona led the first 2 days of Sunrayce 95 and dipped down to fourth place on Days 6 and 7. By rebounding with a strong first-place finish on Day 8, the Intrepid Too moved up a notch into third place. Interestingly, for the third Sunrayce in a row, the top qualifier has finished the Rayce in third place.

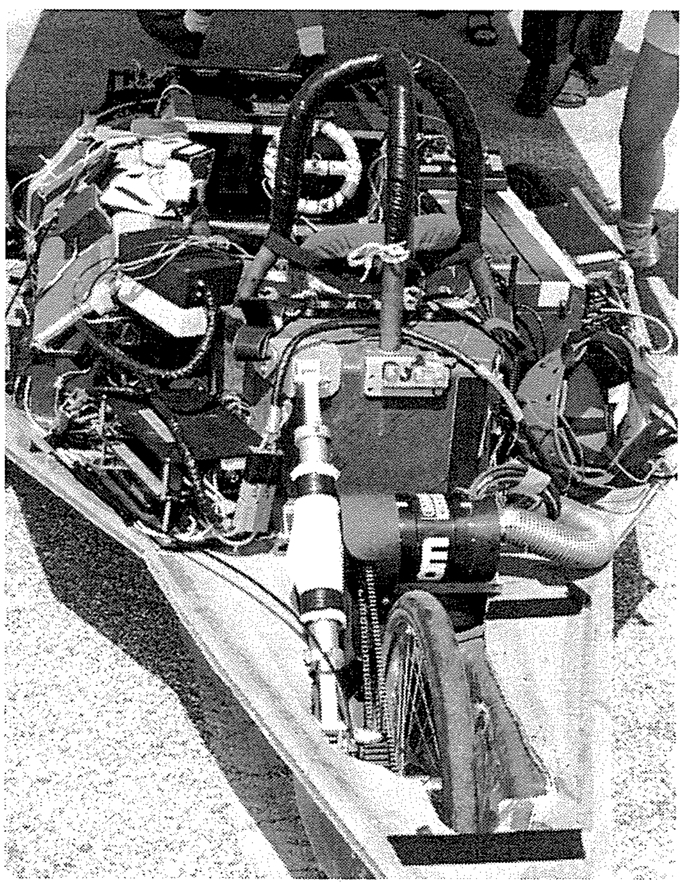


Figure 5.3.5: Rear view of Stanford's chassis. The Unique motor was later replaced by a Solectria BRLS8 loaned from Cal-Berkeley. Note the double-ended Risse airshock and the tiny 1/4" pitch chain.

4th Place: George Washington University's GW

The team from George Washington University was another big pre-race favorite, best known for squeezing their drivers into the absolutely thinnest profiled cars in the solar racing. Possibly the only car in solar racing history to be thinner was the Florida Institute of Technology entry from the 1990 GM Sunrayce USA.

The GW was a second-generation version of their successful fourth-place entry from Sunrayce 93. This group of veterans prepared a car loaded with all the latest technology, including an axial-flux (as opposed to the conventional radial-flux) hub motor, which allowed the team to tailor the motor's torque curve by varying the air gap between the motor's rotor and stator. The GW rolled on a set of Bridgestone Ecopia solar car tires pumped up to 130 psi, mounted on GH Craft carbon-fiber disk wheels. The rolling resistance coefficient (Crr) at this inflation pressure was estimated at an impressive 0.0045. The composite tub was finely crafted, as were the precision-machined suspension pieces. Though the GW won the "Artistic Design" and "Propulsion/Electronics Technical Innovation" awards, it was not without problems. First, the solar array produced only about half the intended power. The problem was that the silver-based conductive epoxy used to string the laser-cut ASE Americas solar cells into a tight shingled array reacted with the aluminum backing on the solar cells. This galvanic corrosion increased the resistance at the solar-cell junctions when the array was active, limiting the array power to under half the anticipated 1000 watts.

Other problems experienced by the team included motor glitches, drum brake dragging, and mechanical interference problems with the compact rotating front wheel fairings. The fairing difficulties left the GW occasionally running with sections of the fairing assembly missing. Had this team had an extra month to debug their components, many would agree that GW could have become Sunrayce 95 champions.

The GW team really showcased their creation on the two overcast days (Days 5 and 6), when everyone else's solar power decreased to GW's level. With a powertrain efficiency advantage of about 10 percentage points at typical operating conditions, and an ultra-low rolling resistance coefficient about two-thirds that of the competition, the GW was unbeatable on an even power playing-field. The GWU team plans to bring back the GW to Sunrayce 97, but without the bugs.

5th Place: Stanford University's Afterburner

Stanford has been racing Sunrayces since the inaugural race in 1990, placing in the top-10 in both previous Sunrayces (7th and 5th). The Stanford Afterburner's body shape borrows from the 1990 MIT Galaxy—a thin, central-canopy design that can successfully trade off solar power for reduced aerodynamic drag.

The battery pack of the Afterburner was a set of Electrosource Horizon batteries. Because the individual battery units were much larger than those used by other teams, the bus voltage was limited to only 60 volts. The spec sheets showed close to an extra kilowatt-hour of energy capacity (at the 3-hour discharge rate) over the battery packs used by most of the competition.

The Afterburner started the race slowly, plagued with solar-array maximum-power-point-tracker problems. However, once a Stanford solar-car team alumnus was called in to make a few adjustments, the Afterburner's array came to life and propelled Stanford to consistent top-5 finishes on the last 4 days of the race. A strong fourth-place showing on the final grueling day raised Stanford's overall position three places to an excellent fifth-place finish. Also, the Stanford team had excellent leadership qualities as evidenced by team captain Kate Von Reis. At the victory banquet, Von Reis was presented the "Stars of Sunrayce" award for the female who best exemplified the spirit of Sunrayce.

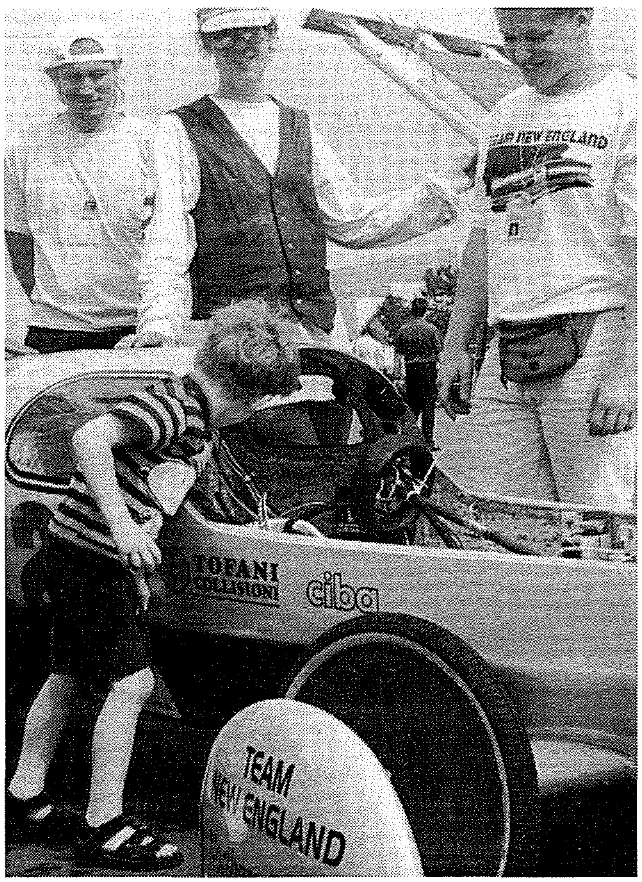


Figure 5.4.1: A curious youngster inspects the chassis of Northern Essex Community College's TNE-3 during evening charging. The TNE-3 was perhaps the highest composite-content car of the event, using carbon fiber, Kevlar, and fiberglass on almost everything—including their monocoque structure/body, the front suspension, the wheels, and even the steering "bagel."

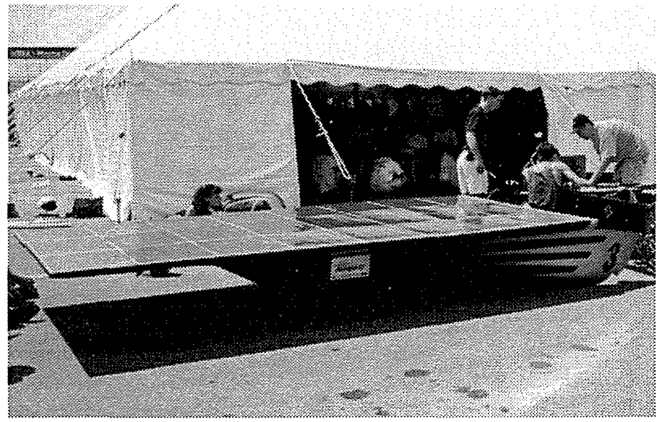


Figure 5.4.2: Mankato/Winona students work on the chassis (built by Winona) of the Northern Light III, as the body and array (both built by Mankato) soak up the sun.

5.4 Honorable Mentions

7th Place: Northern Essex Community College's (a.k.a. Team New England) TNE-3

The entry from NECC, dubbed TNE-3, was without a doubt the most unique "solar car" of Sunrayce 95. This innovative and controversial design had the solar array stored *inside* a streamlined bullet. The team traded on-road solar power for reduced aerodynamic drag (CdA of 0.07 m^2) and hoped to recharge in the afternoon sun. This sprint-and-charge tactic was first attempted by MIT in the 1991 Arizona Solar Electric 500, in which the MIT car ran head-to-head with the then-world-champion Biel team. The TNE-3 satisfied the solar-array visibility rules by housing the car's array storage area within a Plexiglas hood.

Some unique features of the TNE-3 include a true stressed-skin composite monocoque structure, a front suspension made up of a pair of downhill skis and home-made carbon fiber disk wheels (also see Section 6.6). The NECC team was unique also in that it included students from NECC, Boston College, University of Massachusetts at Lowell, Arizona State University, and University of Wisconsin.

Once on the road, the TNE-3 ran very fast, placing in the top-3 on numerous days. NECC's fall from the top-5 came when the weather did not cooperate for 2 days in a row. The ideal weather for NECC was dark overcast racing periods, sandwiched by sunny morning and afternoon charging periods. On Days 5 and 6, the other teams had been conservatively sipping in flashes of sun on the route. The TNE-3, however, blazed passed everyone only to find themselves stranded at the bottom of a hill, recharging. The main shortcoming of NECC's sprint-and-charge strategy was that once the race started, all the solar energy collected necessarily had to first be stored in the batteries. Thus, NECC was taxed by the batteries' round-trip energy loss on every precious watt-hour of solar energy collected. Also, when the TNE-3 had to stop on the route for a repair, they lost not only race time, but also critical charging time.

The NECC team was also awarded the "Cost Effectiveness" award, showcasing that a small community college with a measly $20,000 budget can run with the top teams of North America. Although rules have been changed to eliminate array reconfiguration, NECC plans to return to Sunrayce 97 with an entirely new tactic that promises to be just as controversial.

9th Place: Mankato/Winona State Universities' Northern Light III

The Northern Light III from Mankato/Winona State Universities was one of only two cars at Sunrayce 95 built by students from more than one institution—with NECC being the other. Mankato and Winona State Universities are located about 130 miles apart in southern Minnesota. This partnership of 25 Mankato and four Winona students formed the ninth-place-finishing Mankato/Winona State Universities' Northern Light III team.

Mankato, a veteran of Sunrayce 93, wanted to make more extensive use of composite materials in their Sunrayce 95 solar car. According to Mankato advisor Professor Bruce Jones, although the Mankato camp had considerable expertise in mechanical and electrical systems, they lacked the composite structures knowledge they felt they needed to be competitive. It just so happened that another state school about 2-hours drive away specialized in composites. The faculty and students from each institution first met in February of 1994. Over the following 17 months, the two schools conducted the

Figure 5.4.3: Aluminum space frame of the Solar Rolar from the South Dakota School of Mines and Technology. Notice the motorcycle-type front suspension, low battery placement, and the well-triangulated roll cage.

majority of their correspondence by multi-camera interactive-TV sessions held once a week, for 30 minutes at a time.

The Northern Light III had a composite beam frame to which all the suspension components and body shell attached. The project was divided such that the beam frame was constructed at Winona, and everything that interfaced it, including the external body shell, was constructed at Mankato. The incredible part about this venture was that students from the two schools were together in the same room a total of only five times prior to the race, and all the parts fabricated (even the composite ones) in the two locations actually fit together.

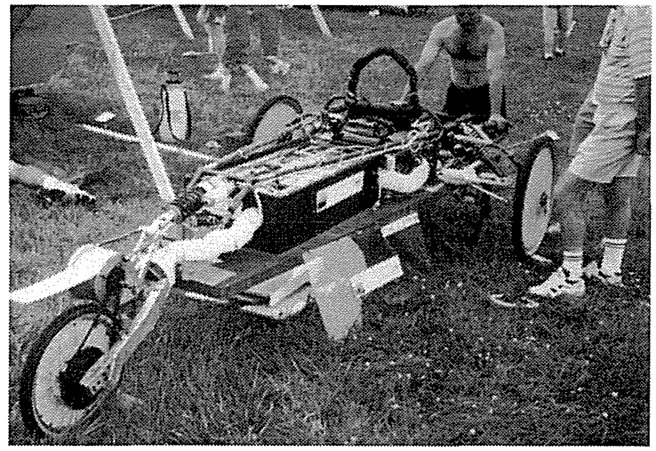


Figure 5.4.4: The hybrid composite-plank/steel-tube frame chassis of the Double Black Diamond from Montana State University.

The Northern Light III stood out in Sunrayce 95 as the only team to carry substantially less than the maximum-allowed battery weight. Because the Northern Light III carried only 77 kg of batteries, it was the 2nd lightest solar car in the race, tipping the scales at 349 kg (767 lbs). The rationale behind their choice of battery pack is discussed in Section 6.4.

16th Place: South Dakota School of Mines and Technology's Solar Rolar

The Solar Rolar from the SDSM&T was awarded the "Best Use of All Technology" award by EDS. In addition, team member Ragner Toennesson received a humanitarian award for going above and beyond the call of duty when the Iowa State solar car had an accident and needed assistance on the last day. The Solar Rolar team finished in 16th place, outpacing many teams with prior Sunrayce experience. This achievement makes SDSM&T the clear choice for "Rookie-of-Sunrayce 95" honors.

The Solar Rolar solar car had a catamaran-style (or inverted U) body, similar to the 1990 Crowder College entry. The driver was offset to the right side of the car to prevent canopy shading of the solar cells on the westerly route. To compensate for this weight bias, five of the eight batteries were positioned between the left wheels. A great advantage of the Solar Rolar's body design

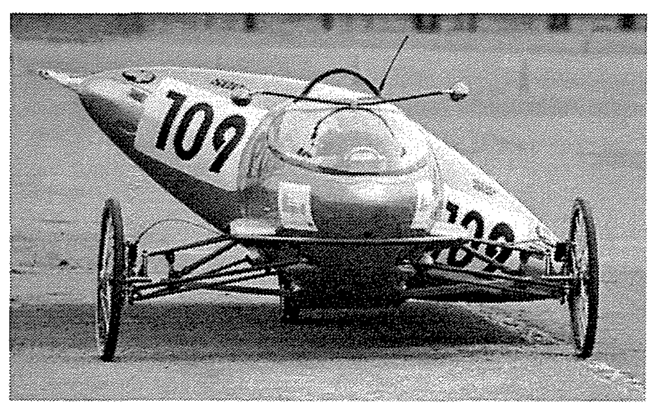


Figure 5.4.5: The Tonatiuh from Universidad Nacional Autonoma de Mexico makes its laps around the IRP road course during the Seeded Qualifiers.

was the tremendous amount of ambient solar exposure during cloudy days. However, the two consecutive foul-weather days and the hilly terrain forced even the Solar Rolar to be trailered on Days 5, 6, and 8.

The Solar Rolar team had an extensive testing program. The project began in January of 1994, and by spring break of 1995, the SDSM&T team was testing the Solar Rolar at the Bonneville Raceway Park in Utah. SDSM&T members put on 200 miles at the raceway and road-tested another 600 miles in preparation for Sunrayce 95.

24th Place: Montana State University's Double Black Diamond

Montana State University's solar-car team was one of the smallest and ambitious teams at Sunrayce 95. The decision to build a solar racer for Sunrayce 95 came in December of 1994, and construction of the Double Black Diamond started in February of 1995.

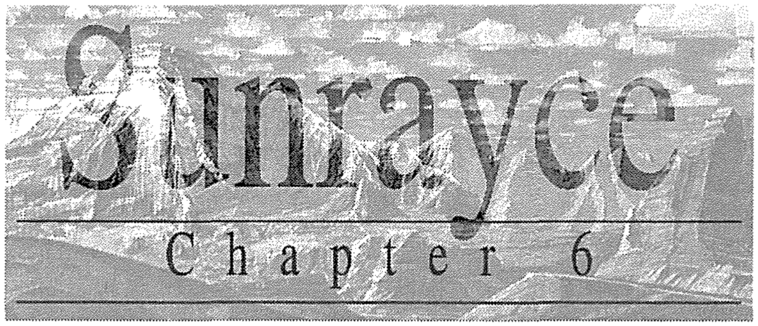
A unique aspect of the Montana State entry was the frame. The DBD's frame was a hybrid composite-floored space frame. The base of the frame, which doubled as the car's belly pan, was a carbon fiber/Nomex sandwich plank two inches thick and weighing about 20 lbs. Mounted on top of the plank was a chromoly tube frame structure weighing another 25 lbs. Though Montana finished 24th due to several significant array and motor problems, their efforts are still an impressive accomplishment. The DBD was a very beautifully finished solar car, and Montana was one of very few teams—possibly the only team at Sunrayce 95—that actually built their own motor controller. Montana State's best showing was on Day 6 when the DBD raced to a sixth-place finish for the day.

29th Place: Universidad Nacional Autonoma de Mexico's (UNAM) Tonatiuh

UNAM's Tonatiuh was the first-ever Mexican entry in Sunrayce history. The highly enthusiastic team from UNAM constructed a solar car designed for the World Solar Challenge in Australia. To meet Sunrayce 95 regulations, a few modifications to the car were required. The major modification was that they could not make use of their rotating solar array while racing. The UNAM Tonatiuh had a teardrop-shaped body (in side view), with the front suspension protruding out of the body. The entire rear two-thirds of the body rotated along the longitudinal centerline of the vehicle. However, because Sunrayce rules disallow moving arrays, the UNAM team had to run with the array in a fixed position. UNAM opted to run with the array tilted toward the south for this westerly race. Other modifications included extra metal tubing around the front and sides of the nose to meet Sunrayce crush-space rules and a roll-bar attachment on the roof just behind the Plexiglas canopy.

During vehicle scrutineering at IRP, a DuPont representative inspected all composite-structured solar cars in attendance to see which team made the best use of composite materials in terms of vehicle design, structure, driver safety, and aesthetics. With a host of compound curves, close-fitting seams between the nose and rotating array, and an emaculate surface finish, the Tonatiuh was the clear winner. The UNAM team was presented the "DuPont Best Use of Composites" award and a $5,000 check from DuPont for their efforts.

The Tonatiuh almost failed to qualify for Sunrayce 95 because of the make of their solar cells. The rules stated that the solar cells had to be manufactured in North America. However, UNAM could only procure Kyocera cells from Japan. Because the Kyocera cells were no more efficient than the North American cells, the officials let UNAM compete—but at a cost. The penalty was an additional 15 minutes to their daily elapsed time for each race day. Though this penalty totaled 2 hours 15 minutes, it did not change the outcome of the race. UNAM finished in 29th place, about 3-1/2 hours behind 28th-place Mercer.



Performance Comparison

6.1 Project Budget

In May 1995, teams submitted an estimate of their project cost, including both cash and in-kind contributions. Teams may have different accounting methods and varying degrees of completeness. Project costs do not necessarily reflect the solar-car cost, other than an upper bound. Project costs could include salaries, spare parts, space rental fees, and prototype solar cars.

What makes the project budget comparison even more confusing is that several of the solar cars in this race were not built specifically for Sunrayce 95. For example, UPenn's reported budget of $10,000 was their budget for Sunrayce 95, but the car had already been built at least a year earlier for the American Tour de Sol race. Their reported budget for the Liberty Bell from the start of the project is estimated at $100,000. Drexel University had also raced their solar car at prior events. The initial budget for the Sun Dragon IV for Sunrayce 93 was $75,000, and an additional $40,000 was spent for their Sunrayce 95 effort.

The project budgets of Sunrayce 95 teams plotted against overall finishing order are shown in Figure 6.1.1. The pre-race budget is charted along side the total project cost reported in the post-race survey. The costs varied from a low of $10,000 for the University of Pennsylvania to a high of $1.2 million for the University of Michigan. The average pre-race budget for 36 teams was $163,000, and the average post-race budget for the 28 respondents was $167,000.

A "Cost Effectiveness" award was presented to Northern Essex Community College for finishing seventh, with an estimated $20,000. The winner, Massachusetts Institute of Technology, estimated their project cost at $75,000—less than half the cost of the race average. Clearly, there is no correlation between higher project cost and better overall finish position.

Many teams are envious of the University of Michigan for their large project budget, to the point that they feel it is not fair. This $1.2 million figure, therefore, begs for an explanation. Having won both previous Sunrayces, the team from Michigan had in-kind sponsorship opportunities that were not available to most teams. However, direct monetary sponsorships were still scarce compared to material and service offers. For example, according to Michigan team member Michael Liao, Michigan was sponsored for two 1-year licenses of a powerful computer-aided-design (CAD) program. This sponsorship had a net retail value of $150,000. Many other universities purchased less expensive CAD packages for, say, $5,000. By simply accepting

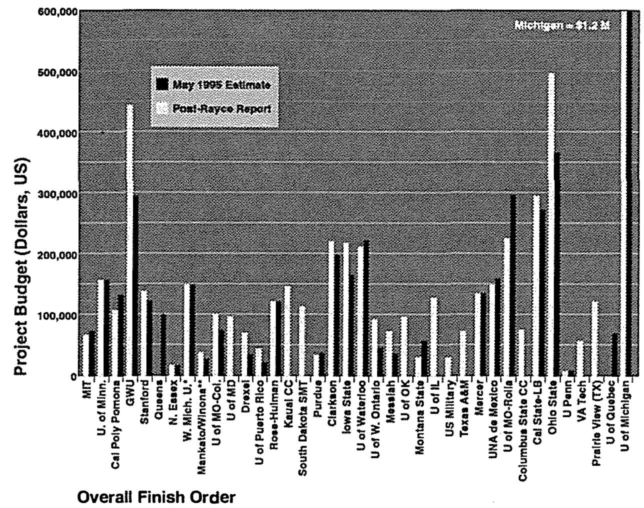


Figure 6.1.1: A comparison of project budgets of Sunrayce 95 teams. Charted are the budgets estimated in a May 1995 pre-race survey and the budgets reported in the post-race evaluation.

this CAD sponsorship, the Michigan team had already racked up their budget to well above many Sunrayce 95 teams' total project budgets.

6.2 Solar Resource and Performance

Lots of sunshine—even with three rainy days—resulted in the fastest Sunrayce yet. Figure 6.2.1 shows the average daily irradiance in June and the measured irradiance during the race. With respect to the average irradiances, Days 5, 8, and 9 were far below normal; Day 1 was below normal; Days 3 and 4 were normal; and Days 2, 6, and 7 were above normal.

The horizontal global irradiance was measured using a combination of pyranometers that were stationary or traveling. The irradiance and temperature were measured every 5 seconds, and the averages were recorded every hour. The daily irradiance is the integral of the hourly averaged data. Total measurement errors of about 10% are possible from non-level placement of the pyranometers and from the effect of traveling, which could add up to 15 minutes of additional irradiance when traveling west.

Also shown on Fig. 6.2.1 is the average daily speed of the top-5 solar cars. Solar irradiance and speed do not correlate strongly because solar cars can store the equivalent of a day's solar energy in their batteries. Strategy, which includes considering irradiance, determines the speed of the solar car. On

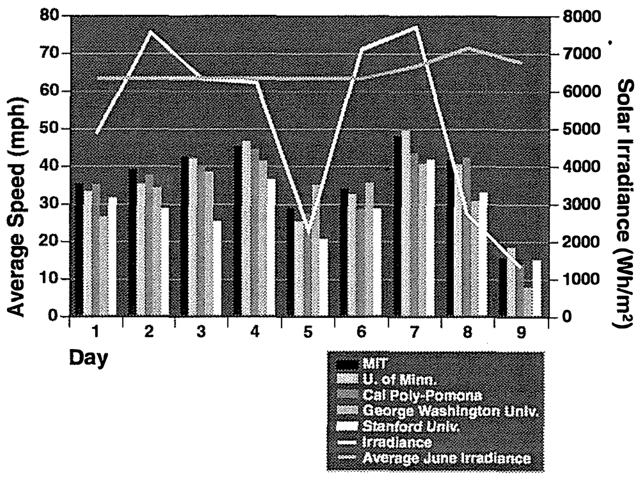


Figure 6.2.1: The average daily irradiance in June and the measured irradiance during the race. Also shown is the average daily speed of the top-5 solar cars.

Day 7—the best solar day—the University of Minnesota set a new Sunrayce speed record with an average speed of 50.42 mph. That is close to the limit for that day when all speed limits are observed.

6.3 Solar Arrays

A new rule for Sunrayce 95 was the requirement that the photovoltaic cells used be manufactured in North America. Only commercial technology widely available at less than US$10/watt 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 had an efficiency at standard test conditions close to 14 percent. Seven of the top-10 teams, including the winner, used cells manufactured by ASE Americas.

While racing, the car's solar array had to remain in a fixed orientation relative to the vehicle chassis. However, when the solar car was stopped for battery charging, the array could be reconfigured and tilted, as long as it remained within the imaginary box having dimensions of 8 m^2 by 1.6 m. To ensure that the solar cars properly displayed the source of their power, the rules required that all portions of the solar array used for propulsion be mounted visibly on the outside of the solar car when racing. Most teams took advantage of this rule and mounted auxiliary photovoltaic panels on the underside of the vehicle. When racing, these auxiliary panels contributed no additional aerodynamic loss (potentially), but they could be repositioned during charging hours to increase the array area facing the sun.

The Northern Essex Community College team took the extreme approach of fan-folding their entire array into the "trunk" of their torpedo-shaped vehicle. This greatly reduced aerodynamic drag, but sacrificed all solar power while racing. In this configuration, the cells near the bottom of the fan folds were barely visible, but were judged to satisfy the visibility regulation. This team's approach of driving to the finish line each day entirely on battery power, then deploying their array to recharge their battery, proved quite effective on days with clear, sunny evenings. The NECC team climbed to within 30 minutes of the leader after Day 5. But, cloudy skies during the second half of the race forced them to stop and recharge before reaching the finish line, dropping them out of contention.

Figure 6.3.1: Sunrayce 95 teams position their arrays toward the evening sun.

The "Technical Innovation" award for the solar-array design went to Messiah College of Grantham, Pennsylvania. This team used a strong, lightweight, sprayed aluminum-foam matrix as the substrate for their solar array. This structure withstood an incident on Day 5 in which a reckless individual on in-line skates smashed headlong into their array. The team also integrated convective air-cooling channels into the array to reduce cell temperature and thereby increase efficiency (Figure 6.3.3). In addition, they divided the solar array into easily manageable sections that could be individually removed to facilitate replacement of damaged cells, or to gain access to the car's interior.

Because Sunrayce is a solar-powered car race, one would expect that the solar car with the most powerful array would win, or at least would be a top contender. However, the previous statement holds true if and only if the other components of the vehicles are comparable in performance. Another difficulty in comparing solar power and performance of the 38 teams is that not all teams had telemetry or data-acquisition devices. Many teams reported their maximum array power as the maximum value seen on their meters, even if it were just for a few seconds. Other teams acquired the solar-array power values over the entire day through telemetry systems. Because data-acquisition systems have finite sampling rates, many of the short-duration power spikes can be aliased out. This probably was the case for Cal Poly Pomona. Pomona's telemetry data showed a maximum charging power of about 1150 watts, as shown in Figure 6.3.4. However, according to Cal Poly Pomona's array engineer, Brett Gaviglio, the array produced more than 1400 watts for short periods of time.

In contrast, MIT did not have any telemetry or data-storage equipment, so MIT's reported maximum charging and road solar power was instantaneous peak readings.

With the above in mind, we can take a look at Figure 6.3.5. Though the solar power in racing configuration is scattered as a function of overall finish position, the charging power favors the top-10 finishers slightly, with the exception of George Washington University. Also shown in Figure 6.3.5 is the solar power in racing configu-

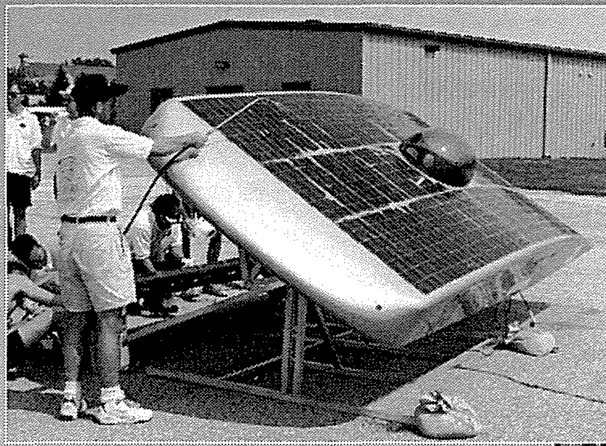


Figure 6.3.2: The Minnesota team setting up their booster panels for the evening charge of Day 2. Minnesota secured their canopy directly to the body structure so that solar area would not be lost to hatch opening seams and hardware. To exit the vehicle, the entire upper body shell hinged about the left side of the belly pan. A disadvantage of this design during charging was that they could not remove the canopy hatch and replace the area with a solar-cell block, as was done by other teams such as MIT, Cal Poly Pomona, and South Dakota School of Mines & Technology.

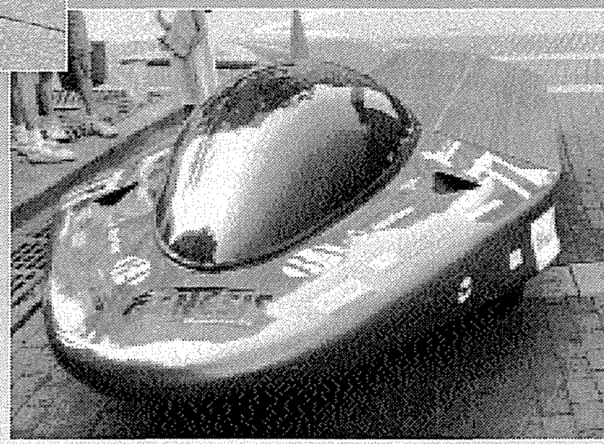


Figure 6.3.3: The Genesis from Messiah College force-fed the backside of their solar array via air ducts located on either side of the canopy.

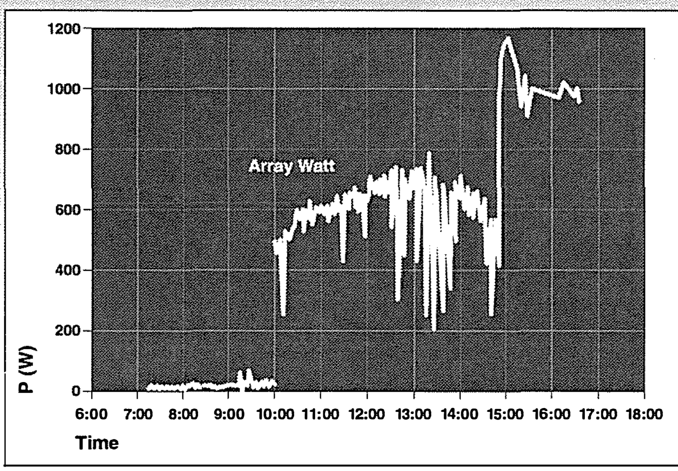


Figure 6.3.4: Solar-array power recorded by Cal Poly Pomona's data acquisition system. The three distinct power levels represent the morning charging, on-road racing, and evening charging sessions.

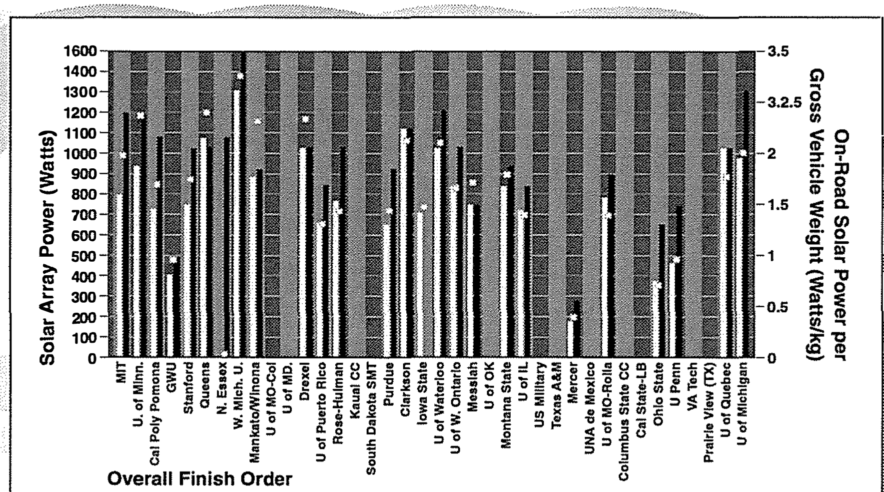


Figure 6.3.5: Solar-array power in racing and charging configuration, and racing power per gross vehicle weight plotted against overall finish position.

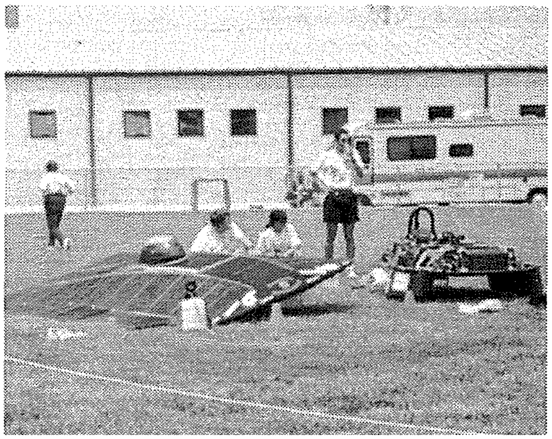


Figure 6.3.6: Some teams outran the support vehicles that carried their array charging rack. Large vehicles were required to travel an alternate route. Stanford University students wait for their rig on Day 7.

ration normalized by the gross vehicle weight (GVW). Again, these data are scattered, but they slightly favor the top finishers. Because the racing solar-power data was so random, we can assume that the normalized solar-power curve is roughly the inverse of the GVW curve shown in Figure 6.6.2. Also note that the racing-configuration solar power reported by some teams is bordering on impossible, because a likely upper bound for this figure is about 1130 watts—given 1000 W/m^2 ("one-sun") of solar radiation, a solid 8-m^2 array, and 14.1%-efficient solar cells. A possible explanation for these power figures is the short bursts of sun in the presence of white clouds. The highest racing-configuration array power reported was 1400 watts, from the multi-faceted, 960-cell ASE Americas array constructed by Western Michigan University.

6.4 Batteries

In the first Sunrayce in 1990, battery capacity, rather than mass, was used as the limiting factor. Also, any type of battery was allowed, including the exotic silver-zinc and the potentially risky zinc-bromine. For Sunrayce 93, the rule was modified to allow only commercially available lead-acid batteries, to keep down project costs. However, because capacities change with the number of charge/discharge cycles, and some manufacturers did not rate their cells at the C20 (20-hour discharge) rate, there was still some confusion. The rule for Sunrayce 95 was much simpler: 140 kg of rechargeable, commercially available, unmodified, lead-acid batteries.

The most popular battery for Sunrayce 95, by far, was the Delphi DRX-62555. These GM EV-1 electric-car batteries were supplied by Delphi Automotive Systems to any team that requested them. Twenty-one of the 38 teams ran with the Delphi batteries, including five of the top-7 finishers. These 12-volt batteries weighed about 19 kg each, resulting in a 134-kg, 84-volt pack. The rated capacity was a favorable 58 amp-hours at the C3 rate (4.9 kW-hr), or 64 amp-hours (5.4 kW-hr) at the C20 rate. This increase in capacity due to a lower discharge rate is typical for batteries. Some teams conducted their own battery tests and found different capacities. Scott Grabow of the University of Minnesota commented, "The Delphi batteries were the only batteries we tested that were within 95% of their manufacturing specifications." Minnesota found their pack to have a 60-amp-hour (5-kW-hr) capacity at a C5 rate.

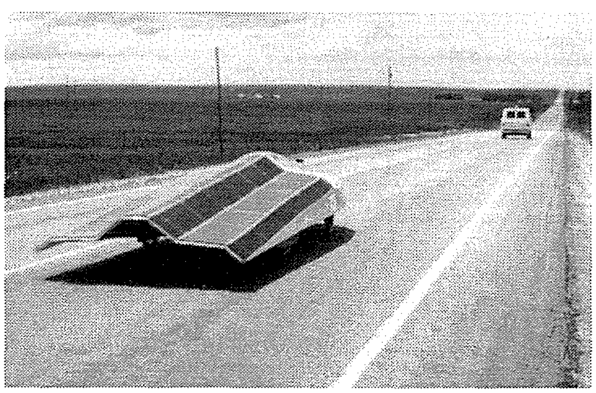


Figure 6.3.7: Western Michigan University's Sunseeker 95 cruises down the Midwest highways under a bright sky with scattered white clouds. WMU's solar array reportedly generated 1400 watts on the road.

Northern Essex Community College arrived in Indianapolis hoping to use a 120-volt set of Trojan electric-vehicle batteries. However, they had mistakenly been delivered a slightly different battery from what they had ordered. To pass scrutineering, NECC switched over to the Delphi units and were pleasantly surprised. According to NECC's Olaf Bleck, their Delphi pack reliably put out 64.5 amp-hours (5.4 kW-hr) at the C3 rate.

Team feedback on the Delphi batteries has been extremely favorable. According to Rose-Hulman Institute of Technology advisor Professor Bill Eccles, RHIT ran their pack to below 2 volts per battery more than once. They even ran them down to flat zero on one occasion, and the batteries bounced right back during charging.

Several top-finishing teams opted to use batteries other than the Delphis. MIT's 108-volt Trojan DC-22F batteries were rated at 57 amp-hours (6.2 kW-hr) at the C20 rate, and 42 amp-hours (4.6 kW-hr) at the C3 rate. Three teams, including fifth-place Stanford University, used the Electrosource Horizon H12N95 batteries. Although these batteries were "commercially available," they proved to be difficult to purchase. The only other teams to successfully get from Electrosource's waiting list to customer status were the University of Michigan and Ohio State University. Because the Horizon batteries were designed for full-sized electric vehicles, only 60-volts worth fit within Sunrayce 95 battery-weight regulations. However, the higher current necessary to output the same power, and the extra weight of the heavier wiring, was more than offset by the incredible rated capacity of 95 amp-hours (5.7 kW-hr) at the C3 rate. All three teams reported that the Horizons' performance varied from battery to battery. But once a suitable matched set was assembled, their performance was very good. An Electrosource engineer was present at the race to assist the teams in getting the most out of the Horizons.

Ninth-place Mankato/Winona State University was the only team to choose a battery pack that weighed far less than the maximum-allowed 140 kg. The Northern Light III carried only 77 kg of Exide U1-GTX lead-acid batteries, totaling a scant 2.4 kW-hr at the C20 rate. According to Mankato State advisor Bruce Jones, the students based this decision on three factors. First, Mankato/Winona's Northern Light III did not carry auxiliary charging panels on the sides or bottom of their car, so the team estimated they would only get to charge the batteries to about 2+ kW-hr capacity each day. Second, because the Northern Light III rolled on bicycle rims and tires, the lighter payload reduced the stresses on those vital components and the rest of the chassis structure, thus guaranteeing a safer vehicle. And third, because Sunrayce 95 was largely an uphill battle, carrying extra unused battery capacity could only hurt performance. By many teams' standards, this strategy may seem risky, because in Sunrayce 95 there were 2 days—the first and fifth—in which total battery capacity could have played a large role in overall finishing order. However, the strategy worked for Mankato/Winona, netting them a place in Sunrayce history as a top-10 finisher.

Another unusual battery pack was that used by 22nd-place Messiah College. Messiah's Genesis used 134 kg of Trojan batteries at an extremely low 36 volts. Six Trojan SCS150s, each weighing over 22 kg (49 lbs), were connected in series. The rated energy capacity at the C3 rate was a competitive 5.3 kW-hr, and that at the C20 rate was an impressive 7.2 kW-hr.

Comparing the capacities of MIT's Trojans to that of the Delphis at the C20 and C3 rates, we can see that a battery-choice-optimization analysis has to be made (given a team has the flexibility of running the respective pack voltages). If a team expects the battery draw to be relatively low, the 15%-higher energy capacity (kW-hr) of the Trojans at low amps would be the smart choice. On the other hand, if a team expects to draw higher amps from

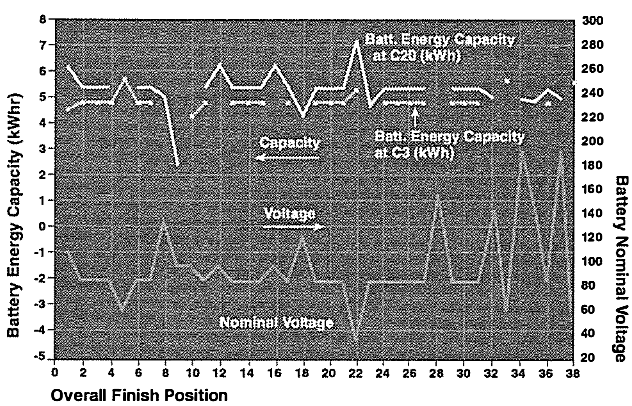


Figure 6.4.1: Manufacturer's rated battery-pack energy capacity at C3 and C20 rates, and battery-pack voltage of Sunrayce 95 teams plotted against overall finish position.

the battery, then the Delphi pack—which has slightly higher energy capacity at the C3 rate—may be the choice. The reason for the "may" is that the 108-volt Trojan pack would require a lower current draw to output the same power compared to the 84-volt Delphi pack. Thus, from a power-systems standpoint, the Trojan pack may offer comparable, or even superior, energy capacity depending on how high-power the driving schedule is. Once other crucial variables are taken into account—such as battery charging efficiencies at certain currents, solar-array power during racing and charging, and

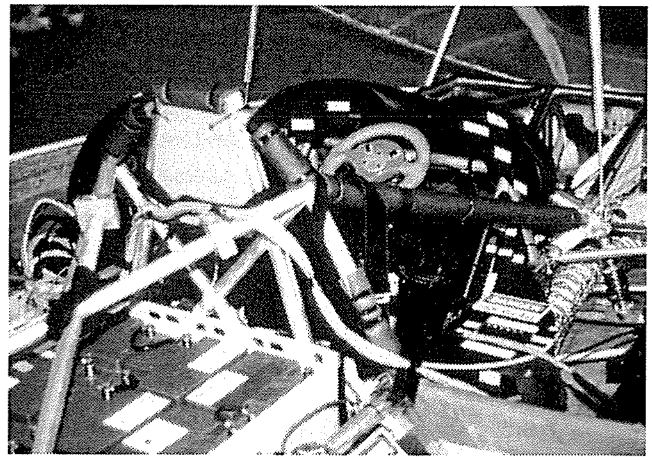


Figure 6.4.2: The 132-volt Sonnenschein gel-cell battery pack of Western Michigan University. The pack was rated at 5 kW-hr at the C20 rate and weighed 135 kg.

Figure 6.4.3: Northern Essex Community College co-captain James Nelson checks the Delphi battery pack positioned at the base of the vehicle. The driver was isolated by a Kevlar battery enclosure and seat.

powertrain efficiencies at certain loads—the battery-choice equation can get quite involved.

Shown in Figure 6.4.1 are the teams' battery capacities and voltages plotted against overall finishing order. There is no correlation between battery capacity and Sunrayce 95 finishing order. There were about the same number of the popular Delphi batteries used in the top half of the field as there were in the bottom half, and two of the three Electrosource users finished 33rd and 38th. The standard deviation of battery energy capacity at the C3 rate was only 0.7 kW-hr, for an average capacity of 4.9 kW-hr.

The battery voltage curve at the bottom of Figure 6.4.1, however, shows an interesting feature. All five of the teams that chose to use pack voltages above 140 volts finished toward the back of the pack. It is possible that the greater number of battery units led to pack-balancing difficulties, electronics issues, and general reliability problems associated with a large number of parts. In the case of UPenn, difficulties arose when modifying their American Tour de Sol spec solar car for Sunrayce. According to UPenn's Yas Kohaya, the addition of a larger array and battery pack heavily biased the vehicle's weight to the rear. In addition, the only place left to install the maximum-power-point trackers (MPPT) was in the rear. Because of this weight balance problem, a low budget, and a misjudgment that MPPTs would not be very important at the high 192 volts, UPenn decided not to run with MPPTs. However, with the unregulated array power, the team's only 200-volt controller got spiked just as the team was making their way to the Challenger's Qualifiers. The group of Ivy Leaguers rushed to repair their power system, but with only limited success because their replacement system was designed for 92 volts. The original equipment was repaired by the third to last day of the race. But by then, according to Kohaya, "It was pretty much over for us." Mercer University, however, did not report any battery-pack-related problems.

6.5 Body Shapes and Aerodynamics

The first solar car that strived to optimize the solar-cell-exposure vs. aerodynamic-drag equation was the revolutionary 1987 General Motors Sunraycer. Since then, several other shapes have evolved from GM's very basic, but extremely vital and elegant, solution of the streamlined uni-body solar car.

Because streamlined solar cars exhibit no flow separation (except possibly near the wheels), the aerodynamic pressure drag component is essentially eliminated, greatly reducing the total drag of the car by as much as an order of magnitude. Because the main drag component of a non-lifting streamlined body is skin friction, further aerodynamic drag reduction can be pursued by: extending the region of laminar flow, reducing the wetted surface area, or recontouring curves to reduce the air velocities near the surface of the car. Notice that reducing frontal area is not listed [6.5.1, 6.5.2, and 6.5.3].

The total aerodynamic drag is proportional to the "drag area," which is defined as the product of a coefficient of drag (Cd) and a characteristic area (A). In the automotive industry, the characteristic area used is the frontal area (A_f), because all production cars are bluff bodies—bodies that exhibit flow separation. Therefore, the resulting Cd used in the auto industry is that based on the frontal area. Because people who construct solar cars usually

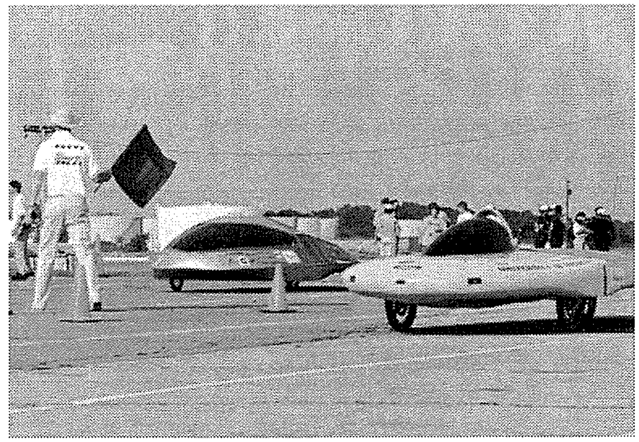


Figure 6.5.1: University of Michigan's Solar Vision (right) cruises past the front stretch at IRP, as the Queens Quest prepares to head back on the track from pit row. The Michigan car was based on the Biel design and the Queens car on the GM Sunraycer's.

have roots or interests in the automotive industry, the convention of using A_f as the characteristic area has been carried over.

There is a widely believed myth in the solar-car community that reducing the frontal area of even streamlined cars will reduce the aerodynamic drag. The accepted, but erroneous, logic proceeds as follows: For a given streamlined GM Sunraycer-type body, if its A_f is reduced by a certain factor, the drag area (Cd A_f) will also be reduced by about the same factor. This is based on the false assumption that the Cd essentially remains constant because the general shape has not been significantly altered. What is often overlooked is that this Cd is based on that A_f. Because the drag of a separation-free body is not directly proportional to its frontal area, when the A_f is reduced by a certain factor, the Cd (based on A_f) will increase by essentially the same factor, resulting in essentially the same drag area value.

Solar-car constructors usually strive to avoid bluff bodies as is typically done in the aeronautical and maritime industries. The characteristic areas commonly used in those industries are planform area (area as seen from above) and wetted area, respectively [6.5.4]. Perhaps over the next several generations of Sunrayces, planform area (A_p) or wetted area (A_w) will become the standard.

In 1990, the Biel Engineering School (Switzerland) modified the Sunraycer shape by flattening the solar array and placing the driver's head in a bubble. Solar-car canopy bubbles, unless painstakingly designed, can easily end up as bluff bodies, leading to flow separation, and thus, to high drag. Because aerodynamic drag of bluff bodies is proportional to their frontal area, drag of bubbled cars can be reduced by decreasing the size of the bubble, and if possible, reshaping the back of the bubble to minimize separation. Another popular method of canopy drag reduction is to trip the flow to delay separation. When Biel redesigned their car for the 1993 World Solar Challenge, one of the biggest changes was greatly reducing the size of the canopy bubble. This modification, as well as interference drag reductions in the wheel well areas (and probably subtle contour changes), reduced the drag area of the Biel car by close to 30 percent, from 0.143 m² to 0.105 m² [6.5.5].

Table 6.5.1. A Comparison of Aerodynamic Parameters for Sunrayce 95 Car Bodies

Team	Cd	CL	AREA/SREF	
Cal Long Beach	0.3377E-01	-0.9322E-01	25.668	**problem in file
Minnesota	0.5403E-01	-0.4374	22.809	
Iowa State	0.5456E-01	-0.6117	23.705	
Clarkson	0.5485E-01	-0.3178	25.611	
New Mexico Tech	0.5499E-01	-0.9391E-01	22.478	
Ohio State	0.5756E-01	-0.4178E-01	24.757	
Queens	0.5795E-01	-0.2642	24.805	
Michigan	0.6370E-01	-0.2558	25.666	
Messiah	0.6690E-01	0.7719	24.129	
Cal Berkeley	0.6716E-01	-0.5684E-01	20.700	
West Ontario	0.6793E-01	-0.6108	25.603	
Purdue	0.7033E-01	-0.5850	23.282	
Oklahoma	0.7149E-01	-0.5745	26.207	
New Mexico CC	0.7280E-01	0.2490	24.875	
Puerto Rico	0.7503E-01	-0.5034	21.484	
South Dakota	0.7876E-01	-0.3006	30.911	
Massachusetts	0.8254E-01	-0.2120	24.229	
Virginia Tech	0.8515E-01	-0.9024	26.302	
Missouri-Columbia	0.8584E-01	0.1627	27.604	
Rose-Hulman	0.8798E-01	-0.3960	26.433	
Yale	0.1059	-0.6512	20.534	
SE Oklahoma	0.1069	-0.1607	29.506	
West Point	0.1120	-0.2163	28.825	
Cal Poly Pomona	0.1128	-0.4425	19.137	
Auburn	0.1488	-0.4882	24.256	
Missouri-Rolla	0.1621	0.8325	25.805	
Principia	0.1738	-0.5584	26.581	
Mercer	0.1795	-2.300	26.129	
Prairie View	0.2078	-0.4068	27.148	

In Sunrayce 95, nine teams based their body design on the GM Sunraycer, including sixth-place Queens University. Sixteen teams benchmarked the Biel design, led by fourth-place George Washington University.

In the 1990 GM Sunrayce USA, the Massachusetts Institute of Technology and the University of Waterloo introduced the central-bubble-canopy design, which vastly reduced the length of the vehicle by eliminating the 2-m-long nose section that houses the driver in a GM Sunraycer-style car. Though the MIT and Waterloo "short-cars" were similar in plan view, the underside treatment was quite different. The MIT Galaxy had an almost flat belly pan, with the suspensions and top halves of the wheels enclosed in a roughly airfoil-shaped body. The Waterloo entry, however, had a large curved belly, with wheels enclosed in tall vertical airfoil fairings that extended down from the bottom of the main body. The goal, at least of the MIT Galaxy design, was to trade in the solar-cell area given up to the driver's canopy bubble for reduced total wetted surface area and lighter weight (and thus lower rolling resistance). The canopy bubble of the MIT Galaxy was the spare canopy of the world-distance-record-setting Voyager aircraft. A simplified version of the Galaxy shape was raced by Cal State LA in Sunrayce 93. Second-place University of Minnesota's and fifth-place Stanford's body shapes closely resembled those of Cal State LA and Galaxy, respectively.

There were several other shapes represented at Sunrayce 95. The Mexican entry, Tonatiuh, featured a tilting array that was integrated with the nose of the car—not the traditional tilting-panel design in which a flat panel tilts relative to a separate fuselage. The team from Northern Essex Community College had a very aerodynamic torpedo design with carefully faired front-suspension components and wheels. Finally, several teams ran with the classic solar-car design of a flat solar-array panel attached to a separate driver compartment.

Over the year and a half leading up to Sunrayce 95, Electronic Data Systems (EDS) provided VSAERO aerodynamic computer simulations for any team that sent in a mathematical description of their solar-car body shape. Some teams ran as many as six different body styles with numerous iterations of each. Vehicles were modeled in a consistent manner to reduce the variation between the models. When fairings were used, the wheels were not modeled. A majority of the Cd ratings were comparable—in the range of 0.054 to 0.087. The Cd is normalized with the reference area set at 1.0 m^2.

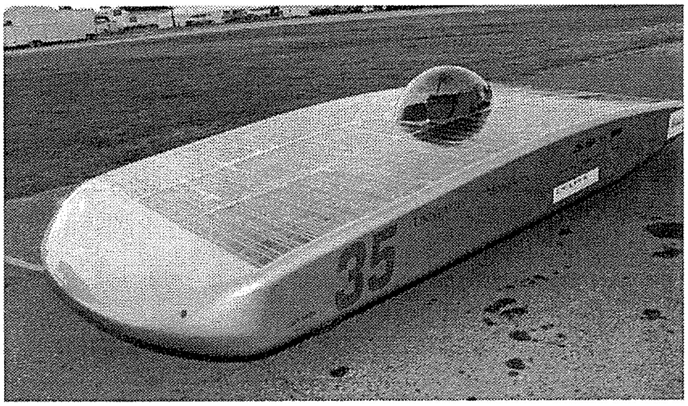


Figure 6.5.2: The University of Minnesota's Aurora II, piloted by Lance Molby, shines in the afternoon sun. Note the carefully sculpted (and stickerless) nose section tailored to promote laminar flow.

Of the 32 teams that submitted designs to EDS, second-place University of Minnesota's body shape netted the lowest drag area (CdA). According to Minnesota's Scott Grabow, the Aurora II's EDS result was a drag area (CdA) of 0.01439 m^2. The values of the EDS VSAERO results are invaluable when making design changes to the body contours. Grabow commented that the EDS staff was very helpful and even took the time to look into the actual VSAERO code to solve yaw-flow solution problems.

In comparison to the EDS data, Minnesota's measured drag area was expectedly higher by an order of magnitude. Some unmodeled aspects of the solar car included wheel-well openings, wheel and suspension components, and body and array surface irregularities. Coast-down tests performed before the race showed a drag area of 0.1938 m^2, but Grabow warned that the test was not very well controlled, and many environmental factors such as a slight incline (0.5 ft per 100 ft) probably affected the result. From power-consumption data acquired during the race, the resulting drag-area value was 0.114 m^2. Again, Grabow warned that the data were taken under non-ideal conditions and could have been influenced by wind speed, hills, and temperature.

Another team that spent a great deal of effort developing their aerodynamics was Clarkson University. Clarkson also took full advantage of the EDS service. The Helios' shape was based on the famous Morelli body shape [6.5.6], which was originally conceived as the lowest drag shape that may be applied to a practical car. Clarkson modified the body by lowering the camber profile, flattening the upper surface (most probably for solar-cell application), and lifting the body as high off the ground as possible. The solar array was mounted on the rear two-thirds of the car, but because the seating position was so reclined, the driver's head was well under the array.

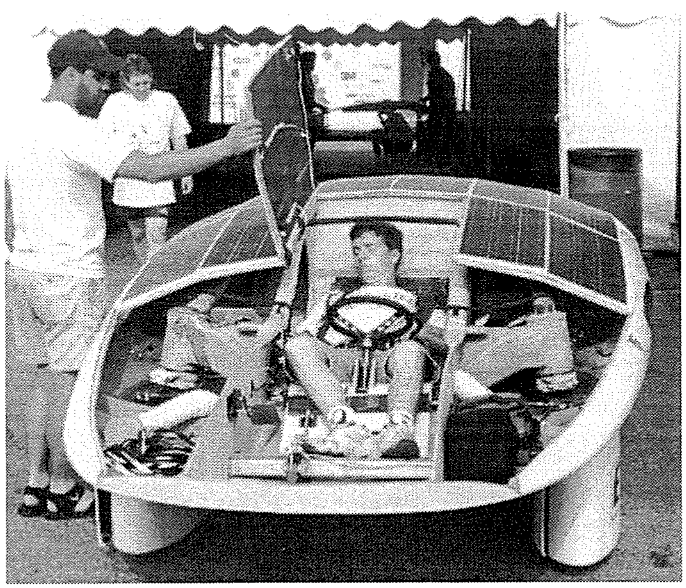


Figure 6.5.3: The Clarkson Helios prepares to head for the scrutineering dynamic tests. Note the front wheel skirt "doors" that open under sharp steering angles.

The Helios, with a large 36.3 cm (25.4 in.) of ground clearance, had the suspension components and the wheels extending far out of the body. However, to keep the aerodynamic drag in check, full wheel skirts were incorporated at all three wheels. To avoid the complication of rotating wheel skirts, Clarkson cleverly designed wheel skirt "doors" that flapped open only under extreme steer angles. Because the front wheels are barely steered when driving at highway speeds, the skirt doors' contribution to the Helios' aerodynamic drag was minimal. The front fairings of the Clarkson Helios are shown in Figure 6.5.3.

Yet another feature of the Helios worth mentioning is its ability to "crab" toward the wind [6.5.7]—that is, the Helios' rear wheel can be steered slightly to allow the vehicle to drive toward the wind at a yaw angle. Vehicles with vertical airfoil sections can greatly reduce their aerodynamic drag in a crosswind by "sailing." This effect has been demonstrated by Biel [6.5.8], and the crabbing concept has been applied by Western Washington University's Viking XX [6.5.9]. Because any type of rear-wheel steering can lead to catastrophic vehicle-handling issues, constructors should take great care when designing a "crabbing vehicle." According to Clarkson advisor Dr. Eric Thacher, the full-scale wind tunnel tests showed the drag area of the Helios to be a respectable 0.139 m^2.

Perhaps fourth-place George Washington University conducted the most extensive aerodynamics analyses of all the teams in the race. The GW from George Washington University was one of the most stunning vehicles of the race. Wherever the GW went, crowds of people followed. According to GWU team captain and chief aerodynamicist Cory Knudtson, there were literally hundreds of subtle body-shape iterations made before the final shape was determined.

For Sunrayce 93, GWU created the Sunforce-1, which was similar to the 1990 Biel car. What really differentiated the GWU car was that the main body was thinned dramatically, and the driver bubble was made taller to satisfy the driver eye-height rule. After the 1993 season, the Sunforce-1 was tested full-scale at the Lockheed wind tunnel. According to Knudtson, the Sunrayce 93 car, with several aerodynamic enhancements for the 1993 World Solar Challenge, netted a drag area (CdA) of 0.29

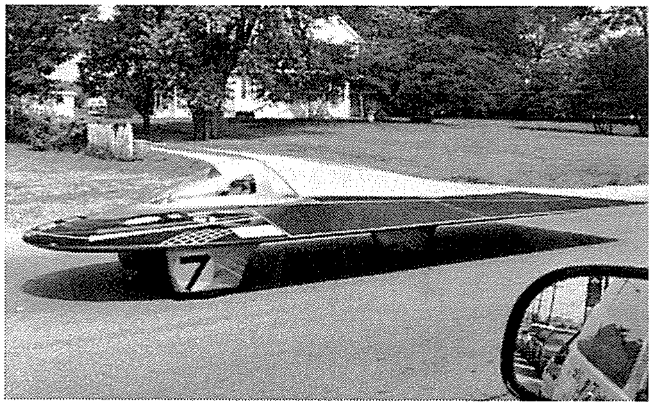


Figure 6.5.4: The GW from George Washington University was artwork on wheels. The GW's rotating wheel fairings sealed off the main body from the outside air, greatly reducing underside interference drag. Though the large canopy stole some solar area, a small auxiliary array was mounted inside the canopy to power the instrumentation.

m². In the following hours, the GWU team installed full wheel fairings around the exposed suspension hardware and wheels, and it experimented with the body's angle-of-attack. The final drag area of the Sunforce-1 after all modifications was 0.19 m². One high-drag feature of the Sunforce-1 that could not be easily modified was the faceted solar array, which caused local flow separations.

When it came time to develop the GW for Sunrayce 95, the GW team formed a partnership with Analytical Methods, Inc., the makers of the VSAERO software. The first item on GW's agenda was to make sure that the code could accurately predict the drag values of an actual solar car. Using the abundant wind-tunnel data from the Sunforce-1, the input parameters were changed until the simulation results correlated with the experimental results. Because there was no time to test the GW in a wind tunnel, the aerodynamic drag results generated by the VSAERO code would be used in GWU's Sunrayce 95 strategy program.

The GW was a second-generation version of the Sunforce-1. The wind tunnel-enhanced Sunforce-1 was set as the benchmark. To mathematically describe the body contours of the GW, longitudinal sections of several areas of the car (e.g., nose, bubble, array, underside) were represented by third-order polynomial curves. A surface mapping defined by these curves was then meshed into over 4000 panels. Even each of the smoothly integrated wheel fairings was made up of over 500 panels. The coefficients of all the polynomials of all the sections were given allowable ranges corresponding to geometric constraints defined by the race rules and aerodynamic considerations. For example, one of the rule constraints imposed on the canopy design was that the driver must have at least 15 cm of horizontal clearance. An example of an aerodynamic constraint was the slope of the rear underside of the tail. The slope at the very end was constrained to be zero plus/minus a certain number of degrees relative to the ground. During the summer of 1994, Knudtson and another team member spent 10 hours a day for a solid 2 months designing the GW body on a SP2 supercomputer.

Because the GW had tight packaging constraints on its large canopy bubble and on its underside components, to minimize the pressure (or form) drag caused by flow separation, Knudtson turned to EPH (ellipsoid-paraboloid-hyperboloid) shapes. For minimum drag, it is customary to use airfoil sections that potentially exhibit no separation. However, in the GW design, a vertical-airfoil-shaped canopy would have prohibitively intruded on the solar-cell area. Because using a streamlined bubble with a truncated rear tail section (as was done by several teams) would have led to excessive flow separation losses, the EPH shapes were used as the optimum solution for the given constraints. The main reason for using the EPH shapes for the wheel fairings was again a compromise between packaging constraints and aerodynamic drag. The frontal area of the bluff body components were minimized, and the hyperboloid rear sections of those components were tailored to yield as little separation as possible. The yaw flow effects on drag were also studied extensively. The final shape showed a drag increase of less than 10% at 12 degrees of yaw, mostly attributable to the canopy. The resulting drag area of the final GW shape as predicted by VSAERO was between 0.15 and 0.17 m². According to Knudtson, the power-consumption data acquired during the race correlated well with the VSAERO data.

The MIT Manta shape was a hybrid of several highly successful body shapes, including the 1990 MIT Galaxy, the 1992-94 MIT Aztec (two-seat electric car), and the 1990 University of Maryland Pride of Maryland. The main goals of the Manta shape were safety and overall vehicle power efficiency. For safety, the first thing that had to be eliminated from the Galaxy design was the bubble canopy. One of the drivers of the Galaxy commented that he could not scratch his face, rub the fog off the "windshield," had difficulty reading the meters velcro'ed to his chest, and worst of all, was concerned about being decapitated in the slightest frontal impact. To make the bubble canopy practical, and to also meet the increasingly safety-conscious Sunrayce rules, the bubble dimensions would have to grow to a point where the validity of the solar power vs. aerodynamic drag trade-off would be ques-

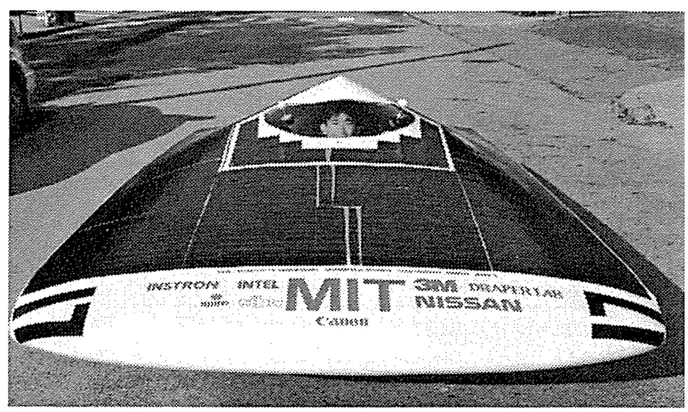


Figure 6.5.5: The goal of the MIT Manta body was to maximize the ratio of solar area to aerodynamic drag. The side/rear view mirrors were a necessary evil for safety reasons. According to Goro Tamai (seated), each mirror provided a field of vision of over 120 degrees.

tionable for a Galaxy-style car. (The new Sunrayce 97 solar-array rule partially addresses this issue.)

For aerodynamic energy efficiency, MIT's number-one goal was to keep the flow attached to the body. Given that MIT did not have access to a full-scale wind tunnel, and that stickers would be applied to the nose of the car days before the event, turbulent flow was assumed to be dominant across almost the entire car surface. Without laminar flow across a large portion of the 2-m nose of Sunraycer-style cars (as GM's car did [6.5.1]), a "short car" would be the lower aerodynamic drag solar car. This was especially true for MIT, considering the solar-cell and vehicle fabrication technology available to the team for Sunrayce 95.

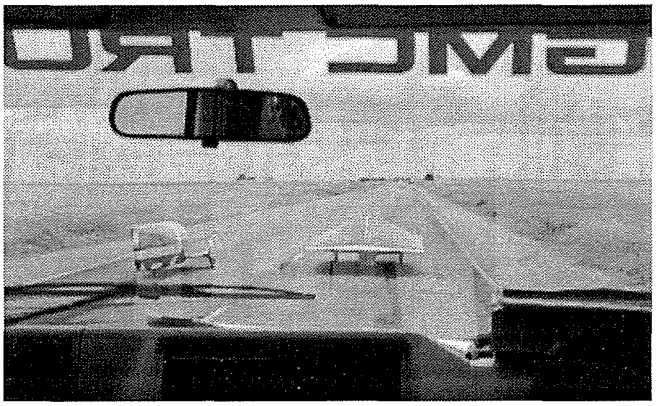


Figure 6.5.6: The TNE-3 from Northern Essex Community College passes MIT's Manta on one of many long stretches of highway on the Sunrayce 95 route. Notice that if the TNE-3 body were unwrapped, its surface area would be about the same as just the top-side surface area of the MIT car.

To ensure that the flow would remain attached, the first thing that had to change from the Galaxy design was again the canopy bubble. The Manta canopy, like that of the Aztec, was integrated with the body, forming a true uni-body form. Along with this integration, MIT was able to bring the solar-array coverage all the way up to the top of the canopy region, thus potentially giving up only the windshield area of solar-cell coverage. The spined rear section borrows from the 1990 Maryland car and accomplishes several functions. First, the high-rising spine integrates well with the Manta canopy design and provides a smooth gradual pressure gradient down the back of the body. Second, as found by Hampson et al. [6.5.10], the spine reduced cross-wind lift, and thus, drag and risk. Finally, the spine served to flatten the rear solar-array sections and simplified cell mounting relative to an arched or faceted array.

Underbody flow attachment was also given attention. The rear wheel and suspension assembly were fully enclosed in a streamlined fairing. The drag of the front wheels was reduced by implementing leading and trailing "half fairings," similar to those popularized by the 1990 Honda car [6.5.11]. The front wheel cutouts in the belly pan were trimmed as tightly as possible, and all blunt suspension components exposed to the wind were covered with auxiliary fairings. The belly pan solar cells, which were only used during charging, were inset into the belly pan to keep the surface as smooth as possible. The front wheel cutouts on the belly pan were originally sealed with plates that rotated with the suspension uprights, but were removed at the qualifier due to lack of development time. Another team that encountered a similar wheel-well-sealing scenario was Queens University.

Table 6.5.2. Sunrayce 95 body shapes and overall finishing position. Lengths indicate total length of solar cars.

Body Style	Originator	Sunrayce 95 Overall Finish Position
Cockpit with separate array	1985 Mercedes-Benz, Solar Mobile [6.5.12].	26, 27, 31, 34, 36.
Airfoil uni-body w/ driver fully enclosed in nose (6 m long).	1987 General Motors, Sunraycer.	6, 8, 17, 18, 19, 21, 25, 32, 37.
Catamaran version of GM Sunraycer (6 m long).	1990 University of Michigan, Sunrunner.	N/A
Catamaran (inverted-U) with driver bubble canopy within solar array.	1990 Crowder College, Star II (6 m long as 2-seater).	16
Airfoil with driver bubble canopy in center of solar array (4+ m long).	1990 MIT, Galaxy.	2, 5, 13
Driver bubble canopy in center of array w/ curved belly and large vertical wheel/suspension fairings (4+ m long).	1990 University of Waterloo, Midnight Sun.	3
Modified GM Sunraycer w/ bubble canopy and "flat" array (6 m long).	1990 Biel Engineering School, Spirit of Biel II.	4, 9, 10, 11, 12, 14, 15, 20, 22, 23, 24, 28, 30, 33, 35, 38.
Modified GM Sunraycer w/ tilting solar array (6 m long).	1990 Northern Territory University, Desert Rose.	29 (open-wheel).
Torpedo with enclosed array.	1991 MIT 5x.	7
Modified 1990 MIT Galaxy w/ integrated canopy into uni-body (4+ m long).	1995 MIT, Manta.	1

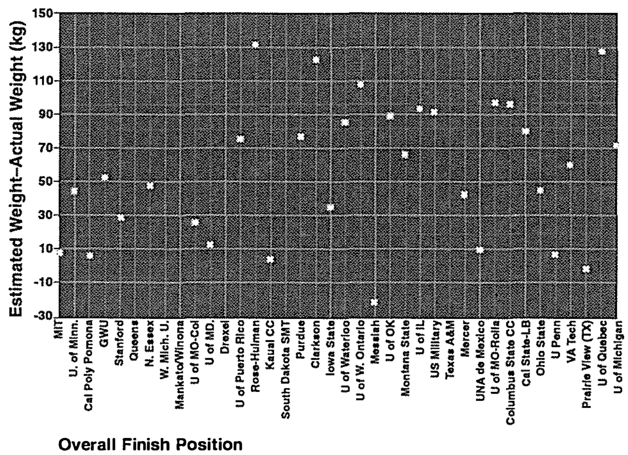


Figure 6.6.1: Weight under-estimation of Sunrayce 95 teams plotted against overall finish position.

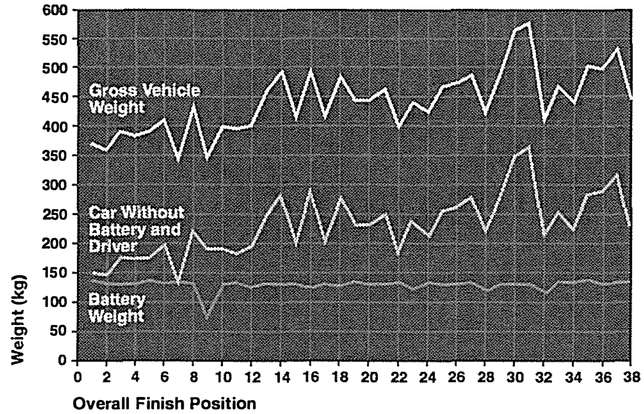


Figure 6.6.2: Gross vehicle weight, vehicle weight without batteries and driver, and battery-pack weight plotted against Sunrayce 95 overall finish position.

There was some debate on how effectively the Manta's array shape would capture the solar energy for the westerly race. The decision to proceed with what became the final Manta shape was based on the balancing of on-road solar exposure, overall vehicle energy efficiency, and stationary charging potential. The side solar arrays, though much smaller than those used by Cal State LA in 1993, were added late in the project to help performance on cloudy days. From post-race power-consumption data, the MIT Manta's drag area was estimated to be 0.134 m^2 (+/- 0.006 m^2).

Finally, the solar car with the lowest aerodynamic drag of Sunrayce 95 was more of an electric car with recharging solar panels in the "trunk." The TNE-3 from Northern Essex Community College was a 3.8-m-long torpedo with fully faired wheels and suspension components. With a wetted area of less than half that of most solar cars in the race, the TNE-3's power consumption revealed an incredibly low drag area of about 0.07 m^2. It was no wonder that NECC was able to run with the top teams on days with sunny charging periods (see Section 5.4 for an explanation of NECC's strategy).

Table 6.5.2 shows how each body configuration represented at Sunrayce 95 finished, along with the originators of the body shapes.

6.6 Solar-Car Weight and Chassis Design

Vehicle weight is, without a doubt, one of the statistics most obsessed over in solar racing. In preparing for this race up the great plain, many teams went to great lengths to design the lightest solar car possible. In the following paragraphs, weight and mass will be used interchangeably because most of us are accustomed to thinking of "weight" in units of pounds (weight) or kilograms (mass). Solar-car weight and chassis design are lumped into a single section because the chassis is what basically defined the weight of a Sunrayce 95 solar car. All teams except one used battery packs having very close to the same weight.

The Sunrayce 95 program listed the estimated weights of most of the registered solar cars. Some claimed to be as light as 216 kg (475 lbs) without driver, while others estimated their weight at a hefty 363 kg (800 lbs). As shown in Figure 6.6.1, many teams grossly under-estimated the mass of their hardware.

How well a team estimates their solar car's mass is a very serious issue. Whether or not a team will have enough energy to carry the extra mass up a hill at the desired speed is a minor concern compared to structural and dynamic issues. A frightening aspect of the these weight discrepancies is that the design analyses for the structural components—including the frame, suspensions, brakes, and steering—were all based on the estimated vehicle mass. For example, the frontal impact criterion was a 5 g' load. The average weight under-estimation was 58 kg (128 lbs), which would result in an extra 2842 N (640 lbs) of force. This extra vehicle mass, unaccounted for in the brake-system design, partially explains the poor brake-test performances in scrutineering (Chapter 2).

The team that most accurately estimated their solar car's weight was Prairie View A&M University, coming within 1 kg of their prediction. Because the weighing equipment probably was not accurate to within one kg, we can

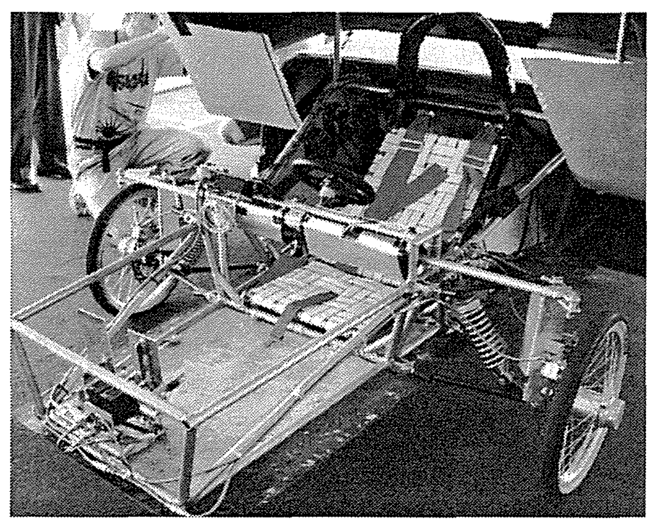


Figure 6.6.3: The Sun Tiger II from the University of Missouri-Columbia raced to a top-10 finish with a lightweight magnesium tube frame. The Sun Tiger II was one of the lighter cars of the event, tipping the scales at 401 kg (883 lbs) including driver.

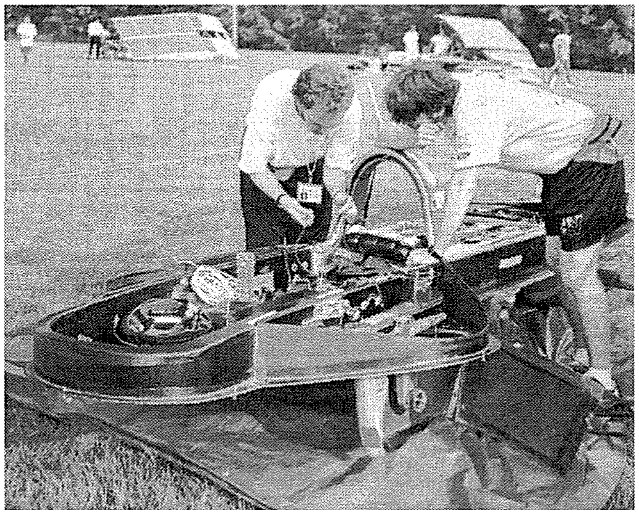


Figure 6.6.4: The George Washington University team did a commendable job in constructing their composite tub. The 4-inch-high hoop—extending from the rear wheel region of the belly pan up to the driver's feet, and back around toward the rear—was laid up as a single hollow hat-section unit. This hoop, when bonded to the belly pan, formed essentially a carbon-fiber tube frame.

assume Prairie View was dead-on. Other teams that predicted their masses reasonably well (within 20 kg) were MIT, Pomona, University of Maryland, Kauai Community College, Messiah, UNAM (Mexico), and UPenn. It was no surprise that Maryland, Kauai, and UPenn are in this group, because they already had their car built for previous races at the time the race program information was due (May 1, 1995). MIT regularly weighed their rolling chassis and body shell using bathroom scales and a few pieces of wood. Cal Poly Pomona had an extensive testing program in which the Intrepid Too was weighed regularly. Also, Cal Poly Pomona had their car in almost race-ready form by the May 1 deadline, as evident from the race program photograph.

Usually, the part of the solar car that sneaks up in weight is the composite shell. If a team is using a composite tub as the vehicle structure, it usually makes matters worse because many novice and even experienced persons who perform lay-ups add extra epoxy to structural components in attempt to guarantee a delamination-free ride. The three teams that under-estimated their vehicle weights by the greatest amount (more than 120 kg or 264 lbs) all used composites as the main load-bearing structure. This is not to imply that composites will necessarily lead to an unexpectedly heavier car. A perfect example is the rookie team from Universidad de Mexico that built a fine composite structure and weighed in only 10.5 kg (23 lbs) above their estimate (assuming their car had not yet been completed at the time of estimation). In absolute mass, the third- through fifth-place finishers all had composite main structures, and all three vehicles had a dry weight (vehicle weight without driver or batteries) of under 180 kg (396 lbs). The average dry weight was 232 kg (510 lbs).

So, did the lightest solar car win? No, but the lighter cars certainly fared better. Figure 6.6.2 shows three sets of data: The top curve represents the gross vehicle weight (GVW) including batteries and driver, i.e., the total package that had to be propelled. The second curve represents the weight of the solar car without batteries and driver, i.e., the hardware over which teams had most control. Finally, the third plot from the top represents the battery weight. As shown in Figure 6.6.2, there is a mild upward trend of GVW with overall finish position. Because many teams experienced vehicle reliability problems, and the vehicle designs of all 38 teams were so different, no statistical analysis of the data was performed.

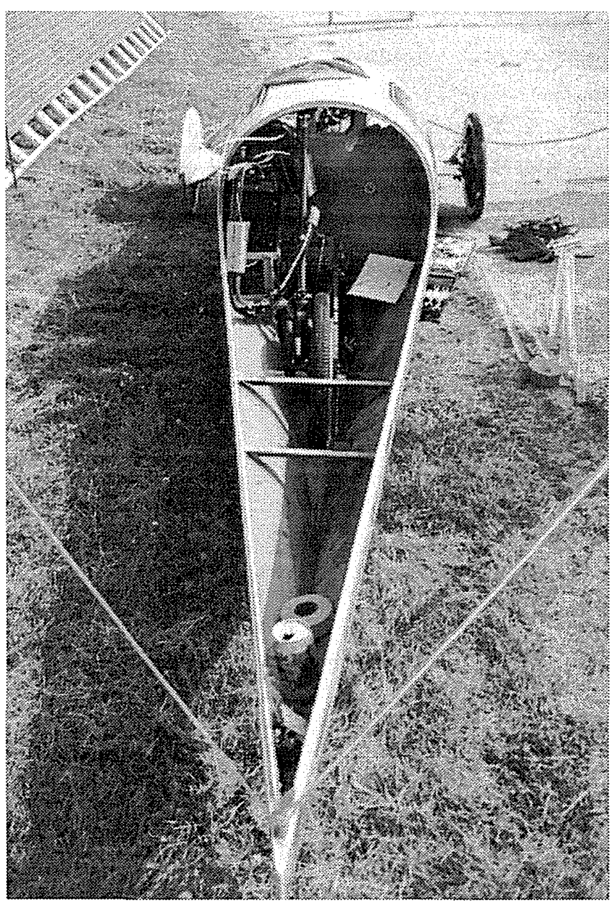


Figure 6.6.5: The composite monocoque of the TNE-3 from NECC was the lightest chassis of the race. Notice the Kevlar lining on the interior for electrical and crash protection.

The featherweight champion was the TNE-3 from the Northern Essex Community College. The TNE-3 originally weighed in at a GVW of 366 kg (802 lbs), but was required to switch battery packs because the pack that they had received just days before the race was not the exact model that they had ordered. Because there was no time to register a new set of batteries, NECC opted to replace their pack with the race-approved Delphi units. The final GVW of the TNE-3 was an impressive 344 kg (757 lbs).

Mankato/Winona State was a close second in the weight contest with a GVW of just 349 kg (767 lbs). However, as shown by the battery-weight curve in Figure 6.6.2, Mankato/Winona carried only 77 kg (169 lbs) of batteries, where the average battery weight of the other 37 teams was 133 kg (293 lbs). Mankato/Winona's all-composite chassis/body was still relatively light at 192 kg (492 lbs).

With the exception of Mankato/Winona State, all the teams had about the same weight of batteries in their cars. Mankato/Winona's battery strategy is discussed in Section 6.4. University of Oklahoma, Mercer, and Cal State Long Beach also carried less battery weight—about 10 kg (22 lbs) under the overall

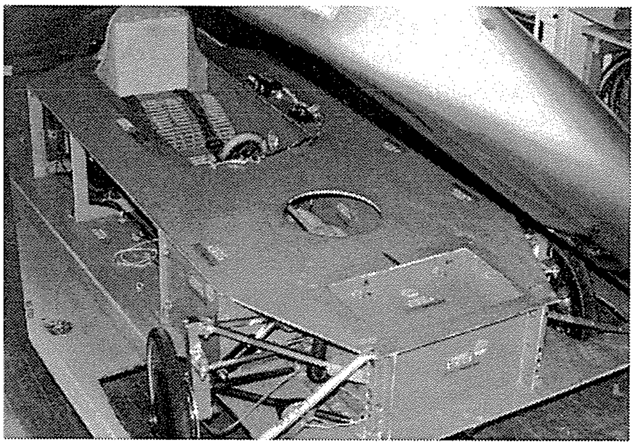


Figure 6.6.6: The fiberglass panel chassis of the Aurora II from University of Minnesota was the lightest full-sized chassis of the race. The box frame structure neatly housed the batteries up front and the electrical components in the side bins.

average of 132 kg (290 lbs). MIT carried the largest battery payload at 139 kg (306 lbs).

The lightest dry-weight car in the race was NECC at 130 kg (286 lbs), followed by University of Minnesota at 147 kg (323 lbs), and MIT at 151 kg (332 lbs). What is interesting to note is that all three of these high-performance cars had vastly different chassis construction designs. There were no structural failures experienced by any of these lightweight-chassis vehicles during the race.

NECC's TNE-3 had a true monocoque structure, where the outer shell itself was the stressed component (Figure 6.6.5). The TNE-3 also owes its light weight to the fact that it was a substantially smaller car without an external solar array. The NECC monocoque was unique in that it was seamless. The right and left sides of the body molds were fastened together, and the pre-preg cloth was laid-up inside through the canopy and trunk openings. This method of construction not only resulted in a lighter body, but a stronger one, because there were no fiber discontinuities. The NECC team, however, did have to reinforce their fold-up array with three layers of fiberglass so that it did not flap excessively when mounted on their charging rack. As mentioned in Section 5.4, NECC's car probably had the highest composites content of any car in the race.

University of Minnesota had the lightest dry-weight vehicle of all the full-sized solar cars at Sunrayce 95. The Aurora II had a box frame constructed of pre-fabricated fiberglass panels (Figure 6.6.6). Other light-weight features of the Aurora II include Risse air shocks, spoked bicycle rims, bicycle tires, and a well-ribbed composite upper body. MIT's dry weight was just slightly heavier than Minnesota's, and the vehicle had a chromoly steel tube frame bolted to a lightweight composite body shell (Figure 6.6.7).

Though Figure 6.6.2 shows a mild upward slope, weight was probably far from the main reason that the lighter vehicles performed better. The case probably was that the higher-placing teams simply did a better job of engineering the entire car, including weight management.

6.7 Powertrain

Almost every solar car at Sunrayce 95 was propelled by a DC brushless (synchronous AC) motor regulated by a MOSFET-driven motor controller. The power from the motor to the wheel was transmitted in most cases by a single- or double-stage chain or belt drive.

Two teams stood out in the motor department: "Propulsion Systems" award-winner George Washington University and third-place finisher Cal Poly Pomona. Both schools had hub motors in which the drive wheel(s) attached directly to the output shaft(s) of the motor, eliminating the heat losses unavoidable with chain or belt systems. GWU's system is briefly described in Section 5.3. The motor was a joint effort by GWU and Northern Territory University (Australia) Professor Dean Patterson. The motor was originally designed for the NTU solar car, so several modifications were necessary to make it ready for Sunrayce 95. Some of the modifications made by the GWU team were reconfiguring the windings and wire sizes for different torque requirements and redesigning the spindle and hub/wheel interface to deal with the higher loads and different wheels.

What made GWU's motor unique was that the magnetic flux lines ran parallel to the axis of the motor shaft; thus, the designation "axial-flux." Traditional solar-car motors are radial-flux—that is, the flux lines run radially out from the magnets toward the current-carrying coils just inside the motor's outer casing. The axial-flux design allowed GWU to tailor the torque characteristics of the motor for each day's leg by simply adding spacers between the motor's rotor and stator. GWU's motor was very compact, neatly fitting inside the dish of their carbon fiber wheels. This setup was also equipped with regenerative braking and dual windings similar to the Solectria system described later. According to GWU's Cory Knudtson, the motor's torque curve was so flexible from adjusting the air gap that the team seldom used the dual-windings feature. Knudtson estimated the GW's wheel motor and controller system's power efficiency at close to 93 percent. This extremely high power transmission gave GWU a tremendous advantage over most of the

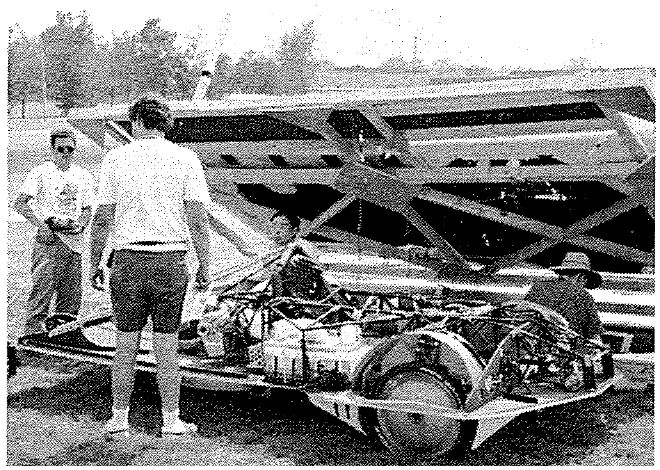


Figure 6.6.7: MIT's solar-array engineer Matt Condell (standing with back to camera) discusses the day's performance. The MIT Manta frame was constructed of 4130 chromoly steel tubes, brazed together. MIT was able to control the weight of the composite body work by using pre-preg composite materials (as did many other teams).

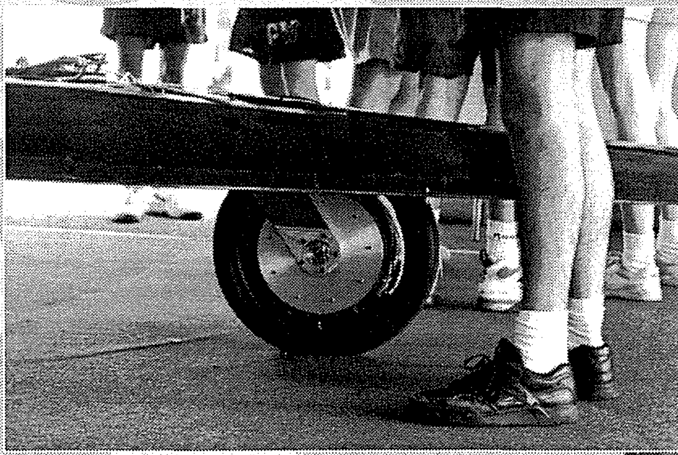
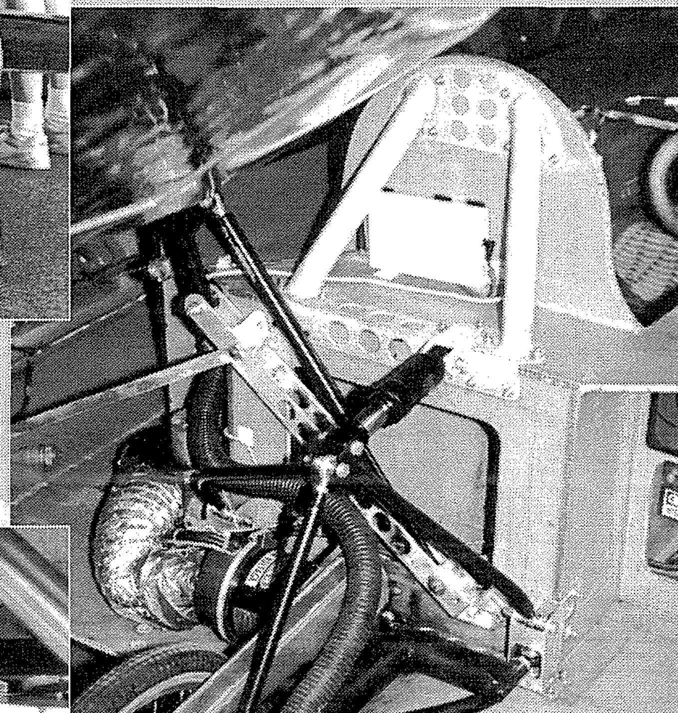


Figure 6.7.1: George Washington University's GW was equipped with the latest in solar-car propulsion technology. The wheel mounted directly to the GW's axial-flux motor, eliminating all transmission losses.

Figure 6.7.2: Minnesota's Unique Mobility motor was mounted on a steel-tube swing-arm assembly. Minnesota ram-air-cooled their motor, but when necessary, a 50-watt blower fan was activated.



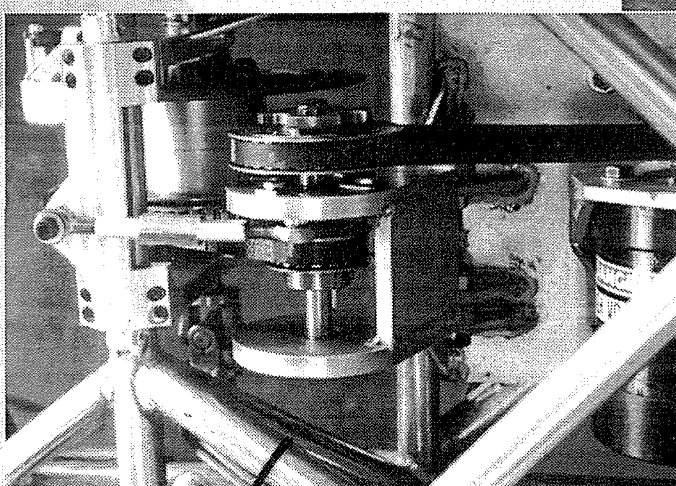


Figure 6.7.3: The transmission system of Western Michigan University's Sunseeker 95. Notice the double-stage belt drive running from the Unique Mobility motor to the differential.

Figure 6.8.1: University of Michigan's Jeff Wimble displays one of their problematic magnesium wheels. Michigan, MIT, and Purdue all used Michelin's radial solar-car tires.

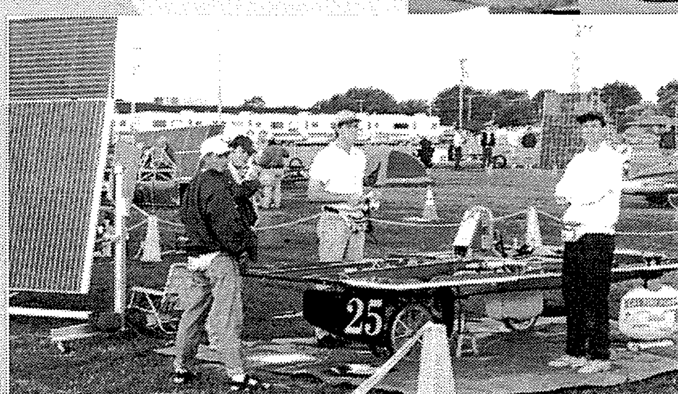


Figure 6.8.2: Cal Poly Pomona team co-captain Brett Gaviglio (far right) and team members pose for the camera in the late afternoon. Notice the 8-spoke aluminum webbed wheels.

field, which had net powertrain (controller-motor-transmission) efficiencies of only 81 to 85 percent.

Cal Poly Pomona's hub motor was a radial-flux machine custom built by Hathaway Inc. The motor housing was mounted to the rear suspension, and an output shaft exited from both ends of the motor. As mentioned in Section 5.3, Cal Poly Pomona's Intrepid Too featured two rear wheels mounted close together on either side of the motor. Cal Poly Pomona experimented with driving both wheels, but due to excessive tire wear when turning, only one of the wheels was driven. Though the motor itself had a claimed power efficiency of about 92 percent, according to Cal Poly Pomona's Tina Shelton, the controller's efficiency was only about 85 percent. Thus, the net powertrain efficiency from controller input to ground was only 78 percent.

Race-winner MIT used a 2-year-old Solectria BRLS8 motor. The motor had been loaned to another team the previous year and was never properly retuned to its specified efficiency. During typical operating conditions, the motor and controller combined ran at approximately 89 percent efficiency as determined by dynamometer tests. This efficiency is about 2 percentage points lower than spec. The Solectria system had two sets of motor windings that could be switched to be connected in series (high torque) or parallel (high speed). This dual-winding configuration effectively gave the driver two "gears" for better driveability in traffic and up hills. The penalty is a small power loss through the large series/parallel switch. The MIT car had a shift lever mounted at the side of the driver that made shifting in the Manta similar in nature to shifting a manual transmission in a regular production car. The MIT Manta was driven through a well-lubricated, single-stage chain drive. Other top teams that used essentially the identical drive system were: Stanford University (5th), Northern Essex Community College (7th), Mankato/Winona State (9th), and University of Missouri-Columbia (10th). A glimpse of the Solectria system can be seen in Figures 6.6.5 and 6.6.7.

The most common motor at Sunrayce 95 was the Unique Mobility DR086s DC brushless unit. Although the Unique motor and controller combination is 6.2 kg (13.7 lbs) lighter than the Solectria system, its claimed power efficiency at typical operating conditions was only 85 percent, versus Solectria's claimed 90+ percent. Second-place University of Minnesota chose the Unique over the Solectria for several reasons, including higher efficiency (according to tests performed at Minnesota's lab), ease of cruise-control adaptation, and cost. Other top-finishing teams that used the Unique system were: Queens (6th), Western Michigan University (8th), University of Maryland (11th), and Drexel University (12th).

Western Michigan University's four-wheeled solar car was the only vehicle at Sunrayce 95 that transmitted its power through a differential. Other wide-track four wheelers such as South Dakota School of Mines and Technology and Purdue University had an asymmetric propulsion system, driving only a single rear wheel. In contrast, the U.S. Military Academy drove both wheels simultaneously through a straight beam axle. Although WMU's differential does contribute a finite amount to the net driveline inefficiency, it is the safe choice for a four-wheeler. One of the most dangerous modes of control loss in a vehicle is the loss of straight-line stability. Some of the ways that a solar-car drive system can malfunction are: motor-controller glitches that cause regenerative braking to be activated, over-heated or contaminated motor bearings that seize the shaft, or a tangled chain or belt that locks up the drive wheel. If any of these events were to occur in a solar car that has an asymmetric drivetrain, a severe yaw moment can be generated unexpectedly. Also, because many solar-car motors, by convention, spin counter-clockwise, many teams mount their motors to drive the left rear wheel. If the left rear wheel were to lock up on a Sunrayce route, the solar car can suddenly swerve into oncoming traffic. The case of sudden acceleration at one wheel causing solar-car directional instability is almost negligible compared to the sudden braking case, because the maximum positive thrust possible out of solar-car application motors is relatively small. Another consideration given for choosing which side to place the drivetrain is road camber, as discussed by Schinckel [6.7.1]. By running a differential, WMU evenly split the motor's torque to the two rear wheels, regardless of motor condition or whether the car was heading straight or taking a turn—all without scrubbing the tires. Western Michigan University's transmission assembly is shown in Figure 6.7.3.

6.8 Tires and Wheels

Reliability is undoubtedly one of the keys to racing success. The most troublesome subsystem of solar cars in Sunrayce 95 was the tire/wheel assembly. With gross vehicle weights ranging from 349 kg (767 lbs) to 579 kg (1273 lbs), the bicycle tires (Avocet Freestyle, ACS RL-Edge) and the lightweight spoked rims were simply overloaded on many vehicles. To add to this, without proper chassis alignment, the tires and wheels could fail. Some common errors include: improper camber adjustment, which created audible spoke "crinkling" noises (not to mention tire wear); suspension components without jam nuts, which nullified any and all rod-end adjustments; and improper thrust-angle alignment, which resulted in tires scrubbing down straight-aways.

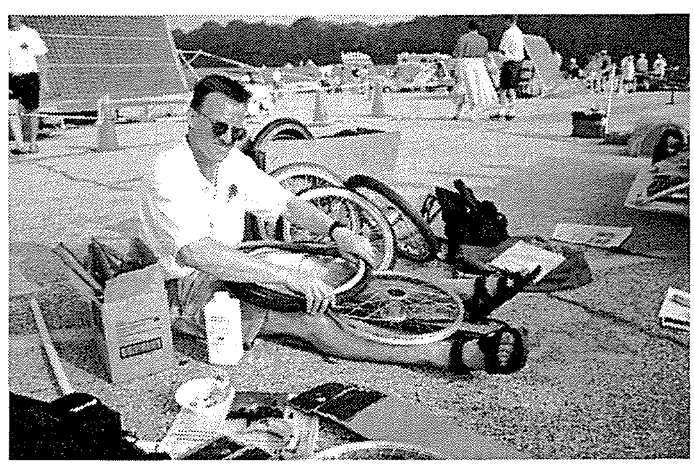


Figure 6.8.3: Inferior components do not equal inferior performance. University of Minnesota used standard bicycle wheels and tires, but experienced only two flat tires. Minnesota completed all 1246 miles and regularly saw speeds in excess of 50 mph. David Craig carefully installs an inner tube using baby powder to keep away dirt and to prevent pinched tubes. Also, notice the heavy-duty rim strips to prevent spoke punctures.

There were only six teams in Sunrayce 95 that had wide-track four-wheeled designs: Western Michigan University (8th), South Dakota School of Mines & Technology (16th), Purdue University (17th), U.S. Military Academy (26th), Columbus State Community College (31st), and University of Quebec (did not finish). There were four other teams that had four-wheelers, but positioned the two rear wheels close together (rear track < 13 in.). Those teams were: Cal Poly Pomona (3rd), Rose-Hulman Institute of Technology (14th), Kauai Community College (15th), and Virginia Polytechnic & State University (35th). All other teams that qualified for Sunrayce 95 ran three-wheelers with two front wheels.

There was actually one two-wheeled vehicle that attempted to qualify for Sunrayce 95. The Roadrunner II from the New Mexico Institute of Mining & Technology team unfortunately did not pass scrutineering due to an accident that badly damaged the car's cigar-shaped body. In this bold approach to solar racing, the car was designed to cruise as a two wheeler with the intention of cutting down on air resistance. At low speeds, a pair of landing gear wheels would retract from the fuselage to provide roll stability.

Many of the top teams equipped their cars with wheels and tires specifically designed for solar racing. However, even these components may be no match for some of the heavier Sunrayce vehicles, because they were designed for the top World Solar Challenge solar cars, which typically have gross vehicle weights of just 275 kg (600 lbs) and far milder braking requirements.

The first-place MIT entry was equipped with the Michelin solar-car tires designed for the former world-champion Biel team. The MIT wheels were custom-made solid magnesium disc wheels (Figures 6.10.1 and 6.6.7). MIT had no choice but to design a ground-up wheel because the tubeless Michelin tires required a specific rim contour to ensure a leak-tight seal. The tires were a 16-in. size by automotive standards—that is, the outside diameter (OD) of the inflated tire was roughly 20 inches. Typical inflation pressures were about 85 psi. On the rainy days (except for the last low-speed day) and Day 4 (to conserve the Michelins), MIT used fully treaded moped tires with inner tubes. It was later found that these tires consumed several hundred extra watts. The MIT team experienced no flats during the race.

Third-place Cal Poly Pomona used the tubeless Dunlop Solar Max tires that were raced by the Toyota Motor Company in the 1993 World Solar Challenge in Australia. Because Pomona had an in-hub motor, they used different-sized tires to change the effective gear ratio. The Dunlops came in 14-in. and 17-in. sizes, which resulted in tire ODs of 19 in. and 21 in., respectively. The Pomona team also used a standard 20-in. x 1.75-in. ACS bicycle tire (20-in. tire OD) as a third alternative. The wheels used for the Dunlops were Excel aluminum rims supplied by Dunlop, fastened to custom-made aluminum webs (Figure 6.8.2). Pomona's Intrepid Too experienced six flats during the race.

Fourth-place George Washington University used the Bridgestone Ecopia solar-car tires, also tubeless, raced by the Kyocera team in Australia. These tires were a 14-in. size, again by automotive standards, which resulted in a 19-in. OD tire. The GW used GH-Craft carbon fiber disk wheels weighing a scant 1.02 kg (2.24 lbs) each. GH-Craft made similar wheels for several teams for use in solar-car races in Australia and Japan. The GW experienced only one flat during the race, despite inflating the tires to 130 psi. According to GWU's Cory Knudtson, the rolling resistance coefficient quoted by Bridgestone at this inflation pressure was an impressive 0.0045. The Bridgestones were available in three rubber hardnesses. The GW's wheels and tires are shown in Figures 6.7.1.

Several other teams used specialized solar-car racing tires. Purdue mounted Michelins with inner tubes on motorcycle rims, and they experienced four flats. University of Michigan also ran with Michelins on custom-made, ultra-light, 3-spoke, cast magnesium wheels. After two wheel failures, the magnesium wheels were replaced by solid aluminum disk wheels. The Michigan team

Table 6.8.1: Tire- and Wheel-Related Incidents.

Initial Failure/Cause	Speed	Secondary Failures	Team
Rear-tire side wall failed due to overload or over-inflation.	30 mph.	None.	Stanford
Rear blowout.	55 mph.	Front flat.	NECC
One of rear tires blew out.	45 mph.	Broken rear suspension arm.	Kauai C.C.
Rear tire failed.	45 mph.	None.	Iowa State
Right front tire failed.	20 mph.	Wheel collapsed.	Texas A&M
Rear tire failed due to over-inflation or spoke overload.	20-30 mph.	Front tire failed during emergency stop.	U. of Missouri-Rolla
Rear tire failed due to over pressure or spokes.	Unknown.	None.	Cal State, Long Beach
a) Wheel failure at qualifier. b) Wheel failure on road. c) Rear flat	a,b) Unknown. c) 35 mph.	a,b) Damaged brake and suspension components. c) Broke steering cable, parts of array and body.	U. of Michigan

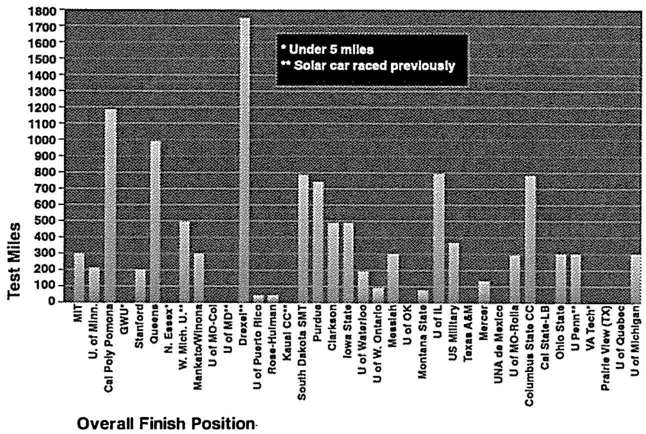


Figure 6.9.1: Number of pre-race test miles plotted against overall finish order. Test miles may include bare chassis testing, as well as prototype car mileage. (Some data provided by University of Pennsylvania survey.)

graciously loaned MIT spare tires after their withdrawal.

There were several teams—not lucky enough to land a sponsorship with the above-mentioned tire manufacturers—that used standard bicycle tires, with custom-made wheels. Those teams included: Northern Essex Community College, with carbon fiber/Nomex composite disc wheels (Figure 5.4.1); Clarkson University, with aluminum mag wheels; University of Oklahoma, with solid composite discs; and University of Pennsylvania, with Rohacell/Kevlar/carbon disc wheels. Table 6.8.1 summarizes some of the tire/wheel-related incidences that occurred during Sunrayce 95.

Figure 6.9.2: The Queens team from Canada used a Duralcan frame that lasted just long enough to carry the Quest to a sixth-place overall finish.

6.9 Solar-Car Testing

Testing is crucial to any and every engineering discipline. No team should ever replace testing with sophisticated modeling analysis or confidence in their experience. Testing is where a large portion of the lessons of the Sunrayce experience surfaces.

The amount of pre-race test mileage for Sunrayce 95 teams in their respective finishing order is plotted in Figure 6.9.1. Similar to the data for almost all the other performance criteria, there is no clear trend. Race-winner MIT had about 300 miles of pre-race testing, of which about 100 miles were cumulated in Indianapolis in daily commutes to IRP. MIT's only unscheduled stop came on the last day when rain infiltrated the motor controller. The motor's gear ratio had been changed in the rain that morning, and the rear-wheel cover was reattached in a hurry with damp duct tape. The rain seeped in and shorted the controller. After the race, the controller was inspected. Though some corrosion was evident on the controller's chip boards, the unit was still functional. Ironically, MIT had tested their car in the rain, but back on campus where the team was not as rushed.

Though second-place Minnesota only had 200 actual on-road test miles, the team thoroughly bench-tested many of their components in lab. Their car ran flawlessly with the exception of two flat tires. Perhaps third-place Cal Poly Pomona had the most extensive test regimen for their Intrepid Too with 1200 test miles. Pomona first started driving there car lightly around isolated roads on campus. Next, they tested on a closed-loop track under controlled conditions for power consumption characterization. Finally, they headed out for four full weekends of road testing.

Fourth-place George Washington University and seventh-place Northern Essex Community College had less than 5 miles of testing combined. The GWU case is unusual, because their car was one of the most "finished" looking cars of the event. Both teams had members with Sunrayce roots as deep as the 1990 GM Sunrayce USA. GWU's GW, a second-generation car, ran surprisingly well for an untested car. It had several problems at scrutineering involving the canopy, wheel fairings, and brakes, and started the race near the back of the pack. Over the first few days, many of these problems were corrected, but a new problem was realized on the second day: the array (Section 5.3). The defective array could not be repaired and possibly cost GWU a spot in the winner's circle.

On the other hand, the NECC car, which was started less than 6 months before the race, ran almost perfectly. The problems encountered were flat tires and a blown controller. Because these failures were not consistently problematic, pre-race testing probably would not have made NECC change their design. What really eliminated NECC from the top slots was poor charging-period weather.

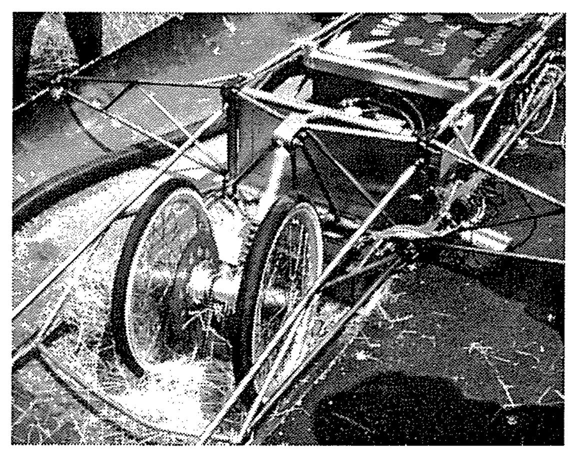


Figure 6.9.3: Kauai Community College broke their titanium rear suspension on Day 3, just after the mid-day. Team members had the broken assembly repaired by a local welder who had never welded titanium before. The weld broke as the team was wheeling their solar car into the impound tent [6.9.1].

Again, because this weather risk was inherent in their strategy, testing probably would not have made them modify their car or strategy.

Near the end of Queens University's 1000 miles of road testing, their Duralcan (ceramic aluminum) tube frame developed a crack. Though it was too late to significantly modify the chassis, this failure was fair warning of what the team should look out for during the race. Though there were no failures during the race, the frame developed numerous cracks at the joints in post-race evaluation sessions. Had these failures occurred during Sunrayce, Queens could have suffered severely. The Queens Quest frame is shown in Figure 6.9.2.

Several schools "recycled" their Sunrayce 93 solar cars. Those teams include: Western Michigan University (8th), University of Maryland (11th), Drexel (12th), and Kauai Community College (15th). The test mileage data shown in Figure 6.9.1 for these teams are the estimated number of miles put on those solar cars in their Sunrayce 95 configurations. WMU's major change was in the power hardware with a brand new array and a new battery pack to comply with the new rules. WMU tested about 500 miles in the new configuration and had a few minor, but potentially costly, on-route problems such as loosening drivetrain parts and telemetry glitches. The chassis, however, was very dependable, finishing the race without even a single flat tire.

University of Maryland's Pride of Maryland II.1 ran very well also. One problem that slowed them down was a seized motor on Day 2. According to Maryland team co-captain Marcus Howell, the team originally thought the problem was road construction debris contaminating their motor. However, upon further inspection, there was a bolt jammed between the magnets and the coils. Luckily, a Unique Mobility engineer was on site and loaned the Maryland team a motor. Though the spare motor was not the same model, it allowed the team to finish the race.

Drexel brought back their 1993 car with a new array and several updated suspension components. The Drexel team started practicing for Sunrayce 95 about a year earlier by competing in the 1994 American Tour de Sol. Drexel's Sun Dragon IV had a few temporary electrical problems, but ran most of the race without difficulty. Finally, Kauai Community College brought back their successful entry from 1993 with modifications to meet the new rules. Kauai Community College's major setback occurred when their titanium rear-suspension arm broke during a crash caused by a flat tire.

What is not evident from these test mileage figures is how those test miles were put on the solar car. If a team had access to a smoothly paved long straight road or a smooth racing oval, it is possible to

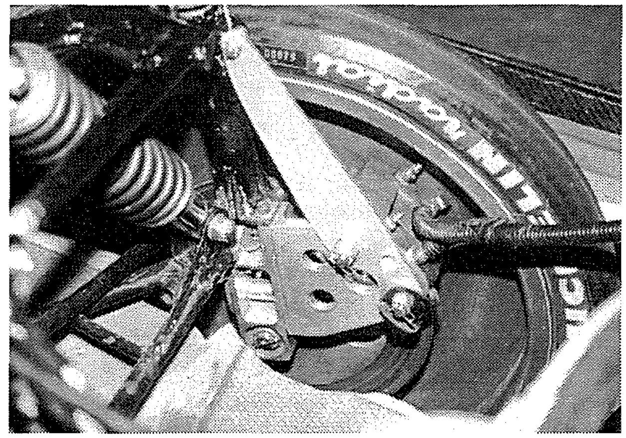


Figure 6.10.1: Close-up of the MIT Manta's front brake assembly. Note the dual brake lines protected by a plastic shield. The pistons on either half of the caliper were connected to separate master cylinders. MIT used fully treaded moped tires on the rainy days, since the limiting braking factor on wet roads is tire traction. The sprung hardware shown was hidden from the wind as discussed in Section 6.5.

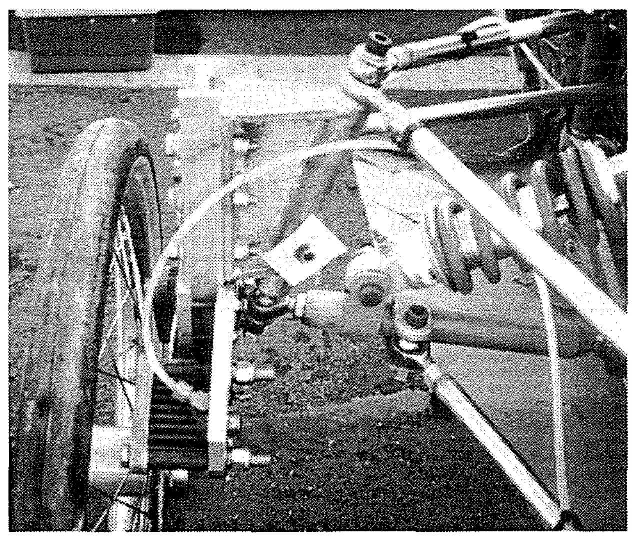


Figure 6.10.2: Close-up of the Iowa State Cynergy's front brake system. An equivalent brake caliper is mounted on the other side of the aluminum I-beam upright.

Table 6.9.1: Time Lost to Unscheduled Occurrences for Top-5 Finishers of Sunrayce 95.

Team	Breakdowns	Penalties	Total Time Lost
1. MIT	15 min. (wet controller)	31 min.	46 min.
2. U. of Minn.	15 min. (two flats)	5 min.	20 min.
3. Cal Poly Pomona	2 hrs 29 min. (flats, electrical, road-side charging for ~2.5 hrs).	25 min.	2 hrs 54 min.
4. GWU	2 hrs 35 min. (one flat, fix fairing, motor glitch, loose wheel, road-side charge for 100+ min.)	6 min.	2 hrs 41 min.
5. Stanford	55 min. (flats, chain, gear change, wheel covers.)	20 min.	1 hr 15 min.

rack up many miles of power efficiency testing without ever mechanically stressing the vehicle. Traditionally, many teams tend to baby their cars during testing because they had worked so hard to construct it. Often in these cases, the flaws do not show up until the middle of Qualifying or even as late as the last leg of the race.

A true test of how well a team constructed the solar car they had on paper (or computer monitor) is to compare how close the car's performance was to the predicted performance. Because these data were not available, the closest comparison that can be made is the amount of time lost to unscheduled occurrences. This of course assumes that all teams did not plan on breaking down or being penalized. This last statement may sound absurd, but some teams (particularly in the World Solar Challenge) actually do design in a certain number of flat tires into their strategy so that they can run with fragile ultra-low rolling resistance tires [6.5.11]. However, this type of strategy would not be wise in Sunrayce because it is held on populated roads. Also, as shown in Figure 4.13.1, some teams drove fewer miles than other lower-finishing teams. In fact, according to University of Maryland co-captain Marcus Howell, Maryland's strategy program had subroutines that estimated their car's performance for almost every conceivable race situation, including: "wait and charge," "tow to the finish and charge," and "tow half way, charge, and finish towing." Although in the case of Rose-Hulman Institute of Technology, absorbing the towing penalty in exchange for greater solar charging time was not figured into their strategy, they still finished ahead of nine teams that completed more miles.

The amount of time lost by the top-5 teams over the entire race course is shown in Table 6.9.1. MIT stopped only once for about 15 minutes, but had the greatest amount of penalty time of the top-5. University of Minnesota stopped twice for flat tires and netted only 5 minutes of penalty time. Third-place Pomona and fourth-place GWU both had several electrical and mechanical problems on the road, but the brunt of their road-side time came on the final day when they had to stop and charge. Pomona eventually finished under their own power, but GWU was trailered when the final day's race was called off earlier due to weather. Stanford encountered a series of minor setbacks on the road and amassed 20 minutes of penalties. Stanford never had to stop and charge on route.

6.10 Brakes

The MIT Manta was equipped with a set of opposing-piston caliper brakes up front and regenerative brakes in the rear. The front calipers floated on heat-treated chromoly brake bracket pins, and the inboard and outboard caliper pistons for each wheel were connected to separate master cylinders. With the two master cylinders connected in parallel to the pedal, this arrangement allowed the brake-pedal travel required to close a given gap between the brake pads and the disc to be halved. If one master cylinder were to fail, the dead caliper piston sides (inboard or outboard) would simply act as anvils as in standard single-sided brake calipers. Even in this failure mode, the braking power potential is not compromised. The MIT brake system is shown in Figure 6.10.1.

The MIT Manta's rear regenerative brakes were actuated by a small brake lever mounted on the left-hand side of the handlebar. The shift lever for the motor's series/parallel winding switch was mounted on the right side of the driver. This ergonomic arrangement allowed swift downshifts (parallel to series) for full use of the regenerative brakes even under mildly severe braking situations. Because the front and rear brakes were decoupled, the chances of a spinout caused by a rear wheel lockup due to slippery roads or a flat tire was greatly reduced. This feature is especially crucial for three-wheelers (with two front wheels) since only one tire contact patch anchors the car from spinning out.

Iowa State's Cynergy was equipped with two completely separate sets of front caliper brake assemblies. The brakes were actuated by motorcycle hand brake levers on either side of the handlebar, and two brake calipers were mounted on each of the front suspension uprights. The advantage of this system is that the brake system can not be shut down by a broken brake pedal (or lever) or caliper mount, both highly stressed components. However, a disadvantage of this system is that if one system fails, the car is left with only half the design braking power. The Iowa State brake system is shown in Figure 6.10.2.

Many teams opted to use a single mechanical brake system up front and a mechanical brake in addition to regenerative brakes in the rear to pass the brake system requirement. In many cars, the regenerative brake activation was not decoupled from the mechanical brake system. Depending on the regenerative brake calibration and the weight transfer characteristics of the solar car, this type of brake system can lead to a loss of traction at the rear wheel(s). Rear-end lock-ups resulted in more than a few displaced cones during the brake tests.

There was at least one team that used a rear tire scrubber as their secondary brake system. Though this type of brake system may be alluring due to its mechanical simplicity and ease of installation, it should be avoided for safety reasons. The use of such a brake system, other than when the vehicle is stopped (parking brake), can easily lead to a flat rear tire and yaw instability.

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Sunrayce Appendix

California State Polytechnic University

Car: #25—"Intrepid Too," California State Polytechnic University, Pomona, College of Engineering, 3801 W. Temple Avenue, Pomona, CA 91768; Contact: 909-869-4367
Team Captains: Dave Chen, Brett Gaviglio, Jeff Michaels
Faculty Advisors: Dr. Michael T. Shelton, Prof. Gerald Herder, Mr. Bill Watson
Cost: $50,000 (car); $135,000 (project)
Project Time: 1 year
Drag Area (CdA): 0.13 m^2 (1.4 ft^2) (matching performance data)
Cd (based on frontal area): 0.14
Frontal Area: 0.9 m^2 (9.7 ft^2)
Gross Vehicle Weight: 393 kg (865 lbs)
Length: 4.5 m (14.8 ft)
Width: 1.7 m (5.6 ft)
Height: 1.2 m (3.9 ft)
Wheelbase: 2.2 m (7.1 ft)
Track Width (front / rear): 1.4 m (4.5 ft) / 0.2 m (0.7 ft)
Ground Clearance: 0.4 m (1.4 ft)
Wheels: 4 wheels; custom spoked aluminum
Tires: Dunlap 2.25" x 14" and 2.25" x 17" solar-car tires; ACS 20" x 1.75" and GT 16" x 2.75" bicycle tires
Estimated Crr: 0.0055-0.010
Flats in Qualifier / Race: 1 / 6
Brakes: Hydraulic disc brakes
Suspension: (Front) motorcycle suspension
Steering: Rack-and-pinion
Chassis: Composite of carbon, Kevlar, fiberglass, and Nomex honeycomb
Motor/Controller: Hathaway Corp., 4-hp, dual windings, brushless DC, 1400 rpm, 900 operating
Transmission: None
Controls and Instrumentation: (1) Cruise control for driver. Digital display of motor rpm, battery voltage and current, controller temperature and battery amp-hours. Analog gauges with battery current, motor current, battery voltage. (2) 21 channels of data telemetered to lead vehicle and acquired by laptop computer for display and analysis. Included 7 battery voltages, 8 array zone currents, motor and controller temperatures, rpm, battery and motor controller currents, and on-board measured amp-hours.
Batteries: Delphi Automotive Systems, seven 12-volt modules, 134 kg (295 lbs)
Solar Cells: Siemens Solar, monocrystalline silicon, 14.1% efficiency, cut and arranged into 8 zones.
Panel Voltage: 160 V peak
Notes and Problems: (1) Series/parallel switch quit working on Day 2. Put into parallel for rest of morning. (2) Motor controller heating problem when running at high speed in parallel. (3) Wheel caps came off several times during the race. (4) Large dog ran between lead vehicle and solar car on Day 2. Intrepid Too swerved into next lane to avoid impact. (5) On rest day—in the pouring rain—a short in the solar array created smoke and excitement.

California State University, Long Beach

Car: # 195—"SolarWave," California State University, Long Beach, USU Box #346, 1212 Bellflower Blvd., Long Beach, CA 90815; Contacts: Levi Javier, Joe Styzens, 310-985-5145
Team Captains: Levi Javier, Joe Styzens
Faculty Advisor: Dr. Reza Toossi
Cost: $275,000
Project Time: 2.75 years
Number of Test Miles: 473
Frontal Area: 1.46 m^2 (15.75 ft^2)
Gross Vehicle Weight: 415 kg (912 lbs)
Length: 5.9 m (19.52 ft)
Width: 2.0 m (6.52 ft)
Height: 1.2 m (3.79 ft)
Wheelbase: 2.6 m (8.67 ft)
Track Width (front / rear): 1.5 m (5.0 ft) / 0
Ground Clearance: 0.12 m (0.39 ft)
Wheels: 3 wheels; 16.5", 36-spoke bicycle rims with 14-gauge galvanized spokes
Tires: ACS RL Edge 20" x 1.75", 100 psi
Flats in Qualifier / Race: 1 / 1
Brakes: 300-102 Wilwood calipers with 300-001 1.25" brake assembly
Suspension: (Front) student-designed double A-arms with Performance Works custom shocks; (Rear) student-designed wish-bone suspension with Performance Works custom shock
Steering: C42-344 Steletto rack-and-pinion 15:1
Chassis: 6061-T6 aluminum student-designed space frame
Motor/Controller: Solectria BRLS-8 DC brushless; BRLS-100H motor controller
Transmission: None
Controls and Instrumentation: 2 Micronto DMMs, AH-100/SH-100 Solectria Ah meter, 2 AMP150 Solectria amp meters, Circuitmate DM25L, BX 612 speedometer
Batteries: U.S. Battery, 12 batteries, 144 VG, 120 kg (264 lbs)
Solar Cells: ASE Americas, 850 cells, 14% efficiency, 100 mm x 100 mm
Power Max on Road: 700 W
Power Avg on Road: 500 W
Power Max Charging: 900 W

Panel Voltage: 12 V
Notes and Problems: (1) Lack of documentation. (2) Low tensile strength on wheels. (3) Weak brakes.

Clarkson University

Car: #4—"Helios," Clarkson University, Box 5725 Clarkson University, Potsdam, NY 13699; Contact: Leslie Ann Hummel, 315-268-3909
Team Captain: Louis Fasulo
Faculty Advisor: E.F. Thacher
Cost: $33,800 (car); $200,000 (project)
Project Time: 2 years
Number of Test Miles: 500
Drag Area (CdA): 0.139 m^2 (1.5 ft^2) (wind tunnel)
Cd (based on frontal area): 0.095
Frontal Area: 1.46 m^2 (15.7 ft^2)
Gross Vehicle Weight: 485 kg (1066 lbs)
Length: 5.969 m (19.6 ft)
Width: 1.995 m (6.5 ft)
Height: 1.116 m (3.7 ft)
Wheelbase: 3.073 m (10.1 ft)
Track Width (front / rear): 1.422 m (4.7 ft) / 0
Ground Clearance: 0.363 m (1.2 ft)
Wheels: 3 wheels; custom, aluminum
Tires: Avocet Fastgrip Freestyle, 20" x 1.75", 100 psi
Estimated Crr: 0.005
Flats in Qualifier / Race: 2 / 1
Brakes: Front and rear hydraulic caliper (adapted mountain bike) and regenerative
Suspension: (Front) composite spring; (Rear) 3 mountain-bike shocks, double A-arm with strut.
Steering: Rack-and-pinion
Chassis: Semi-monocoque carbon composite
Motor/Controller: Solectria BRLS-8
Transmission: direct chain drive, 5.15:1 reduction for most of race
Controls and Instrumentation: Throttle, regeneration, reverse, high-low torque
Batteries: Eagle Pitcher, 40 cells, 36 Ah, 140 kg (309 lbs)
Solar Cells: ASE Americas, 1680 crystalline cells, cut in half and laminated into modules by AstroPower
Power Max on Road: 1200 W
Power Avg on Road: about 750 W
Power Max Charging: about 1200 W
Panel V: 120 V nominal
Notes and Problems: (1) Car was probably 91 kg (200 lbs) too heavy. (2) Should have carried extra solar cells for charging periods. (3) Best aspects were fundraising, vehicle design and construction, and race performance.

Columbus State Community College

Car: # 92—"Spirit of Columbus," Columbus State Community College, Columbus, OH.
Team Captain: Delbert Bructi
Faculty Advisors: Shane Bendle, Dick Bickerstaff, Chris Fleece, Dick Haynes, Herb Jefferson, Tom Kesler, Bob Queen
Gross Vehicle Weight: 579 kg (1273 lbs)
Length: 6.0 m (19.7 ft)
Width: 2.0 m (6.6 ft)
Height: 1.4 m (4.6 ft)
Wheels: 4 wheels, rear wheels 46 cm (18") motorcycle wheels; front wheels 38 cm (15") magnesium automotive wheels
Tires: Goodyear, 38 cm x 8.9 cm (15" x 3.5") racing tires
Brakes: Dual hydraulic, caliper, disk brakes (front and rear)
Chassis: High-strength alloy, tubular steel, welded space structure
Motor/Controller: GE 4-hp, brushed DC, 32 kg (71 lbs)
Batteries: Delphi Automotive Systems, 36 V, 133 kg (293 lbs)
Solar Cells: Siemens Solar
Power Max Charging: 1210 kW

Drexel University

Car: #76—"SunDragon IV," Drexel University, SunDragon Solar Racing Team, ECE Department, 32nd and Chestnut Streets, Philadelphia, PA 19104; Contacts: Race Planning and Strategy Office, 215-895-1288; Main Research and Development (RYD) Area, 215-895-1969
Team Captains: Walter Bednarz (Team leader), Ryan Cahili (Race planning & strategy division leader), Todd Zielinski (Electrical engineering division leader), Doug Austin (Mechanical engineering division leader)
Cost: $75,000 (initial construction, '92-'93); $20,000/year (maintenance/upgrades, '94-'95)
Project Time: Drexel has been in solar car racing since 1989, with teams formed each year. For Sunrayce 1995, the 1995 team was formed to modify SunDragon IV.
Drag Area (CdA): 0.13 m^2 (1.4 ft^2) (data analysis; simulation)
Cd (based on frontal area): 0.13
Frontal Area: 1 m^2 (10.8 ft^2)
Gross Vehicle Weight: 404 kg (888 lbs)
Length: 5.9 m (19.4 ft)
Width: 2.0 m (6.6 ft)
Height: 1.0 m (3.3 ft)
Wheelbase: 1.8 m (5.9 ft)
Ground Clearance: 0.3 m (1.0 ft)
Wheels: 3 wheels; Sun rims; 48-spoke, 5-cross pattern, custom hubs
Tires: 26" specialized Fatboy Slicks; mountain bike
Estimated Crr: 0.3
Flats in Race: 3
Brakes: (Front) hydraulic disc, dual-cylinder; (Rear) regenerative
Suspension: (Front) dual A-arm; (Rear) trailing arm, nitrogen-charged shocks.
Steering: Custom
Chassis: Graphite monocoque composite (carbon fiber, structural glass, Nomex)
Motor/Controller: Unique Mobility, 10-hp (7.5-kW) brushless DC; Unique Mobility motor controller
Transmission: Gates poly chain (belt); custom aluminum pulleys (gears)
Controls and Instrumentation: Custom control box and instrumentation
Batteries: U.S. Batteries, lead-acid, 5.0-kW capacity
Solar Cells: ASE Americas, 14% efficiency; 8 m^2 (86 ft^2)
Power Max Charging: 1100 W peak

Panel Voltage: 108 V

Notes and Problems: (1) Temporary electrical problem early in qualifiers. (2) During race, almost crashed into pickup truck that flipped over 10 ft in front of the solar car while we were cruising at 50 mph. Crash not caused by anything related to team or race. (3) Chase vehicle and trailer got stuck in mud. (4) Temporarily lost a string of solar cells. (5) Temporary brake loss (low brake fluid) in first leg of Day 5. (6) Traffic.

George Washington University

Car: #7—"GW," George Washington University, 801 22nd St., N.W., Suite T704, Washington, D.C. 20052; Contact: Cory Knudtson, 202-994-5952

Team Captain: Cory Knudtson

Faculty Advisor: Dr. Nabih Bedewi

Cost: $300,000

Project Time: 1.5 years

Number of Test Miles: 0

Drag Area (CdA): 0.15-0.17 m^2 (1.6-1.8 ft^2) (VS-AERO methods)

Frontal Area: 0.60 m^2 (6.5 ft^2)

Gross Vehicle Weight: 386 kg (850 lbs)

Length: 5.99 m (19.7 ft)

Width: 1.84 m (6.0 ft)

Height: 0.96 m (3.1 ft)

Wheelbase: 2.25 m (7.4)

Track Width (front / rear): 1.02 m (3.3 ft) / 0

Ground Clearance: 0.35 m (1.1 ft)

Wheels: 3 wheels; GH Craft 14" carbon dished

Tires: Bridgestone Ecopia, 130 psi

Estimated Crr: 0.005

Flats in Qualifier / Race: 0 / 1

Brakes: (Front) drum brakes (redundant cable actuation); (Rear) regenerative braking

Suspension: (Front) dual A-arm with single shock/spring; (Rear) dual A-arm with two shock/springs

Steering: Rack-and-pinion

Chassis: Carbon monocoque, hollow hat-stiffener construction

Motor/Controller: Brushless DC permanent magnet axial flux wheel motor, 10-kW continuous capability. Modified Solectria controller.

Transmission: No mechanical transmission

Controls and Instrumentation: 80386-based instrumentation system; computer cruise control, plus foot pedal and dashboard controls; regenerative braking potentiometer; desired speed and power drain set by custom interface on the steering wheel, including a 4x20 LCD screen.

Batteries: Delphi Automotive Systems, seven 12 V batteries, plus one 12 V, 6.5 Ah, 5.4 lb (2.5 kg) Johnson Controls battery included in the 140-kg (309-lb) pack.

Solar Cells: ASE Americas, shingled, spray conformal coating

Power Max on Road: 430 W

Power Max Charging: 520 W

Iowa State University

Car: #9—"PrISUm Cynergy," Iowa State University, Team PrISUm, 110 Marston Hall, Ames, IA 50011; Contact: Beth Hunter, 515-294-0899

Team Captain: Beth Hunter

Faculty Advisors: Dr. James Hill, Dr. William James, Dr. Alan Potter, Terry Herrmann, Charlie Burg

Cost: $100,000 (car construction); $70,000 (racing and testing)

Project Time: 2 years

Drag Area (CdA): 0.08 m^2 (0.86 ft^2) (Electronic Data Systems fluid dynamic analysis)

Cd (based on frontal area): 0.08

Frontal Area: 1.0 m^2 (10.8 ft^2)

Gross Vehicle Weight: 445 kg (979 lbs)

Length: 6.0 m (19.7 ft)

Width: 2.0 m (6.6 ft)

Height: 1.1 m (3.6 ft)

Wheelbase: 1.0 m (3.3 ft)

Track Width (front / rear): 1.4 m (4.6 ft) / 0

Ground Clearance: 0.20 m (0.7 ft)

Wheels: 3 wheels; 20", 36-spoke

Tires: Avocet Fastgrip 51 cm x 4 cm (20" x 1.75") slick tires, 100 psi

Estimated Crr: 0.0055

Flats in Qualifier / Race: 3 / 9

Brakes: Redundant front and rear hydraulic Airhart disk brakes; regenerative braking.

Suspension: (Front) double A-arm in front with Works Performance coil over gas shocks; (Rear) trailing arm with Works Performance coil over gas shock.

Steering: Ackerman/cable steering, half-turn lock to lock

Chassis: 4130 Chromoly 2.5-cm (1") OD x 0.124-cm (0.049") wall space frame, Kevlar body

Motor/Controller: Unique Mobility, DC brushless, 3.2 kW (4.3 hp) rated, 3.9 kg (8.7 lbs), 5500 rpm, 84 V, 10.76 kg (24.3 lbs) with controller, 86% efficient at operating power level of 800 W, 92% peak efficiency at 2000 W; blower cooling.

Transmission: Cog belt drive to rear wheel, 6.5:1 ratio

Controls and Instrumentation: Constant power/constant speed motor controller; cockpit display of motor rpm, total battery pack voltage, individual battery voltages, ampere/hour for batteries and ampere/hour for array.

Batteries: Delphi Automotive Electric Vehicle, 7 batteries, 84 V, 5376 kWh, 64 Ah, 133 kg (293 lb)

Solar Cells: ASE Americas, 1550 monocrystalline silicon cells, 14.1% single-cell rated efficiency, 7% overall panel efficiency. 7 modules on top and 4 modules on bottom. 11 maximum-power-point trackers, 98% efficient. AstroPower encapsulation.

Power Max on Road: 760 W

Power Avg on Road: 760 W

Power Max Charging: 550 W

Notes and Problems: (1) ISU practiced 640 miles of actual race course with "PrISUm II," its Sunrayce 93 entry. 400 miles of actual race course and 100 miles of other courses were practiced with "PrISUm Cynergy." (2) Solar array experienced much lower efficiency than expected due to overheating of cells because of type of encapsulation used. (3) On last day of race the batteries were changed. An accident occurred about 30 miles from finish line at 45 mph. While driving over a bridge expansion joint, rear tire slipped out of rim, causing intertube to explode. Rim on wet pavement did not provide enough traction to maintain directional stability and "PrISUm Cynergy" collided with concrete bridge rail. Accident permanently disabled the vehicle. This incident showed that all safety systems responded to impact as designed. Since Sunrayce 95, Team PrISUm has rebuilt frame and now has an electric vehicle (array has not yet been replaced). (4) Average speed on last day without penalties was 28 mph.

Kauai Community College

Car: #8—"Ka'a La O Kaua'i," Kauai Community College, Lihue, HI.
Team Captain: Jerry Raquel
Faculty Advisors: Rick Matsumura, Francis Takahashi, Alan Templeton, Tracy Tucker, Charles Yamamoto
Gross Vehicle Weight: 416 kg (916 lbs)
Length: 6.0 m (19.7 ft)
Width: 2.0 m (6.6 ft)
Height: 1.1 m (3.6 ft)
Wheels: 4 wheels, aluminum, 36-spoke, 51 cm (20")
Tires: Avocet, 51 cm x 4 cm (20" x 1.75") slick
Brakes: Hydraulic disk
Chassis: Welded titanium tubing, 2.5 cm (1")/3.18 cm (1.25"), 0.14 cm (0.056") wall
Motor/Controller: Solectria, 8 hp
Batteries: Delphi Automotive Systems, 84 V, 134.5 kg (296 lbs)
Solar Cells: Siemens Solar
Power Max Charging: 1053 W

Mankato State and Winona State Universities

Car: #3—"Northern Light III," Mankato State and Winona State Universities, Automotive Engineering Technology, Mankato State University 48, Mankato, MN 56002-8406; Contact: Bruce Jones, 507-389-6700
Team Captains: Kevin Schatz, Ryan Minnig
Faculty Advisor: Dr. Bruce Jones
Cost: $30,000
Project Time: 18 months
Gross Vehicle Weight: 349 kg (767 lbs)
Length: 6.0 m (19.7 ft)
Width: 2.0 m (6.6 ft)
Height: 1.1 m (3.6 ft)
Wheelbase: 1.93 m (6.3 ft)
Track Width (front / rear): 1.54 m (5.1 ft) / 0
Ground Clearance: 0.23 m (0.8 ft)
Wheels: 3 wheels; Sun Chinook 26" x 1.95" (drive); Sun Rhyno 26" x 1.95" (front)
Tires: Tioga City Slicker 130 Tektite 26" x 1.95"
Flats in Qualifier / Race: 0 / 0
Brakes: Pro-Stop mountain cycle calipers with 8" rotors
Snspension: (Front) aluminum double A-arm, Bimba air cylinders for shocks; (Rear) rectangular tubing mond-stay
Steering: Rack-and-pinion
Motor/Controller: Solectria BRLS-8, DC brushless, 15-hp max peak, 8-hp continuous
Transmission: Electric. Series and parallel wound motor; chain drive with quick-change gears
Batteries: GTX-3000, 8.2 kg (18 lbs) each; 26 Ah each
Solar Cells: ASE Americas, 781 cells, laminated
Power Max on Road: 942 W
Power Avg on Road: 514 W
Power Max Charging: 982 W

Massachusetts Institute of Technology

Car: #17—"Manta," Massachusetts Institute of Technology, 77 Massachusetts Ave, MIT room 20D-007, Cambridge, MA 02139; Contact: 617-253-6140
Team Captain: Goro Tamai
Faculty Advisor: Kathleen Allen
Cost: $75,000 (includes monetary, service, and material donations)
Project Time: 1.5 years total (1 year for construction).
Number of test miles: 300
Drag Area (CdA): 0.134 m^2 (±.006m^2) (1.4 ft^2) (from road power consumption data. Aero development by 1/4-scale wind-tunnel tests, computer simulations, and road tests.)
Cd (based on frontal area): 0.12
Frontal Area: 1.1 m^2 (11.8 ft^2)
Gross Vehicle Weight: 370 kg (814 lbs)
Length: 4.55 m (14.9 ft)
Width: 1.98 m (6.5 ft)
Height: 1.01 m (3.3 ft)
Wheelbase: 1.78 m (5.8 ft)
Track Width (front / rear): 1.27 m (4.2 ft) / 0
Ground Clearance: 0.29 m (0.96 ft)
Wheels: 3 wheels; 16" machined magnesium disc
Tires: (Front) Michelin radials, tubeless. 65/80-16. 80-100 psi. (Rear) Cheng-Shin moped tire (75% worn) with Pro-lite tubes, 16" x 2.25", 85+ psi.
Est. Crr: 0.0072 ±.0004
Flats in Qualifier / Race: 2 / 0
Brakes: Dual-piston enduro kart hydraulic calipers, aluminum rotors (front); regenerative (rear).
Suspension: (Front) double wishbone with coil-over shock. Kinematics optimized to minimize tire scrub; approximately zero track change, camber change and bumpsteer. Roll stiffness of 10 degrees per lateral g'; natural frequency of 2 Hz; damping ratio of 0.4; (Rear) aluminum box beam trailing arm with coil-over shock. Natural frequency of 2 Hz, damping ratio of 0.4.
Steering: Handlebar to rack-and-pinion to tie-rods, one full Ackerman progression.
Chassis: Carbon fiber/honeycomb core with a fiberglass layer for electrical insulation. 4130 chromoly space frame, Gasflux manganese-bronze welded. Tube O.D. range: 3/8"-1", wall thickness range: 0.028"-0.035".
Motor/Controller: Solectria BRLS-8, brushless DC motor with dual windings, typical power = 800-1900 W, peak power = 5 kW, redline = 6000 rpm. Solectria MOSFET controller. About 89% efficiency including controller at operating point. Lent motor to another team and never re-tuned for peak efficiency.

Control and Instrumentation: Accelerator at right foot; hydraulic front brakes at left foot; parallel/series motor switch ("gear shifter") at right hand; regenerative rear brake lever at left hand; amp, volts, kWh meter at left eye, speedometer at right eye; radio communication at right ear and mouth.

Transmission: U.S.Tsubaki extended-bushing 3/8" pitch chain to Azusa aluminum sprocket w/ PJ-1 lube. 6.25:1 typical ratio.

Batteries: Trojan DC-22F, deep-cycle lead-acid, 108 V nominal; cycled and sorted in lab for maximum capacity; 139 kg (306 lbs).

Solar Cells: ASE Americas, 14% efficiency. 724 cells on top, 58 cells on sides (combined), 204 on belly.

Power Max on Road: 850 W

Power Max Charging: 1280 W. Four Brusa maximum-power-point trackers during racing, one extra during charging.

Panel Voltage: about 95 V

Notes and Reported Problems: (1) No mechanical problems, one electrical failure (motor controller) on last day in rain, lost 15 minutes. (2) Manta handled superbly. Very stable at high speeds (60+ mph). (3) 300 miles of Boston and Indianapolis street testing. Manta registered as experimental motorcycle. (4) 3-wheeler comments: Balanced constraints of aerodynamic shell and chassis; low as possible center-of-gravity, coupled with optimum weight distribution among carefully positioned 3 wheels to minimize longitudinal and lateral weight transfer for stable braking and cornering. Front and rear brakes decoupled for active brake biasing; can prevent rear wheel lock up in rain or with flat tire. Used bullet-proof DOT-approved rear tire; ran same tire for entire race. Also, bias-ply rear tire offered greater lateral stiffness over radials for better handling. Front tires changed periodically due to nicks and cuts, but center beads and "hairs" never wore away during race. (5) Array charging rig was vital to success. Full deployment in well under 10 minutes. (6) Simple strategy on spreadsheet was very effective. (7) Thanks to University of Michigan team for loaning us tires. (8) The MIT team has been racing 2-seat electric "commuter cars" for past three seasons. Manta is first solar racer built at MIT since 1990 GM Sunrayce entry, Galaxy. Team has 40+ improvements for next solar racer.

Mercer University

Car: #90—"SunScream II," Mercer University, School of Engineering, Mercer University, Macon, GA 31207; Contact: Jack Mahaney, 752-2255

Team Captain: Brad Cody

Faculty Advisor: Dr. John Schaefer

Cost: $135,000

Project Time: 18 months

Number of Test Miles: 150 on rolling chassis only, none on completed vehicle

Cd (based on frontal area): 0.18 (from "drag breakdown" approach)

Frontal Area: 1.05 m^2 (11.32 ft^2)

Gross Vehicle Weight: 423 kg (930 lbs)

Length: 5.99 m (19.7 ft)

Width: 1.99 m (6.5 ft)

Height: 1.24 m (4.1 ft)

Wheelbase: 2.5 m (8.2 ft)

Track Width (front / rear): 1.5 m (4.8 ft) / 0

Ground Clearance: 0.3 m (0.83 ft)

Wheels: 3 (2 front/1 rear) when race began. In Kansas City, converted to tandem rear axle; SunMetal 20", 36 14-gauge spokes, custom hubs

Tires: ACS tires, 100 psi

Flats in Qualifier / Race: 0 / 1

Brakes: (Primary) regen braking; (Secondary) mountain-bike disk brakes. 1 unit per wheel.

Suspension: (Front) unequal-length A-arms; (Rear) rear trailing arm

Steering: Rack-and-pinion

Chassis: Welded 4130 steel space frame, square tubing, 0.028 and 0.035 wall, TIG welded

Motor/Controller: Solectria, 8-hp, brushless DC

Transmission: Toothed belt/sprocket with changeable main-drive gears

Batteries: East Penn EV-UI batteries (13 modules), 121 kg (267 lbs). Bus voltage 156 V nominal. 33 Ah at C20 rate.

Solar Cells: Siemens Solar, 88 cells, trimmed to about 3.5" x 4" rectangles.

Notes and Problems: All mechanical problems stemmed from one fact: no testing of completed vehicle. We put about 150 miles on rolling chassis (no body, no array) but did not complete construction of vehicle until day after first scrutineering appointment! Among our problems: (1) Cracked motor mount during last-chance qualifier. Rewelded at shop in Clermont, gave excellent service for rest of race. (2) Steel pins pressed into aluminum main drive gear fell out on Day 1. Repaired in Rose-Hulman machine shop, no further problem. (3) Severe overloading (due to excessive vehicle weight) of single rear wheel, causing wheel stress and handling instability. Designed new rear axle in Alton, IL, had our machining sponsor make it and ship it to us in KC. Installed during rest day. No further problems with wheels or handling. (4) Brakes did not stop car well. Probably due to car being 180 lbs over design weight. No resolution; design new brake system. (5) Excessive wear of drive pinion due to excessive drive belt tension. (6) Friction galling and welding of drive pinion on motor housing due to drive pinion being too close to housing. Not detected until post-race tear down. (7) Several rim failures due to overtightening of spokes (in some cases) and overload on single rear wheel (in others). (8) Almost total failure of solar array as race wore on. On a bright, sunny day it might put out half of what is should. On a cloudy day we got effectively nothing. Post-race inspection revealed at least six broken leads in cell wiring. (9) Excessive flexure of array panel (structural part) allowed cell edges to contact one another, creating shorts and hot spots. Remedied by separating cells with dremel tool. (10) Cell corrosion under Tefcel covering; cause not yet determined.

Messiah College

Car: #77—"Genesis," Messiah College, Grantham, PA 17027; Contact: Patrick Wensel, 717-691-8669

Team Captain: Patrick Wensel

Faculty Advisor: Dr. Don Pratt, Dr. Tim Whitmoyer

Cost: $40,000

Project Time: 18 months

Drag Area (CdA): 0.26 (measured from a CAD projection)

Cd (based on frontal area): 0.2
Frontal Area: 1.3
Gross Vehicle Weight: 400 kg (881 lbs)
Length: 6.0 m (19.7 ft)
Width: 2.0 m (6.6 ft)
Height: 0.79 m (2.6 ft)
Wheelbase: 2.3 m (7.5 ft)
Track Width (front / rear): 1.27 m (4.2 ft) / 0
Ground Clearance: 0.25 m (0.8 ft)
Wheels: 3 wheels; Sun rims, aluminum
Tires: Avocet slicks
Flats in Qualifier / Race: 0 / 2
Brakes: Wilwood hydraulic disc
Suspension: (Front) composite leaf spring; (Rear) composite leaf spring
Steering: Translation altering arm
Chassis: Composite/chromoly
Motor/Controller: Lynch motor; GE EV-T6 motor controller
Transmission: none
Batteries: Trojan, 140 kg (309 lbs), 7200 kWh @ C20
Solar Cells: ASE Americas, Inc., 6 cells
Power Max on Road: 800 W
Power Avg on Road: 750 W
Power Max Charging: 800 W
Panel Voltage: 100 V
Notes and Problems: (1) Not enough testing. (2) Not enough consideration for aerodynamics.

Montana State University

Car: #406—"Double Black Diamond," Montana State University, Sub Box 34, Bozeman, MT 59717; Contact: Dave Caditz, 406-586-2883
Team Captain: Aaron Morrow
Faculty Advisor: David Caditz
Cost: $60,000
Project Time: About 1 year
Frontal Area: 1.1 m^2 (11.8 ft^2)
Gross Vehicle Weight: 428 kg (942 lbs)
Length: 5.15 m (16.9 ft)
Width: 2.0 m (6.6 ft)
Height: 0.85 m (2.8 ft), including bubble
Wheelbase: 2.61 m (8.6 ft)
Track Width (front / rear): 1.60 m (5.2 ft) / 0
Ground Clearance: 0.2 m (0.7 ft)
Wheels: 3 wheels; bicycle with custom hubs; 26" (front), 20" (rear)
Tires: Avocet slicks (front); ACS Edge (rear)
Flats in Qualifier / Race: 4 / 8
Brakes: (Front) hydraulic disc (Enginetics master cylinder, Performance machine calipers); (Rear) hydraulic disk (Magura)
Suspension: (Front) double A-arm; (Rear) single-sided swing arm
Steering: Cable
Chassis: 2"-thick carbon/Nomex plank and chromoly subframe and roll bar
Motor/Controller: MFM brushless DC motor, custom IGBT controller, rating: 300 V, 100 A, 5 lbs (2.3 kg) , 4" x 5" x 5"
Transmission: Single-ratio quick-change chain drive
Controls and Instrumentation: Current mode control, 4 quad/2 quad, regen, fwd/rev
Batteries: Delphi Automotive Systems, 7 total batteries in series (84 V), 19 kg (42 lbs), 56 Ah
Solar Cells: Siemens Solar, 646 cells on top, 90 cells on side
Power Max on Road: 900 W
Power Avg on Road: about 400 W (averaged over entire race)
Power Max Charging: about 1000 W
Panel Voltage: 140 V
Notes and Problems: (1) Panel not working first 3 race days traced to problems with maximum-power-point trackers; hard-wired half of panel for rest of race and borrowed trackers from helpful competitors. (2) MFM motor tossed large chunk of magnet on Day 6 (epoxy holding magnet failed), causing poor performance and low efficiency. (3) Telemetry system failed Days 3-6, traced to suspicious reprogramming of ID code. (4) Our homebuilt motor controller didn't like rain, but otherwise performed flawlessly.

Northern Essex Community College

Car: #28—"TNE," Northern Essex Community College, 8 Spouting Horn Rd., Nahant, MA 01908; Contact: Olaf Bleck, 617-595-6243/617-275-9444 (work)
Team Captains: Olaf Bleck, James Nelson
Cost: about $20,000 (car $5000-8000, cells $6000, travel $5000)
Project Time: 2000-3000 hours
Number of Test Miles: 1
Drag Area (CdA): 0.7 m^2 (7.5 ft^2) (back-calculated based on power consumption)
Cd (based on frontal area): 0.10
Frontal Area: 0.7 m^2 (7.5 ft^2)
Gross Vehicle Weight: 344 kg (757 lbs)
Length: 3.8 m (12.5 ft)
Width: 1.35 m (4.4 ft)
Height: 1.0 m (3.3 ft)
Wheelbase: 2.0 m (6.6 ft)
Track Width (front / rear): 1.27 m (4.2 ft) / 0
Ground Clearance: 0.2 m (0.5 ft)
Wheels: 3 wheels; TNE custom, aluminum rim bonded with tri-laminated carbon fiber/Aramid honeycomb structure with co-cured hard points.
Tires: Avocet Fastgrip slicks and RL Edge treaded, 20" x 1.75" with oversized rims; 110 psi nominal
Estimated Crr: 0.045
Flats in Qualifier / Race: 0 / 5-6
Brakes: Honda ATV hub/drum assembly, hydraulic, used a Geo Metro master cylinder
Suspension: (Front) custom TNE leaf from K2 downhill skis; (Rear) chromoly swing arm and Risse air/oil shock
Steering: Rack-and-pinion
Chassis: Carbon monocoque with 1/4" and 3/8" Aramid honeycomb core, Kevlar interior lining for driver shock protection and crash splinter/shatter resistance. CIBA unidirectional carbon prepreg. Seamless lay-up for chassis shell and bonded bulkheads.
Motor/Controller: Solectria BRLS-8
Transmission: Single-stage Gates Polychain GT belt, 8-mm pitch, 12-mm

width, 4:1 nominal, custom aluminum sprocket set
Controls and Instrumentation: Potentiometer box with driver regen bias control (serves as cruise control)
Batteries: Delphi Automotive Systems, 64.5 Ah @ 3-h rate = 17.6 Wh/lb @ 3-h rate
Solar Cells: Siemens Solar, 30 panels, 32 cells each
Power Max Charging: 1150 W
Panel Voltage: 10 panels in series, 0.5 V, 32 cells/panel=160 V
Notes and Problems: (1) Kudos to Dan Prater (Delphi) for helping in a pinch. (2) No car ever passed us "while on road" during whole race. (3) Traveled the speed limit whole time except when dangerous, like 65 mph in rain. (3) Pike's Peak is an excellent event; a hill climb time trial should be part of the event.

Ohio State University

Car: #33—"Red Shift," Ohio State University, 930 Kinnear Rd., Columbus, OH 43210; Contact: Ed Kaiser, 614-548-5802
Team Captain: Ed Kaiser
Faculty Advisor: Tony Luscher
Cost: $370,000
Project Time: 2 years
Gross Vehicle Weight: 470 kg (1035 lbs)
Length: 5.5 m (18.0 ft)
Width: 2.0 m (6.6 ft)
Height: about 1 m (3.3 ft)
Wheelbase: 1.5 m (4.9 ft)
Track Width (front / rear): 2.5 m (8.2 ft) / 0
Ground Clearance: 0.245 m (0.80 ft)
Wheels: 3 wheels; Sun rims
Tires: Avocet Fastgrip slicks (front); Goodyear (rear)
Estimated Crr: 0.003
Flats in Qualifier / Race: 0 / 0
Brakes: Dual piston calipers
Suspension: (Front) twin A-arm with coil over shock; (Rear) single swing arm with torsion bar
Steering: Rack-and-pinion
Chassis: Hollex-Nomex composite
Motor/Controller: Switch reluctance, custom by U.S. Motors/Emerson
Transmission: Single-reduction toothed belt, later changed during race to single-reduction chain drive
Controls and Instrumentation: Combination regen and hydraulic brake pedal
Batteries: Electrosource, 4-5 kWh, 12N95, 140 kg (308 lbs)
Solar Cells: Siemens Solar, 900 cells, laser-cut some on campus, some at Edison Welding Institute.
Power Max on Road: 4500 W
Power Avg on Road: 2000 W
Power Max Charging: 700 W
Panel Voltage: 60 V
Notes and Problems: (1) Front left wheel failure. (2) Belt slippage. (3) 60 V to 120 V Up-Converter unit never worked, resulting in running our motor at very inefficient voltage. (4) Composite failures (delamination). Hurt us in array structure and caused severe cell breakage.

Prairie View A & M University

Car: #619—"Sunpanther," Prairie View A & M University, Prairie View, TX.
Team Captain: Kedra Baltrip
Faculty Advisor: Dr. James Morgan
Gross Vehicle Weight: 502 kg (1104 lbs)
Length: 5.5 m (18.0 ft)
Width: 2.0 m (6.6. ft)
Height: 1.6 m (5.2 ft)
Wheels: 3 wheels, Performance Machine, custom spun aluminum, 51 cm x 7.6 cm (20" x 3")
Chassis: ABS plastic and 0.10 cm (0.04") thickness 3003 aluminum
Motor/Controller: Unique Mobility, 8.4 kW (11.3 hp)
Batteries: Power Battery Company, Inc., 96 V, 128 kg (282 lbs)
Solar Cells: AstroPower
Power Max Charging: 1100 W

Purdue University

Car: #371—"Boilermaker Solar Special II: Heliophile," Purdue University, Purdue Solar Racing, Box 40 Electrical Engineering, Purdue University, West Lafayette, IN 47906; Contact: 217-494-9277
Team Captain: Michael Gaines
Faculty Advisor: Jeff Gray, Galen King
Cost: $40,000
Project Time: 1.5 years
Gross Vehicle Weight: 419 kg (921 lbs)
Length: 5.7 m (18.8 ft)
Width: 1.9 m (6.2 ft)
Height: 1.2 m (3.9 ft)
Wheelbase: 1.8 m (6.0 ft)
Track Width (front / rear): 1.7 m (5.7 ft) / 1.7 m (5.7 ft)
Ground Clearance: 0.3 m (0.8 ft)
Wheels: 4 wheels; custom hub with SunMetal rim and motorcycle spokes
Tires: 16" Michelin solar-car tires
Estimated Crr: 0.006
Flats in Race: 4
Brakes: 4-wheel disk brakes
Suspension: (front) single A-arm; (rear) semi-trailing arm with sprint-car type shocks and springs
Steering: Chain drive from steering wheel to rack-and-pinion type steering
Chassis: 0.035 wall, chromoly, space frame with various diameters, about 16 kg (35 lbs)
Motor/Controller: Unique Mobility DR 127; CR-100 controller
Transmission: 0.375 pitch chain drive
Controls and Instrumentation: Telemetry system based on Z-World microcontroller.
Batteries: Delphi Automotive Systems, 7 lead-acid batteries
Solar Cells: ASE Americas, 728 cells, arranged in 7 panels
Panel Voltage: 22.5 V to 115 V
Notes and Problems: (1) Michelin tires worked superbly. Three flat tires caused by alignment problem, too much mileage on tire (about 3

days). Some tires went about 225 miles before changed. (2) Only mechanical problem was broken motor mount caused by large pot-hole outside Topeka. (3) Would have improved our place by more time road testing car to better characterize it. (4) 4-wheel disk brakes provided excellent stopping power and weighted only 3.6 kg (8 lbs). 0.6 g's and better acceleration was easy to achieve. System is easy to design and assures passing brake test.

Queens University

Car: #100—"QUEST," Queens University, Jackson Hall, Rm. 115, Kingston, ON, K7L 3N6; 613-545-6682.
Team Captain: Grant Freeman
Faculty Advisor: Dr. Steve Harrison
Cost: $140,000 Canadian
Project Time: 14 months
Drag Area (CdA): 0.17 m (1.8 ft^2) (tested in full-scale 9-m wind tunnel)
Cd (based on frontal area): 0.13
Frontal Area: 1.32 m^2 (14.2 ft^2)
Gross Vehicle Weight: 410 kg (903 lbs)
Length: 5.95 m (19.5 ft)
Width: 1.98 m (6.5 ft)
Height: 1.10 m (3.6 ft)
Wheelbase: 2.5 m (8.2 ft)
Ground Clearance: 0.20 m (0.7 ft)
Wheels: 3 wheels; Sun rims/custom hubs
Tires: Avocet tires (front); Perigrin tires (rear)
Estimated Crr: 0.008
Flats in Race: 4
Brakes: Modified Sachs mountain-bike disk brakes
Suspension: (Front) double A-arm; (Rear) trailing arm with Risse shocks
Steering: Rack-and-pinion with push/pull cable steering
Chassis: Duralcan space frame

Rose-Huhnan Institute of Technology

Car: #74—"Solar Phantom III," Rose-Hulman Institute of Technology, Terre Haute, Indiana
Project Time: 1.5 years
Gross Vehicle Weight: 494 kg (1086 lbs)
Length: 6.0 m (19.7 ft)
Width: 2.0 m (6.6. ft)
Height: 1.2 m (3.9 ft)
Track Width (front / rear): rear track: 0.32 m (1.5 ft)
Wheels: 4 wheels; 36-spoke, 51 cm (20")
Tires: Avocet slicks, 20" x 1.75 (51 cm x 4.5 cm)"
Flats in Race: 0
Brakes: Hydraulic disk (front and rear)
Chassis: Composite beam frame
Motor/Controller: Unique Mobility, 8.2 hp (3.2 kW), 6.8 kg (15 lbs)
Batteries: Delphi Automotive Systems, 84 V
Solar Cells: Siemens Solar
Power Max Charging: 1175 W

South Dakota School of Mines & Technology

Car: #777—"Solar Rolar," South Dakota School of Mines & Technology, Rapid City, SD.
Team Captain: Chris Scolton
Faculty Advisor: Dr. Dan Gerbec
Gross Vehicle Weight: 497 kg (1093 lbs)
Length: 5.4 m (17.7 ft)
Width: 1.8 m (5.9 ft)
Height: 1.5 m (4.9 ft)
Wheels: 4 wheels, 51 cm (20"), Sun Rhine rims laced to motorcycle hubs
Tires: Avocet Fastgrip, 51 cm (20") slicks
Brakes: Drum
Chassis: Aluminum space frame
Motor/Controller: Solectria, 5 hp, brushless DC, 14.5 kg (32 lbs)
Batteries: U.S. Battery, 96 V, 127 kg (280 lbs)
Solar Cells: Siemens Solar
Power Max Charging: 900 W

Stanford University

Car: #16—"Afterburner," Stanford University; Contact: Forest Deuth, 415-473-0471
Team Captain: Kate Von Reis
Cost: $125,000
Number of Test Miles: 200
Drag Area (CdA): 0.167 m^2 (1.8 ft^2) (extrapolated from 1/6-scale-model tests)
Gross Vehicle Weight: 393 kg (865 lbs)
Length: 4.3 m (14.1 ft)
Width: 2.0 m (6.6 ft)
Height: 1.0 m (3.3 ft)
Wheelbase: 1.8 m (6.0 ft)
Track Width (front / rear): 1.2 m (4.0 ft) / 0
Ground Clearance: 0.3 m (0.9 ft)
Wheels: 3 wheels; Peregrin, 48-spoke bicycle
Tires: Avocet Fastgrip, 20" x 1.75"
Flats in Race: 3
Brakes: (Front) Enginetics hydraulic disk; (Rear) cable-actuated bicycle disk, regenerative
Suspension: (Front) aluminum double A-arm, Risse airshocks: (Rear) composite trailing arm, Risse airshocks
Steering: Rack-and-pinion
Chassis: Carbon fiber/honeycomb planks folded into box frame
Motor/Controller: Solectria BRLS-8, 72 V winding
Transmission: 1/4" pitch chain
Controls and Instrumentation: Foot pedals for accelerator and mechanical brakes, regen knob, Fluke telemetry
Batteries: Electrosource Horizon, 60 V, 5.5 kWh at C3
Solar Cells: ASE Americas
Power Max on Road: 800 W
Power Max Charging: 1120 W
Notes and Problems: (1) Unique Mobility motor overheated during scrutineering. Switched to Solectria system loaned from Cal-Berkeley. (2) Spun 180 degrees due to rear flat tire; scraped rear corner of body when up on two wheels. (3) Twenty minutes lost to skipped chain. (4) Telemetry failed on Day 8. (5) Climbing three positions on last day credited to superior capacity of Electrosource batteries.

Texas A&M University

Car: #12—"Aggie Beamer," Texas A&M University, College Station, TX.
Team Captain: Ray Jungmann
Faculty Advisors: Tim Coppinger, Tom Talley
Gross Vehicle Weight: 491 kg (1080 lbs)
Length: 5.9 m (19.5 ft)
Width: 2.0 m (6.6 ft)
Height: 1.3 m (4.3 ft)
Wheels: 3 wheels, 51 cm (20"), Sun Chinook rims on custom hubs
Tires: ACS RL Edge tires, 51 cm x 32 cm (20" x 1.25")
Brakes: Dual hydraulic disk
Chassis: Aluminum space frame, 2.5 cm (1") diameter, aluminum, 0.17 cm (0.065") wall
Motor/Controller: Unique Mobility, brushless DC, 3.2 kW rated, 11 kg (24 lbs)
Batteries: Delphi Automotive Systems, 84 V, 133 kg (293 lbs)
Solar Cells: Siemens Solar
Power Max Charging: 1000 W

United States Military Academy

Car: #27—"Spirit of Onondaga," United States Military Academy, Solar Car Project, Department of Civil and Mechanical Engineering, West Point, NY 10996-1792; Contact: Prof. George D. Catalano, 914-938-2816
Team Captain: Adam Wallen
Faculty Advisor: Prof. George D. Catalano
Cost: $27,000
Project Time: 9 months
Drag Area (CdA): 0.21 m2 (2.25 ft2) (roll-down method)
Cd (based on frontal area): 0.25
Frontal Area: 0.84 m2 (9.0 ft2)
Gross Vehicle Weight: 476 kg (1048 lbs)
Length: 3.9 m (12.7 ft)
Width: 0.8 m (2.7 ft)
Wheelbase: 3.0 m (10.0 ft)
Track Width (front / rear): 1.1 m (3.7 ft) / 0.7 m (2.3 ft)
Ground Clearance: 0.2 m (0.7 ft)
Wheels: 4 wheels; Mavic OPEN 4 CD rim with 36-spokes (composite)
Tires: Avocet Fastgrip Clincher
Flats in Qualifier / Race: 0 / 6
Brakes: Sachs (front); Diacompe (rear)
Suspension: Modified Hotchkiss (front); swing-arm (rear)
Steering: Mouison rack-and-pinion
Chassis: Chromoly 2.2 cm (0.875") OD tubing
Motor/Controller: Solectria, 8 hp
Batteries: Delphi Automotive Systems, seven 12-volt batteries, 147 kg (325 lbs)
Solar Cells: Solarex, 678 polycrystalline silicon, 9.5 cm x 11.4 cm (3.7" x 4.5") cells, on 18 laminated panels.
Power Avg on Road: 750 W
Power Max Charging: 945 W
Panel Voltage: 114 V

Universidad Nacional Autonoma de Mexico

Car: #109—"Tonatiuh," Universidad Nacional Autonoma de Mexico, Centenario #129 Col. Portales C.P. 03660 Mexico, D.F.; Contacts: Daniel Amador, 525-532-6177, or Gabriel Cordoba, 527-382-0407
Team Captain: Gabriel Cordoba
Faculty Advisor: Beatriz Padilla, Ezequiel Ruiz
Cost: $160,000 U.S.
Project Time: 2.5 years
Number of Test Miles: 30
Drag Area (CdA): 0.132 m ($1.42 ft^2$) (scale model)
Cd (based on frontal area): 0.12
Frontal Area: 1.1 m^2 (11.8 ft^2)
Gross Vehicle Weight: 490 kg (1079 lbs)
Length: 5.9 m (19.4 ft)
Width: 2.0 m (6.6 ft)
Height: 1.0 m (3.3 ft)
Wheelbase: 1.95 m (6.4 ft)
Track Width (front / rear): 3.10 m (10.2 ft) / 0
Ground Clearance: 0.12 m (0.4 ft)
Wheels: 3 wheels; (Front) 2 aluminum 26" x 1.5"; (Rear) steel 17" x 2"
Tires: (Front) Avocet Fastgrip 26" x 1.5", 120 psi; (Rear) Pirelli, 17" x 2", 90 psi
Est. Crr: 0.006
Flats in Qualifier / Race: 1 / 3
Brakes: Hydraulic disk front and rear, and regenerative braking
Suspension: (Front) double wishbone fiberglass leaf spring; (Rear) trailing suspension with shock absorber and spring
Steering: Rack-and-pinion
Chassis: Kevlar with carbon fiber reinforcements, monocoque
Motor/Controller: Unique Mobility DR086S/CR10-100
Transmission: Chain, 6:1 ratio
Controls and Instrumentation: Amp-hour meter
Batteries: Delphi Automotive Systems, 7 lead-acid batteries, 84 V, 56 Ah, 19 kg (42 lbs) each
Solar Cells: Kyocera, 852 polycrystalline silicon cells, 13% efficiency
Power Max on Road: 990 W
Power Avg on Road: 700 W
Power Max Charging: 1000 W
Panel Voltage: 130 V
Notes and Problems: (1) Not enough testing. (2) Motor heating (poor ventilation). (3) Poor communications due to bad equipment and controller noise. (4) Brake friction. (5) Excellent batteries.

University of Illinois, Champaign/Urbana

Car: #22—"Sunchief," University of Illinois, Champaign/Urbana, IL.
Team Captains: Brandon Masterson, Bob Reppa
Faculty Advisors: Profs. Robert White, Phillip Krein, Bob Turnbull, Angus Rocket
Gross Vehicle Weight: 470 kg (1034 lbs)
Length: 6.0 m (19.7 ft)
Width: 2.0 m (6.6 ft)
Height: 1.0 m (3.3 ft)
Wheels: 3 wheels, 51 cm (20"), bicycle wheels
Tires: ACS slicks

Brakes: (Front) disk, caliper, hydraulic; (Rear) disk, caliper, hydraulic
Chassis: Structural foam/carbon fiber sandwich composite with polyester resin
Motor/Controller: Able/University of Illinois, AC induction, 1.5 kW (2 hp), 8.2 kg (18 lbs)
Batteries: Delphi Automotive Systems, 72 V, 114 kg (252 lbs)
Power Max Charging: 1200 W

University of Maryland

Car: #2—"Pride of Maryland II.I," University of Maryland, College Park, MD.
Team Captains: Marcus Howell, Melissa Judd
Faculty Advisor: Dr. David Holloway
Gross Vehicle Weight: 398 kg (875 lbs)
Length: 6.0 m (19.7 ft)
Width: 2.0 m (6.6 ft)
Height: 1.0 m (3.3 ft)
Wheels: 3 wheels, 51 cm (20") bicycle rims
Tires: Avocet Slicks, 51 cm x 4.4 cm (20" x 1.75")
Brakes: Hydraulic (front); hydraulic (rear)
Chassis: Composite monocoque construction; graphite/Kevlar/Nomex sandwich composition for body
Motor/Controller: Unique Mobility, 8.4 kW (11.3 hp), 7 kg (15.4 lbs)
Batteries: Delphi Automotive Systems, 84 V; Electrosource, Inc., 60 V
Solar Cells: Solarex
Power Max Charging: 1300 W

University of Michigan at Ann Arbor

Car: #1—"Solar Vision," University of Michigan at Ann Arbor, University of Michigan Solar Car Team, 3411 EECS, 1301 Beal Ave., Ann Arbor, MI 48109-2116; Contact: 313-764-2257
Team Captain: Betsy White
Cost: $1,200,000
Project Time: 18 months
Drag Area (CdA): 0.099 m^2 (1.07 ft^2) (estimated)
Cd (based on frontal area): 0.106 (estimated)
Frontal Area: 0.93 m^2 (10.0 ft^2)
Gross Vehicle Weight: 448 kg (986 lbs)
Length: 6.0 m (19.7 ft)
Width: 2.0 m (6.6 ft)
Height: 1.05 m (3.4 ft)
Wheelbase: 2.2 m (7.2 ft)
Track Width (front / rear): 1.45 m (4.8 ft) / 0
Ground Clearance: 0.235 m (0.8 ft)
Wheels: 3 wheels; custom magnesium 3-spoke racing rims
Tires: Michelin solar-car racing tires, 65/80-16 radials, 85 psi
Flats in Race: 2
Brakes: Redundant front hydraulic disk brakes with custom aluminum matrix composite rotors
Suspension: (Front) carbon fiber top, steel bottom double A-arms with custom coil over Monroe shocks and carbon fiber wrapped titanium kingpins; (Rear) steel trailing mono arm with custom coil over Monroe shock
Steering: Redundant steel pull-pull cables to a custom pseudo-rack driving carbon fiber tie rods
Chassis: Monocoque of carbon fiber/Nomex and Korex honeycomb sandwich construction
Motor/Controller: Custom permanent magnet DC brushless motor, 1.35 kW rated, 5 kW maximum, 2000 rpm, 92% efficient
Transmission: Single-reduction chain drive
Batteries: Electrosource Horizon, 60 V
Solar Cells: Siemens Solar, 3238 monocrystalline silicon cells, 14.2% efficiency, 3 facets of 5 modules each, 98.6% packing factor, shingled.
Power Max on Road: 1050 W peak
Power Max Charging: 1400 W peak
Panel V: 135 V
Notes and Problems: (1) Michigan practiced 200 miles before race. (2) Rear bulkhead delaminated during trailering; rebuilt and reinforced with titanium triangulation. (3) Cold weld in titanium lower control arm led to crash at 10 mph. (4) Glue bond in carbon fiber bottom A suspension arm failed under shear, replaced with steel arm. Glue bond in rear suspension monoarm failed. Caused by thermo expansion from welding near glue joint. (5) Kevlar steering cable snapped in testing, replaced with steel cable. (6) Failure of right kingpin due to cold weld led to underbody damage during testing. (7) During Dynamic Scrutineering braking test, driver snapped carbon fiber brake pedal; pedal replaced and reinforced. (8) During Last Chance qualifier, front right 3-spoke magnesium wheel failed, destroying brake caliper mount; caliper remounted. Problem with rims isolated to micro fractures. Rim outer micro fractures removed as much as possible and rim wrapped in carbon fiber, until replacement solid aluminum rims were manufactured. (9) Evening before Day 1, rear suspension arm broke while trailering. Suspension broke one facet of array; facet replaced by backup. Arm failure due to cold weld and bad carbon fiber lay-up: replaced by steel arm. (10) Day 2, polished but unwrapped magnesium wheel failed, ripped brake line. (11) Day 4, rear tire blowout caused car to fishtail. Car crashed into a ditch, broke steering cable, cracked back of array, broke winglets. Michigan withdrew because of concern for driver safety.

University of Minnesota

Car: #35—"Aurora-II," University of Minnesota, University of Minnesota Solar Vehicle Project, 111 Church St., SE, 125 Mechanical Engineering, Minneapolis, MN 55455; Contact: 612-626-0599
Team Captains: Mohammad Ali-Aidy, Alex Detrick, Dan Evanson, Jessica Gallagher, Charles Habermann, Paul Kelsey, Lance Molby, Steve White
Faculty Advisors: Scott Grabow, Dr. Virgil Marple, Dr. Patrick Starr
Project Time: 2 years
Drag Area (CdA): 0.1596 m (1.72 ft^2) CFD prediction; 0.1938 (2.09 ft^2) coastdown
Cd (based on frontal area): 0.14 (CFD prediction) 0.17 (coastdown)
Frontal Area: 1.14 m^2 (12.3 ft^2)
Gross Vehicle Weight: 361 kg (794 lbs)
Length: 5.09 m (16.7 ft)
Width: 1.92 m (6.3 ft)
Height: 0.762 m (2.5 ft).
Wheelbase: 2.44 m (8.0 ft)

Track Width (front / rear): 1.35 m (4.4 ft) / 0
Ground Clearance: 0.24 m (0.8 ft)
Wheels: 3 wheels; 48-spoke, 20" (0.508 m) wheels with spoke covers
Tires: ACS 20" x 1.75" (50.8 cm x 4.8 cm) tires. Custom quick-release hub and bearing housing, 100 psi
Estimated Crr: 0.006
Flats in Race: 2
Brakes: Triple redundant system. Dual front hydraulically actuated disc brakes with braided lines for safety. Secondary braking provided by bicycle-style brake on rear wheel's rim. Final braking is regenerative braking, provided by motor.
Suspension: (Front) double A-arms with air/oil spring damper. Linkage design incorporates zero bump steer and advanced zero scrub geometry; (Rear) hybrid double trailing arm made of chromoly with air/oil spring damper. Single rear wheel supported on one side for quick release and wheel changes. Shock mount integrated with rollbar support. Motor mounted to lower trailing arm.
Steering:
Chassis: Pre-fabricated fiberglass/Nomex panels, CNC laser-cut and assembled in monocoque structure. Battery enclosures, electronic enclosures, rollbar and vehicle belly pan are integral structural members. Chassis is nonconductive for driver safety.
Motor/Controller: Unique Mobility, DR086S brushless DC, 3.2 kW rated, 5500 rpm, 84 V, 8 lbs (3.64 kg) motor, 85% efficient at operating power level, 90% peak efficiency. Unique CR10-100 Controller, 12 lbs (5.5 kg), 96% efficient at operating power level, 99% peak efficiency. Blower cooling for motor.
Transmission: Single-reduction direct drive chain to rear wheel, 4.1:1 typical
Controls and Instrumentation: Foot-actuated throttle and brakes. Cruise control. Bicycle-style speedometer/odometer. Constant-speed motor controller. Telemetry of voltages, currents, and speed to the lead vehicle.
Batteries: Delphi Automotive Systems, 7 modules in series, 84 V nominal, 5 kWh at C/5, 60 Ah, 293 lbs (133 kg)
Solar Cells: ASE Americas, 1129 monocrystalline silicon cells, 90% available-area packing, 14% single-cell rated efficiency, 13.5% mean single-cell observed efficiency measured.
Panel Voltage: 117 V provided by top arrays; 94 V provided by array extension.

University of Missouri-Columbia

Car: #43—"SunTiger II," University of Missouri-Columbia, 354 Engineering Building West, Columbia, MO 65211; Contact: Bryan Crane
Team Captain: Bruce Hein
Faculty Advisor: Dr. Cyrus Harbourt, Dr. Hubert Graham, Instructor Richard Whelove
Cost: about $75,000
Project Time: 2 years
Number of Test Miles: 25
Cd (based on frontal area): 0.087 (Electronic Data Systems testing)
Gross Vehicle Weight: 401 kg (883 lbs)
Length: 6.0 m (19.7 ft)
Width: 2.0 m (6.6 ft)
Height: 0.9 m (3.0 ft)
Wheelbase: 1.6 m (5.2 ft)
Track Width (front / rear): 1.5 m (4.9 ft) / 0
Ground Clearance: 0.15 m (0.49 ft)
Wheels: 3 wheels; 48-spoke, 20" (51 cm) wheels
Tires: Avocet Freestyle 20" x 1.75" (51 cm x 4 cm) City Slick tires, 110 psi
Est. Crr: 0.0055
Flats in Qualifier / Race: 1 / 0
Brakes: Hydraulic disk brakes on front only. Cast aluminum calipers with treated aluminum rotors
Suspension: (Front) Unequal non-parallel A-arms; (Rear) rear trail link with single-sided axle joint for quick-change hub
Steering: Rack-and-pinion
Chassis: Magnesium space frame, 16 kg (35 lbs) alone
Motor/Controller: Solectria DC brushless, 6 kW rated, 12 kW max, 6000 rpm, 96 V, 60 amps, 11.8 kg (26.0 lbs), 88% efficient at operating power level, 94% peak efficiency.
Transmission: Direct chain drive
Controls and Instrumentation: Fluke data logger with wireless modem to chase van, cockpit display of speed, voltage, amps, temperature.
Batteries: Hawker Energy, 8 batteries, 3600 Wh, 136 kg (300 lbs)
Solar Cells: ASE Americas, 840 cells, 14% single-cell rated efficiency
Power Max on Road: 900 W
Power Avg on Road: 700 W
Power Max Charging: 990 W
Panel Voltage: 130 V
Notes and Reported Problems: (1) Solar array assembled at last minute due to extremely late delivery of encapsulated modules (received cells in Indianapolis one day before qualifier); led to lower-than-optimum output. (2) Experienced friction between rotors and calipers on brakes. (3) Potentiometer malfunction in foot controls. (4) Little to no testing of completed vehicle prior to race, due to extremely late date of final assembly.

University of Missouri-Rolla

Car: #42—"E-Cubed," University of Missouri-Rolla, 109 Engineering Management, Rolla, MO 65409-0730; Contact: Paul Hirtz, 573-341-4554
Team Captain: Paul Hirtz
Faculty Advisor: Doug Carroll
Cost: $120,000 (car), $300,000 (project)
Project Time: 1.5 years
Number of Test Miles: 300
Gross Vehicle Weight: 564 kg (1241 lbs)
Length: 5.9 m (19.5 ft)
Width: 2.0 m (6.6 ft)
Height: 1.0 m (3.2 ft)
Wheelbase: 2.6 m (8.5 ft)
Ground Clearance: 0.18 m (0.58 ft)
Wheels: 3 wheels; 16.5" rims (Sun Rhyno)
Tires: 20" bike tires, 100 psi
Flats in Qualifier / Race: 0 / 0
Brakes: Floating mount fixed disk (caliper brakes)
Suspension: (Front) double A-arm; (Rear) single A-arm

Steering: Rack-and-pinion
Chassis: Carbon fiber and Nomex honeycomb
Motor/Controller: Unique Mobility
Transmission: Single-speed belt drive with gear reduction
Controls and Instrumentation: 3 control switches (logic, throttle; on/off, frd/rev) Throttle 10k pot 10-20 hp peak; Regen 10k pot. +10V DC (frd) to -10V DC (rev)
Batteries: Delphi Automotive Systems, 7 batteries, 60 A-h capacity, 84 V DC bus, 127 kg (280 lbs)
Solar Cells: AstroPower, 738 cells, Photocomm encapsulation
Power Max on Road: 840 W
Power Avg on Road: 672 W
Power Max Charging: 960 W peak
Panel Voltage: Main 126 V DC, 367 W; 2 x sides 102 V DC, 296.5 W; 2 x bottom 28.8 V DC, 100W
Notes and Problems: (1) Overweight. (2) Brake drag. (3) High rolling resistance. (4) Lack of training time. (5) Bottom solar cells did not work first half of race.

University of Oklahoma

Car: #31---"Spirit of Oklahoma III," University of Oklahoma, Norman, Oklahoma; Contact: Robert Osburn
Team Captain: Stewart Mills
Faculty Advisor: John Fagan
Gross Vehicle Weight: 443 kg (974 lbs)
Length: 5.8 m (19.0 ft)
Width: 2.0 m (6.5 ft)
Height: 0.9 m (3.0 ft)
Wheels: 3 wheels; aluminum rim/aluminum facing over aluminum honeycomb
Tires: Avocet
Brakes: Dual cylinder hydraulic disk brakes all around
Chassis: 2 layer 90/90 carbon fiber over Nomex honeycomb, monocoque design
Motor/Controller: Brushless DC
Batteries: Advanced Bi-polar
Solar Cells: Siemens Solar, 1982 etched silicon cells

University of Pennsylvania

Car: #67—"Liberty Bell," University of Pennsylvania, 297 Towne Building, 220 S. 33rd St., Philadelphia, PA 19104; Contact: Yas Kohaya, 215-573-5256
Team Captain: Yas Kohaya
Faculty Advisor: Dr. Charles D. Graham
Cost: $10,000 (for '95), $100,000 (for initial construction)
Project Time: 2 (car originally built for Tour de Sol 94)
Gross Vehicle Weight: 442 kg (973 lbs)
Length: 6.0 m (19.7 ft)
Width: 2.0 m (6.6 ft)
Wheelbase: 3.15 m (10.3 ft)
Track Width (front / rear): 1.5 m (4.9 ft) / 0
Ground Clearance: 0.25 m (0.8 ft)
Wheels: 3 wheels; custom Rohacell/Kevlar/carbon fiber composite, 20"
Tires: Semi-slick, high-pressure bicycle tires
Estimated Crr:
Flats in Qualifier / Race: 1 / 5
Brakes: Hydraulic disc brakes, front and rear. Wilwood pedal and calipers, aluminum discs. Regenerative on rear
Suspension: (Front) custom monoshock system, Penske racing shock absorber, double wishbone setup; (Rear) trailing arm with coil over shock, Carrera racing shock absorber.
Steering: Rack-and-pinion
Chassis: Carbon fiber/Kevlar/Nomex composite monocoque
Motor/Controller: Unique Mobility, DC brushless
Transmission: Double-reduction chain drive
Controls and Instrumentation: Foot-operated throttle and brake with regeneration
Batteries: Powersonic 12260, 26 Ah, total 4.5 kWh, 8.3 kg (18.3 lbs) each
Solar Cells: AstroPower, 14.1% efficient, 4 strings of 7 modules with quarter-sized cells
Power Max on Road: 500 W
Power Avg on Road: 400 W
Power Max Charging: 800 W
Panel Voltage: 360 V open circuit
Notes and Problems: (1) Car originally built for Tour de Sol class; thus, nearly impossible to convert to Sunrayce class. Added weight from increase in solar panel area and extra batteries caused excessive load on rear tire, which caused tire bursts and chain popping. (2) Due to lack of power trackers, unregulated voltage caused panel to spike our 200 V controller; had to rewire entire car down to our only 100 V spare controller system. Motor and one DC/DC converter were also damaged during incident.

University of Puerto Rico-Mayaguez Campus

Car: #500—"Shining Star II," University of Puerto Rico-Mayaguez Campus, Department of Mechanical Engineering, Mayaguez, Puerto Rico 00681; Contact: Dr. David Serrano, 809-265-3826 or 809-832-4040 x2522
Team Captain: Miguel Perez
Faculty Advisor: Dr. David Serrano
Cost: $25,000
Project Time: 15 months
Number of Test Miles: 50
Gross Vehicle Weight: 463 kg (1018 lbs)
Length: 4.3 m (14.1 ft)
Width: 1.8 m (5.9 ft)
Wheelbase: 1.0 m (3.3 ft)
Track Width (front / rear): 1.6 m (5.2 ft) / 0
Ground Clearance: 0.2 m (0.5 ft)
Wheels: 3 wheels; ACS RL Edge, 48 spoke, 51 cm
Tires: Avocet Fastgrip Freestyle 51 cm x 4.4 cm (21" x 1.75"), 100 psi
Estimated Crr: 0.368
Flats in Qualifier / Race: 0 / 1
Brakes: (Front) Pro-Stop disks and Airhart caliper, bike caliper emergency brake
Suspension: (Front) Soloflex arm and strut; (Rear) trailing arm with Soloflex
Steering: Rack-and-pinion
Chassis: Aluminum space frame
Motor/Controller: Solectria brushless permanent magnet motor type

BRLS-8, 6000 rpm, 72 V, 8 hp and corresponding controller
Transmission: Direct belt drive
Controls and Instrumentation: Current cruise control
Batteries: Delco-Remy, 6 acid-lead batteries, 12 V, 20 kg (44 lbs)
Solar Cells: ASE Americas, 800 cells, laminated
Power Max on Road: 700 W
Power Avg on Road: 600 W
Power Max Charging: 900 W
Panel Voltage: 92 V
Notes and Problems: (1) Canopy became loose and flew off. (2) Wheel spokes punctured rear tire. (3) Peeled thread on front spindle.

University of Quebec—Ecole de Technologie Superieure

Car: #101—"Eclipse," University of Quebec—Ecole de Technologie Superieure; Contact: 514-289-8800 ext 7635
Team Captain: Eric Dube
Faculty Advisor: Kamal Al-Haddad
Cost: $70,000 U.S.
Project Time: 5000 hours
Cd (based on frontal area): 0.15
Frontal Area: 1.3 m^2 (14.0 ft^2)
Gross Vehicle Weight: 533 kg (1173 lbs)
Length: 5.8 m (19.0 ft)
Width: 1.8 m (5.9 ft)
Height: 0.9 m (3.0 ft)
Wheelbase: 3.0 m (9.8 ft)
Ground Clearance: 0.2 m (0.5 ft)
Wheels: 4 wheels; 20" rims
Tires: 20" x 1.75" ACS tires, 100 psi
Flats in Race: 5
Brakes: (Front) disk brakes; (Rear) regenerative with bicycle caliper brakes (rear)
Chassis: Monococque fiberglass with PVC core
Motor/Controller: Baldor, 2.7 hp, DC brushless, 6000 rpm, 8-hp peak
Transmission: 7:1 belt
Controls and Instrumentation: Custom
Batteries: Power Sonic, 16 batteries
Solar Cells: Siemens Solar, 730 cells
Power Max on Road: 1100 W peak
Panel Voltage: 3 x 100 V in parallel
Notes and Problems: (1) Blown AC-DC converter. (2) Blown motor on Day 1. (3) Blown power tracker on Day 3. (4) Micro controller failures.

University of Waterloo

Car: #24—"Midnight Sun III," University of Waterloo; Contact: Dave Walsh, 519-888-4567 x2234
Team Captain: Amanda Sealey
Faculty Advisor: Prof. Gordon Savage
Cost: $300,000 Canadian
Project Time: 14 months
Drag Area (CdA): 0.51 m (5.5 ft^2) (coastdown testing/modified SAE procedure)
Cd (based on frontal area): 0.32
Frontal Area: 1.6 m^2 (17.2 ft^2)
Gross Vehicle Weight: 448 kg (985 lbs)
Length: 6.0 m (19.7 ft)
Width: 2.0 m (6.6 ft)
Height: 1.1 m (3.6 ft)
Wheelbase: 2.4 m (7.9 ft)
Track Width (front / rear): 1.5 m (4.9 ft) / 0
Ground Clearance: 0.18 m (0.6 ft)
Wheels: 3 wheels, 22" (53 cm)
Tires: Goodyear Eagle, 22" x 25" (56 cm x 6 cm)
Estimated Crr:
Flats in Qualifier / Race: 0 / 2
Brakes: Single-disk caliper hydraulic (both systems)
Suspension: (Front) MacPhearson Strut with elastomer spring/damper; (Rear) double-sided trailing arm with elastomer spring damper
Steering: Rack-and-pinion
Chassis: 6061-T6 aluminum welded space frame
Motor/Controller: Unique Mobility, 11 hp, DC brushless, permanent magnet, 16.9 kg (15 lbs)
Transmission: Fixed-gear belt drive
Controls and Instrumentation: Velocity
Batteries: Delphi Automotive Systems, 7 batteries, 5 kWh, 84 V pack, 140 kg (309 lbs)
Solar Cells: Siemens Solar, 910 cells
Power Max on Road: 1100 W
Power Max Charging: 1300 W
Panel Voltage: 170 V
Notes and Problems: (1) Rear trailing arm somewhat unstable at higher speeds, causing car to wobble from side to side. (2) Project philosophy was to aim for simplicity and robustness in design. Target was achieved: vehicle had very little down time during race. Less emphasis was placed on aerodynamics; so car could not be competitive at high speeds. (3) During qualifier, drive shaft broke due to poor manufacturing and excessive belt tension. Took 45 minutes to repair. (4) On Day 1, rear swingarm started to flex. Due to lack of stiffness, whole vehicle would oscillate at speeds greater than 25 mph. Problem was not repaired for 4 days, when it was replaced with spare. Design was flawed, but pre-race testing was insufficient to discover error. (5) Tires were tubeless, which meant that they would dislocate from rim under severe bumps. Twice this resulted in complete loss of tire pressure and a broken wheel. (6) Battery pack caused much frustration at low levels due to uneven discharge of battery modules. In the end, this was attributed to uneven cable lengths connecting modules due to the irregular shape of battery box. (7) Overall recommendations for future cars include greater concentration on all efficiency issues, and time budgeting to allow for necessary testing.

University of Western Ontario

Car: #96—"SunStang 96," University of Western Ontario, The SunStang Project, Engineering Sciences Building Rm. 1069, University of Western Ontario, London, ON N6A 5B9; Contact 519-679-2111 ext. 8312
Team Captain: Rasha Al-Naji
Faculty Advisors: Dr. J. Tarasuk, Dr. P. Castle

Cost: \$50,000 U.S.
Project Time: 28 months
Cd (based on frontal area): 0.15
Frontal Area: 1.5 m^2 (16.2 ft^2)
Gross Vehicle Weight: 464 kg (1020 lbs)
Length: 6.0 m (19.7 ft)
Width: 2.0 m (6.6 ft)
Height: 1.2 m (3.9 ft)
Wheelbase: 2.4 m (7.9 ft)
Ground Clearance: 0.3 m (1.0 ft)
Wheels: 3 wheels; 26" modified mountain bike wheels with 38 spokes; 26" x 1.25"
Tires: Mountain-bike tires, 95 psi
Estimated Crr: 0.166
Flats in Race: 8
Brakes: Hydraulic, high-performance motorcycle brakes
Suspension: (Front) lateral trailing arm with vertically mounted, coil-over shocks
Steering: Push/pull linkage steering
Chassis: Magnesium alloy space frame
Motor/Controller: Unique Mobility, 11 hp
Transmission: Chain-drive, eccentric center tensioning
Controls and Instrumentation: Fluke Hydra
Batteries: Delphi Automotive Systems, 140 kg (309 lbs)
Solar Cells: Siemens Solar
Power Max Charging: 900 W
Panel Voltage: 72 V
Notes and Problems: (1) Problems with wires vibrating loose. During qualifying, a telemetry wire vibrated loose in high-voltage box, resulting in 30 minutes of down time. During Day 7, one of the battery connectors in high-voltage box vibrated loose, resulting in blown motor controller and 45 minutes of down time. (2) After Unique controller was blown, we installed our backup motor, an 8-hp Solectria motor. This motor had already proven its reliability during 1993 Daido-Hoxan World Solar Challenge.

Virginia Tech

Car: #6—"Solaray IV," Virginia Tech, Blacksburg, VA.
Team Captain: Sean Lessman
Faculty Advisors: Drs. Charles Hurst, Dan Chen
Gross Vehicle Weight: 504 kg (1109 lbs)
Length: 6.0 m (19.7 ft)
Width: 2.0 m (6.6 ft)
Height: 1.5 m (4.9 ft)
Wheels: 4 wheels, 66 cm (26") spoked rims
Tires: Avocet Fastgrip racing tires
Brakes: Hydraulic disk brakes (front and rear); regenerative antilock braking in rear
Suspension: 4-wheel independent suspension, dual trailing swing-arms, double wishbone front suspension
Chassis: Aluminum box frame
Motor/Controller: Motion Control Systems, Inc., 8 hp, DC brushless servo, 10 kg (22 lbs)
Batteries: Powersonic, 139 kg (308 lbs)
Solar Cells: ASE Americas
Power Max Charging: 900 W

Western Michigan University

Car: #95—"Sunseeker 95," Western Michigan University, Sunseeker 95, Department of Industrial and Manufacturing Engineering, Western Michigan University, Kalamazoo, MI 49008; Contact: Dr. Richard Munsterman, 616-387-3737
Team Captain: Robert Haeske
Faculty Advisor: Dr. Frank Wolf, Dr. Richard Hathaway, Dr. Jerry Hamelink, Mr. Fred Sitkins
Cost: \$150,000
Project Time: 1 year
Drag Area (CdA) : 0.145 m^2 (1.5 ft^2) (VS AERO through Western Michigan University)
Cd (based on frontal area): 0.135
Frontal Area: 1.07 m^2 (11.56 ft^2)
Gross Vehicle Weight: 435 kg (957 lbs)
Length: 5.95 m (19.5 ft)
Width: 2.0 m (6.6 ft)
Height: 1.0 m (3.3 ft)
Wheelbase: 2.3 m (7.5 ft)
Track Width (front / rear): 1.6 m (5.2 ft) / 1.6 m (5.2 ft)
Ground Clearance: 0.23 m (0.8 ft)
Wheels: 4 wheels; SunMetal 20" rims with custom hubs; 48-spoke 4-cross pattern
Tires: ACS semi-slicks and Advocet Fastgrip slicks
Estimated Crr: 0.0055
Flats in Qualifier / Race: 1 / 0
Brakes: Mountain cycle Pro-Stop disc brakes, 2 front, 1 rear on differential
Suspension: (Front) Zero Scrub, unequal A-arm four-bar linkage with Noleen Racing coil-over shocks; (Rear) double A-arm with Noleen Racing coil-over shocks
Steering: Strange Engineering rack-and-pinion
Chassis: Aluminum frame
Motor/Controller: Unique Mobility DC brushless, 7.5 kW rated, minimum of 85% efficiency at operating power level
Transmission: 2-step-reduction belt chain with differential to both rear wheels
Controls and Instrumentation: Fluke Data Bucket telemetry; custom digital instrumentation monitored all array voltages and currents, battery voltage, temperature, and current, motor current, temperature, and rpm.
Batteries: Sonnenschein Dry Fit, 11 gel lead-acid batteries, 132 V, 136 kg (300 lbs)
Solar Cells: ASE Americas, 190 cells per plane, 4 planes on top, 1 plane on bottom of 200 cells for charging configuration.
Power Max on Road: 1400W
Power Avg on Road: 1000 W
Power Max Charging: 1600 W
Panel Voltage: 100-120 V before maximum-power-point trackers; trackers stepped it up to 144 V for the battery
Notes and Problems: (1) Day 1—wheel cover came loose 3 miles out on wheel with speedo pickup, 15 minutes on side of the road; steel set screw in aluminum pulley backed out, keyway slid out and caused

loss of drive, 10 minutes on side of road. (2) Fluke modem in car and modem in van reset when voltage went too low (drenched in rain storm), 4.5 days without telemetry, had to contact manufacturer during race. (3) Low battery pack after Day 8 kept us from finishing on Day 9. (4) Had to make 0.030" brass washer after Day 1 to hold one tire on tight. (5) Shorted two batteries when installing night before race, allen wrench dropped across two terminals, minor burns to person, wrench destroyed. Batteries went whole race.