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Using Solar Cars to Excite Middle School Students About Engineering

Liz Kisenwether[1], Andy Lau[2], Toby Short[3], Kathy Gee[4]

[1]KidTech, State College, PA

[2]Penn State, University Park, PA

[3]Volunteer, State College, PA

[4]Teacher, Bald Eagle Area High School, Wingate, PA

Abstract

This paper describes the history, administration, and in-school experience of middle school students in the design, construction, and running of model solar-powered cars. The authors lead a team that includes university faculty, middle school teachers, a non-profit company, and community volunteers. Over the past 16 years we have grown the event from a single classroom project to an annual regional competition of over 250 students from every middle school in the county. Special effort is made to recruit and retain girls and other underrepresented groups. In the process of creating their cars, students employ concepts in earth sciences, math, chemical engineering, and circuits as well as general model building and special skills like soldering. The project was inspired by the Australian-International Model Solar Challenge and the U.S. Junior Solar Sprint (JSS). However, compared to the JSS, the materials, teaching regime, and challenges to the cars have been greatly expanded and improved over time. Workshops on the campus of The Pennsylvania State University for the middle school students have been instituted. Annually, construction components are updated, challenges added, and educational presentations and materials revised. The project applies both instructive and constructive learning, including the engineering process of planning / building and testing as well as using math modeling and electrical principles to make design and building decisions. The culmination of the project is an annual half-day event where the students from all the regional middle schools bring their best entries to a central location to run their cars in a variety of competitions for awards.

Keywords: solar, race, engineering, middle-school, STEM

1. Race Day

Around 9:00 a.m. on a sunny school day in late May, about 150 middle school students from the Centre County region swarm the roller hockey rink behind the State College YMCA (see Figure 1). This excited group represents the best teams of budding engineers whose model solar cars made the final cut to come to Great Solar/Hybrid Car Challenge Day. Either solo, or in teams, the students come with 60 to 80 custom-made and innovative model cars designed to run on either solar power or 9V batteries (for cloudy/rainy days).

The first challenge for the students is to qualify. Qualification means that their car must run the length of a 50-foot long by 36-foot wide rectangle mapped out on the ground without going out of the sidelines or losing any significant parts. The race course is about 78 feet long by 36 feet wide (the size of a tennis court) that has been mapped out in chalk and flags so that cars race toward the sun. The course size is a carryover from the early years of the competition that were held on tennis courts on the Penn State campus. Because there are no guide strings or wires for the cars, the qualification requires a) that the car runs, and b) that it goes straight enough to make it 50 feet without straying outside the side boundaries. Speed is not a factor in qualifying - simply operation and a car with relatively straight steering.

Fig. 1: Great Solar/Hybrid Car Challenge in action under sunny skies

Students in need of adjustments and repairs run over to the repair table for help from adult volunteers. Throughout the event the “repair pit” (Figure 2) is stocked with tools, parts, and scraps, and is overseen by one or more adults with years of kit building and mending experience. The repair pit is always as busy as any other event in the festival.

Fig. 2: Repair table in action

Over the course of 15 years of Challenge Days, the weather has been inadequate for solar power less than half the time. Because we have to schedule the competition for a set date that cannot be adjusted to sunny weather, one of our earliest modifications to the competition was providing 9-volt rechargeable batteries so that races can go on when cloudy or rainy. When there is not enough sun to cast a clear shadow the panels are removed and the cars are run on battery power. In the case of rain, the competition relocates to a nearby church with several large rooms big enough to host the crowd.

Indoors or out, a cadre of about 15 adult volunteers oversees and records performance in the 6 objective challenges:

- Fastest Car (elimination heats over 78 feet);
- Lightest (functional) car;
- Hill climb;
- Straightest car (staying within a one-foot wide path; see Fig. 3);
- Tough terrain (a collection of 8 short “off road” obstacle tracks); and
- Weight tug (pulling a sled of marbles one meter).

Several veteran judges also roam the event searching for outstanding examples in four subjective design categories:

- Coolest design (creative artistic merit);
- Best engineered (novel design approaches);
- Best use of recycled materials (low budget green design); and
- Charlie Brown (most lovable failure).

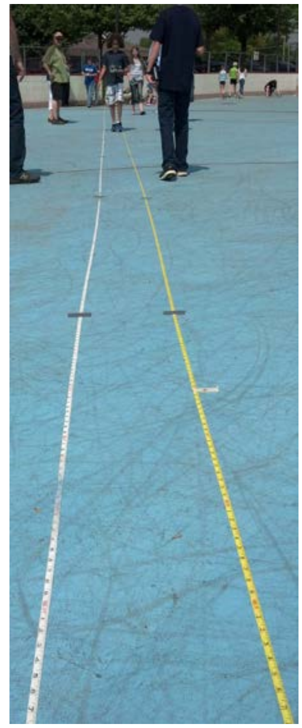


Fig. 3: Straightest car challenge

Except for the Fastest Car race, which is staged in successive heats that eliminate the slowest several cars, all events are open to repeated tries. Teams pit their cars against the various challenges for several hours until time is called and all participants are directed to the race course to cheer the final Fastest Car race event to determine the third, second and first fastest cars. Following the climactic race, all are seated and an awards and appreciation ceremony is held. Medals (made from birch ply cut and etched by a plasma cutter by a now-professional engineer alumnus) are ceremoniously presented. Every participant receives a solar trinket, such as a micro-solar car.

2. History

The Great Solar/Hybrid Car Challenge began as an idea brought back by middle school science teacher Howard Pillot from a teaching sabbatical in Australia in 2000. Since 1994 tens of thousands of Australian students from primary to high school have participated in a hands-on science program of building model solar cars that compete in tiered races that culminate in a national final (nationals.modelsolar.org.au). Howard was impressed by the enthusiasm and ingenuity that his 10-12 year-old Australian students brought to the Australian-International Model Solar Challenge. The U.S. version of this concept is the U.S. Department of Energy's National Junior Solar Sprint (JSS) Program that began in 1990 as a single demonstration race and expanded to 10 regional competitions in 1991. Since 2011, JSS has been offered to 5th through 8th graders under the auspices of the Technology Student Association (www.usaeop.com/programs/competitions/jss).

On return to his 6th grade classroom in the State College Area School District in 2001, Howard enlisted the aid of a parent, Tobin Short, to create a classroom project based on the Australian and American model solar car building programs. In the second year of the project, 2002, Andy Lau and Liz Kisenwether, two Penn State engineering faculty came to observe the races and joined the team for subsequent years. Liz Kisenwether is the founder and president of the non-profit KidTech, which now funds the Great Solar/Hybrid Car Challenge program. Andy Lau brought his 25 years of experience in solar engineering, and had coincidentally developed in 2001, a First-Year Seminar at Penn State, Solar Racers, that was also inspired by the JSS (Lau 2007; Lau et al. 2002, 2005).

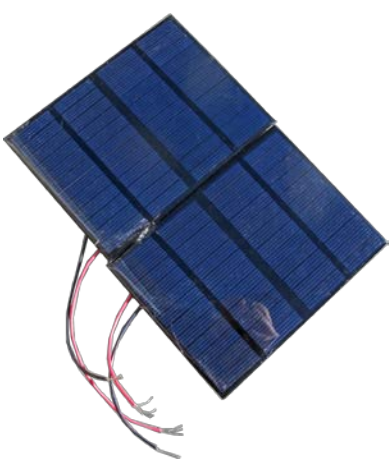


Fig. 4: Solar panel currently provided to all teams (2 Solar Star #CNC85X115-18, assembled and wired by volunteers)

Over the years, the leadership team of Toby, Liz, and Andy have made continuous improvements to make the learning experience more meaningful to students, more affordable, and easier to support. Using engineering analysis and testing, we have selected solar panels and DC motors such that the cars can perform well whether solar or battery powered. We are now on the third generation of the solar panel and motor combinations. The current design uses two smaller, less expensive, and more robust 1.5 W, 12 VDC solar panels (roughly 85 mm x 115 mm epoxy resin) than the official JSS cells (115 mm x 330 mm plastic). One feature of the project since the beginning is using solar modules that allow the panels to be wired in either a series (nominal 24 VDC) or parallel (nominal 12 VDC) configuration. The option is presented so students can find out by experimentation that performance is best with parallel wiring.

Over the last 16 years, with Toby acting as a liaison and advocate across Centre County, Pennsylvania, the project spread to almost all the middle schools in the region. A version was adapted as an ad-hoc project in the local high school. The Penn State First-Year Seminar Solar Racers also supports the hardware development, and students serve as volunteers for the workshops. Liz and Andy also provide a connection to Penn State's Engineering Ambassadors (EA). This service organization of outstanding students from all specialties within the Penn State College of Engineering provides docents for an annual on-campus workshop for the middle school students.

The funding for this project has come from KidTech, an all-volunteer, non-profit organization established in 1997 that provides materials for students, especially underrepresented students, in Centre County to grow their experience and interest in STEM related fields. On request from the middle schools, KidTech also provides funding for bus transportation and substitute teacher pay for a design mentoring workshop and Challenge Day. Over the years, as much as 50% of the students participating in the Solar Challenge have been female. Because the project is open to grades 6 through 8, about one-third compete in the project for more than one year.

Fig. 5: Students cheer on their classmates (Photo courtesy of Nabil Mark, Centre Daily Times)

3. Hands-On Workshops

Early in the car construction schedule, about the first week in April, design mentoring workshops are held for the kids in a large indoor space at Penn State. Schools book a half-day session (2 to 3 sessions are offered) and bus their kids to campus (with financial support from KidTech). A team of about 20 Engineering Ambassadors are scheduled to staff the workshops in two hour shifts. They guide participants through four stations: construction skills (such as soldering, cutting and gluing); how a solar panel works (including electrical fundamentals such as voltage and current, and series versus parallel wiring); and two hands-on demonstrations of the relationship between gear ratio, drive wheel size, and performance.

In the solar panel station, students are engaged in hands-on demonstrations of solar power. For example, using panels from the kits, an overhead projector as a light source, and a DC motor from the kit with a disc directly connected to the shaft, they engage in various demonstrations of how their solar panel would power their motor under different wiring combinations and various lighting conditions. (The kits are fully described in Section 4.) The EA leaders try wiring combinations suggested by the students and measure the voltage and current for each with multimeters. The audible "whine" from the motor, visual observation, and sometimes a digital tachometer, are used to evaluate motor speed. Worksheets are provided for the students to take notes.

The first gear-wheel-performance station consists of kits (Fig. 6) featuring a variety of gears and parts so that many different gearing configurations can be built and tested. The kits are pre-assembled with a variety of gear trains and set out in an open area. Students are invited to simply experiment and play. EA docents patrol the area prompting kids to compare and evaluate the various configurations. Here they can try compound gear trains, different gear ratios, and even four-wheel drive.

The second gear-wheel-performance station is a data collection and evaluation exercise. Students consider the best gear ratio for various drive wheel diameters, or conversely the best drive wheel size for various gear ratios. EA's supervise teams of kids who run prebuilt battery-powered versions of their car kits (see Fig. 7) in a 45 foot hallway. Each team chooses from a collection of cars with a motor gear with 12 teeth, and driven gear of either 20, 30, 40, or 58 teeth. For the chosen car they also choose a pair of drive wheels to attach (radius 2, 4, 6, or 8 centimeters). The smallest (2cm) wheels are permanently attached to each car. Students increase the drive wheel size by sliding larger wheels on to the axle that fasten to the small 2cm base wheels with velcro. The teams run the car several times for each combination of wheel size and driven gear size and record the average number of seconds it takes the car to travel 45 feet (See data sheet in Figure 8). The data are written on color-coded stickers and placed on a graph for examination and analysis at the end of the workshop. Analysis from the first-year engineering seminars at Penn State provided insight into the best drive train and therefore the choices of gears and drive wheel sizes to offer at this station.

Fig. 6: Society of Automotive Engineers (SAE) "A World In Motion" electric car kit (www.awim.sae.org)

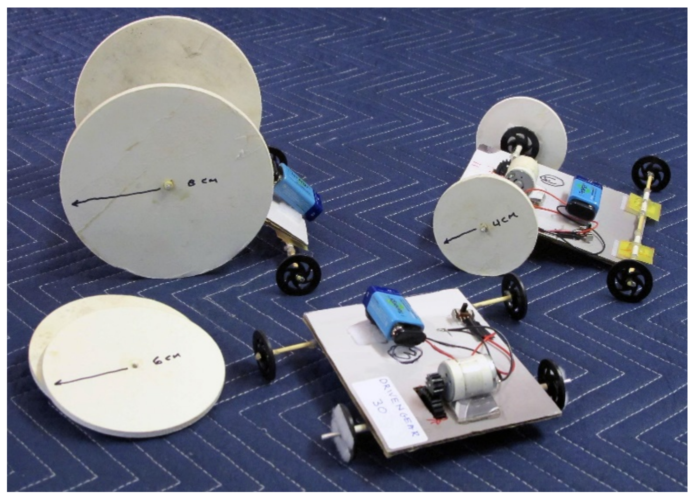
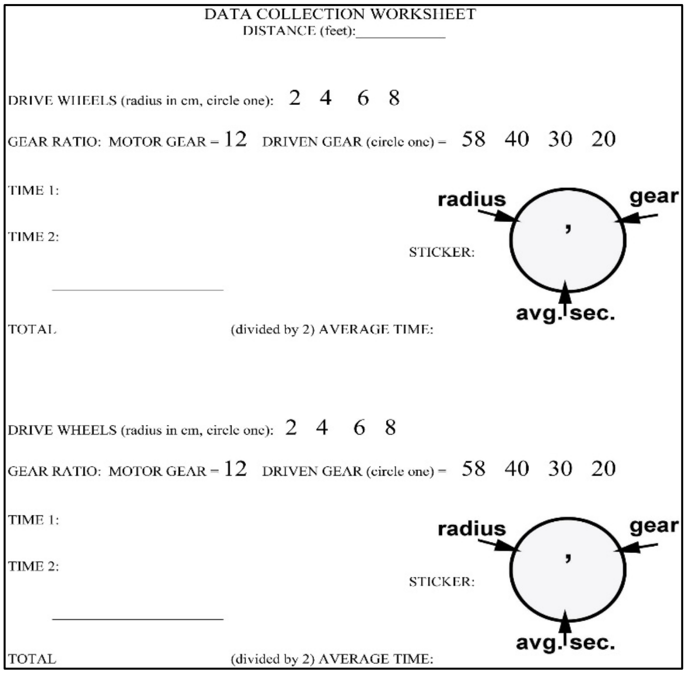


Fig. 7: Examples of pre-made kit cars with different gear ratios and interchangeable drive wheel sizes

Figure 9 is a plot of finish time versus the ratio of wheel size divided by the number of teeth of the driven gear (the size of the motor gear is fixed at 12 teeth in all the cars). Within the scatter of the data, there is trend for each wheel size. For example, for the smallest wheel (radius 2 cm), the fastest times are for a drive gear size of 20. Employing a drive gear size of 58 is nearly half as fast for 2 cm drive wheels. For the largest wheel (8 cm radius), the best drive gear size is 30 or 40 teeth. Having students generate plots like Figure 9 is not only an excellent active learning exercise, it also helps students determine best wheel size and gear ratio for their car.

4. The Kits

The student teams are given, to keep, a kit of simple, inexpensive parts such as gears, wheels, wire nuts, and battery clips available from on-line suppliers. Solar panels and rechargeable batteries are issued on loan. Details of the materials in each kit are listed in Table 1 and the parts are pictured in Figure 10. The total replacement cost of each kit is about $18. Since the solar panel and battery are returned and used again, the annual expendable cost of each kit is currently about $7. See Table 1 for a list of all of the parts currently in use.


DATA COLLECTION WORKSHEET

DISTANCE (feet):___________

DRIVE WHEELS (radius in cm, circle one): 2 4 6 8

GEAR RATIO: MOTOR GEAR = 12 DRIVEN GEAR (circle one) = 58 40 30 20

TIME 1:

TIME 2:

STICKER: radius , gear avg. sec.

TOTAL (divided by 2) AVERAGE TIME:

DRIVE WHEELS (radius in cm, circle one): 2 4 6 8

GEAR RATIO: MOTOR GEAR = 12 DRIVEN GEAR (circle one) = 58 40 30 20

TIME 1:

TIME 2:

STICKER: radius , gear avg. sec.

TOTAL (divided by 2) AVERAGE TIME:

Fig. 8: Data entry worksheet for gear ratio - drive wheel performance data collection

The paper straws are used as sleeves to house the bamboo skewer axles. These are a low-friction bearing for the axle and easy to hot glue to the chassis. One recent addition to the kit are small switches to conserve battery life, along with preventing inadvertent running, and potential damage to the car. Gears with finer teeth than those specified below are prone to meshing poorly. The larger tooth gears we use may cause more friction, but they are less likely to slip and are easier to align.

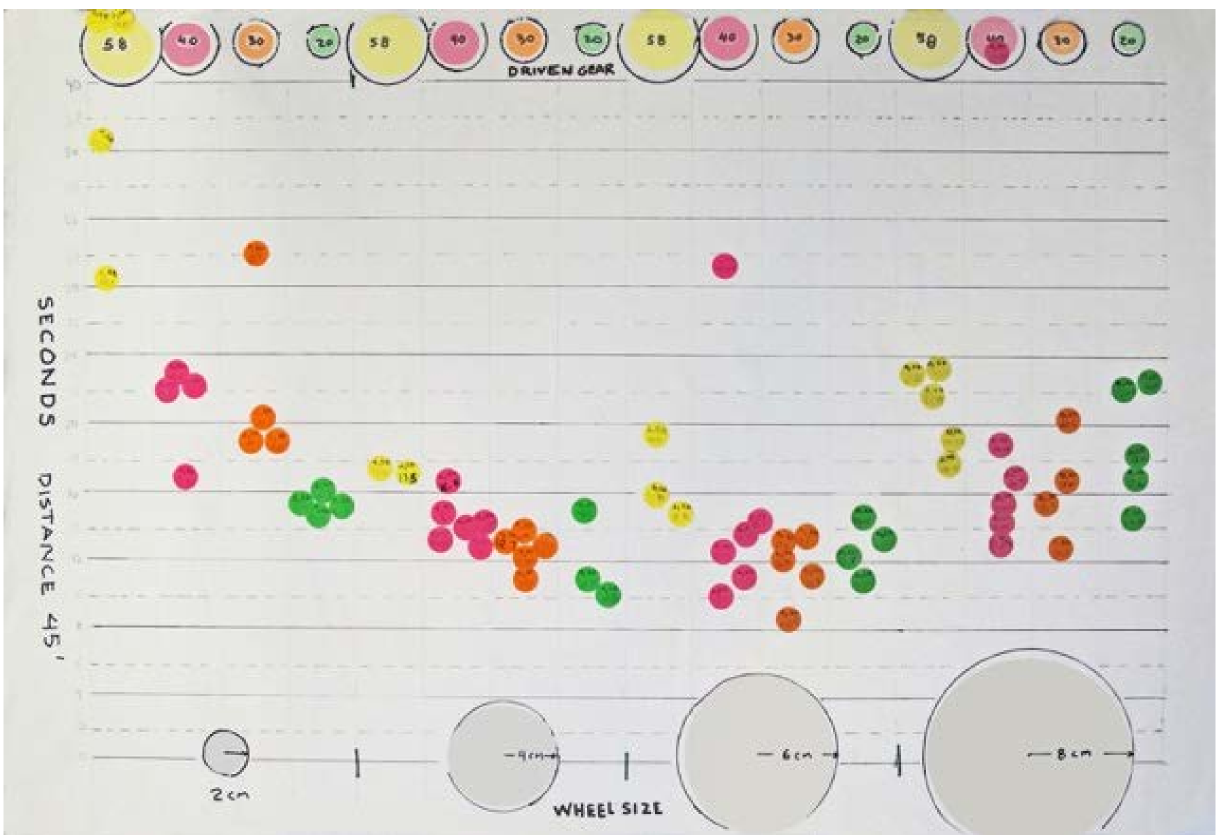


Fig. 7: Student-generated plot of time to travel 45 feet showing influence of gear ratio and wheel size

Tab. 1: List of all materials in the Great Solar/Hybrid Car Challenge Kit, provided to each student team

Item	Amount	Unit Cost	Description	Part Number	Source
Straw	4"	$0.05	7.75”x.125” paper	ASBP0775UXXXB	www.aardvarkstraws.com
Wire nuts	4	$0.10	#22 wire nuts		
Velcro	6"	$0.50	1” sticky-back		
Bamboo skewer	2	$0.10	<1/8" dia. x 10"		
Wire Red	5"	$0.10	22 GA stranded	C2016R-100-ND	www.digikey.com
Wire Black	5"	$0.10	22 GA stranded	C2016B-100-ND	www.kelvin.com
Gear	set	$1.00	12, 20, 30, and 40 tooth	990179	www.kelvin.com
Big gear	1	$0.60	60 mm, 58 teeth	390636	www.kelvin.com
Worm gear	1	$1.00	2 mm shaft	390621	www.kelvin.com
Wheel	4	$0.50			
Battery snap	1	$0.25	9 V snap	12BC092	www.circuitspecialists.com
Switch	1	$0.35	SPDT mini-toggle	25006	www.mpja.com
Motor	1	$2.00	24 VDC	RK-370CA-81050	Mabuchi
SUB-TOTAL Expendable		**$6.65**			
Solar panel	2	$6.78	12V, 1.5 W, 115x85mm	CNC85X115-18	Star Solar
Battery	1	$4.00	9V 250mAh, NiMH		www.all-battery.com
SUB-TOTAL Reuseable		**$10.78**			
TOTAL		**$17.43**			

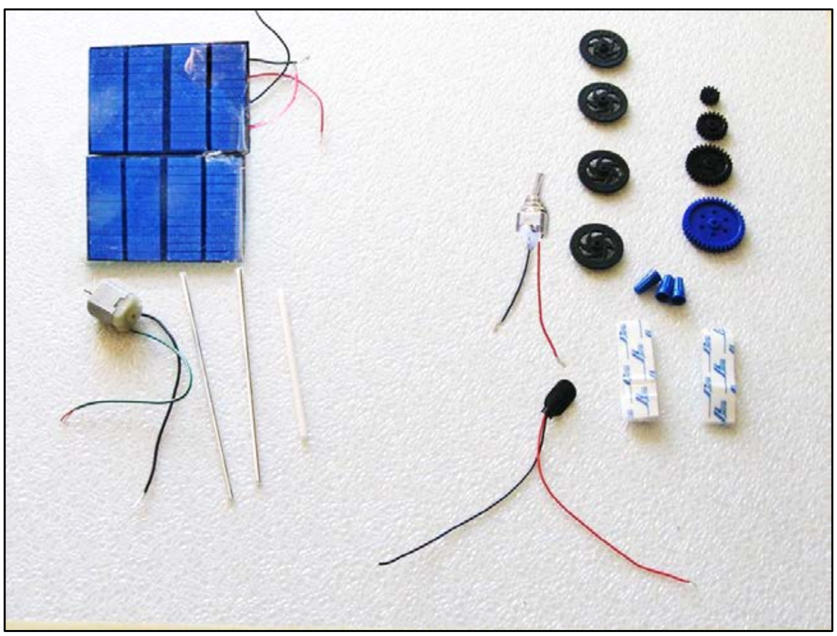


Fig. 8: Contents of a solar car kit

5. Teacher Observations and Insights

From the earliest years of the Great Solar Car Challenge program, the organizers recognized the need for each teacher to define how the solar car design/build/test process is conducted within their school. Three teaching models have emerged: 1) in-classroom curriculum, such as in a technology education or science class, 2) as an after-school activity, sometimes affiliated with tech education or a science club, and 3) as a Learning Enrichment program, for top students. Teachers appreciate the flexibility how, when, and where they work with their students during the weeks before Race Day.

How teachers work with and mentor the students also varies between teachers and schools. The more experienced teachers – who have been offering the Great Solar Car Challenge for over 5 years – often simply request delivery of the kits in March and do all the instruction and mentoring with little support from KidTech volunteers. However, many teachers kick off the Challenge with a presentation and demonstration by KidTech volunteers on the day kits are delivered. Over time, the number of trips per year to the schools to mentor the students on good design approaches has gradually gone down as both students and teachers have gained experience with the program. Teachers observe that "veteran" solar car student engineers freely pass along their knowledge and skills to students building their first cars. While working with the students, teachers generally do a blend of instructive teaching (gear ratios, math models for optimum gear ratio and wheel size, torque) and constructive teaching (engineering design process, teamwork and time management skills). Teachers comment that the solar car project provides a rich yet fun learning opportunity in built-it/test-it/rebuild-it which is not often available in the classroom.

To better understand the teacher's perspective on the Great Solar Car Challenge, five teachers were surveyed about the benefits to the students, challenges, and "ah-ha" moments. The surveyed teachers each have between 3 and 15 years of solar car experience, come from rural or small town school districts, and teach STEM middle school classes.

When asked about the top benefits of the solar car program for the students, the teachers listed developing student capabilities such as creativity and ingenuity to create a car, doing iterative design (rather than just reading about it), using problem-solving skills, analyzing results, and cooperatively considering design options. In addition, the solar car project (including battery option) is an excellent introduction to alternative energy sources delivered in a low-pressure learning environment. The repeated building, failures, and redesigns provide real-world problem-solving rich in learning opportunities.

On the topic of administrative or other hurdles that teachers face, teachers consistently mentioned the challenges of fitting the Race Day (typically in mid-May) into the spring battery of state mandated testing. Students cannot attend both Race Day and the standardized exams. Race Day must be held in May. That is the latest feasible time in the school calendar with good probability of dry weather and clear skies for solar power. Despite assistance provided by KidTech, funding to pay for materials, bus transportation, and substitute teacher pay for Race day is also consistently mentioned as a hurdle. School budgets, especially for field trips, are always tight.

Years of classroom experience has shown that, regardless of effort, not all students produce a solar car that runs reasonably well – meaning it travels in a fairly straight line and holds together over multiple test runs. Yet the success rate is generally high. All five teachers stated that 75% - 95% of the students or teams produce successful cars. Getting all students to a "functional" car by Race Day is a primary goal for the teachers.

A teacher reported that an experienced 8th grade team deconstructed and reconstructed a car in about two hours and then went on to win one of the Race Day events. Another teacher noted that it is not always the higher tracked students or the students that are considered smart by their peers that produce the most successful vehicles. "After the competition, students often view each other in a different light and realize that success is possible through perseverance." One teacher appreciated the overall impact of the program, noting: "It is always rewarding to see a student develop a successful design and participate in the car competition." Another teacher noted that, in spite of his best efforts over time, procrastination is a constant challenge for some students, noting "I think it is just the nature of the age level." As classroom tools advance, new teaching and learning challenges present themselves. For example, many students have the ability to design and print 3D parts for solar cars but 3D parts can warp in the sun and heat, resulting in a very good car becoming non-functional in a matter of minutes.

Comments and feedback from students is consistently positive. One teacher stated: "The student response is overwhelmingly positive although for a variety of reasons. Some students like the team aspect of the project while others enjoy competing. Most agree that the amount of freedom to build from a variety of materials along with the opportunity to customize their vehicle for different types of challenges (hill climb, straightest car, fastest car, etc.) is the best part." The number of repeat participants is an especially gratifying endorsement. A teacher stated that: "Many times students leave the Challenge talking about what they would do differently next time - planning for next year." Another noted: "Students love the event. Many will compete multiple years. I had one student compete 3 years in a row and then was sad because he was moving on to the HS (high school)."

Teachers provided other valuable insights.

- On gender: "Girls have done very well in the Challenge. There have been some fantastic cars created by girl teams and they enjoy participating."
- On program costs: It is important to ensure funds are available to cover Challenge costs on a yearly basis.
- On learning modes: One teacher noted that the Challenge provides a "sweet spot" in hands-on learning. He notes that combining gear ratio decisions with wheel size choice is "a tough one to comprehend" for students. This is the type of math challenge that is addressed by experimentation and iterative learning.
- On design: One teacher noted the value of simple design. Solar cars have many variables that affect performance and it was very difficult to isolate and manipulate just one of the variables to improve the overall design. He has had numerous students discover the path to success is to design one simple car with a minimal amount of effort and with few iterations.

6. General Observations and Conclusions

Over the years, the leadership team has learned to anticipate some of the major challenges to building a model solar car that runs well. During construction sessions and on Challenge Day, the solar car issues are (in order of severity):

1. Some cars just don't go: Wires come loose, parts fall off, gears slip. Often these issues can be fixed at the repair table. Students quickly learn to look for component failures, and build for durability.
2. Going straight: Many cars stray outside the side boundaries of the race course before completing the 78 foot length. Some even go in circles. We encourage students to design ways to adjust their steering. And to test their cars prior to race day.
3. Proper gear ratio and wheel size: In the workshops, students see how experimentation and prototyping can lead to a faster car. This tends to result in more cars being competitive for the races. The slower cars tend to have more torque and therefore perform better in the hill climb, tough terrain, and weight pull contests. Some students design specifically for these contests, like the treaded vehicle shown in Figure 11.
4. Weight: The lightest cars tend to go faster. But, they also are more prone to be affected by wind and race surface irregularities than heavier cars. In addition, lightweight materials may break easier.

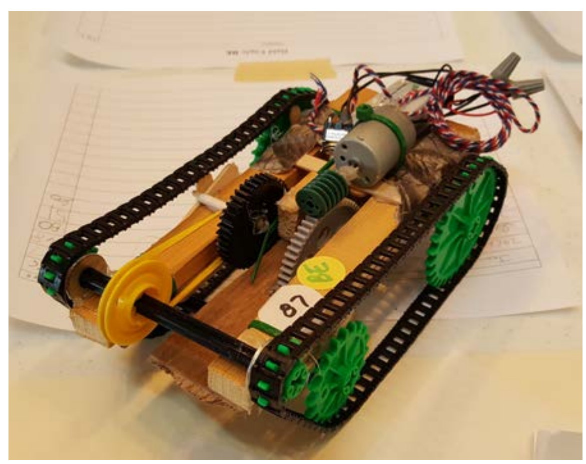


Fig. 9: Car designed for hill climb and weight pull

One thing that is not a challenge is student enthusiasm for the project. They readily engage with the idea of building a solar-powered car, and are therefore open to learning the math, science, engineering, and model-building concepts that are needed to make a cool car.

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