Model Solar Racing Car Design for Dummies. (2007)

or

(Definitely) Building to Win, Without the Cow Manure.

History. Where I'm coming from.

I was first introduced to model solar car racing back in 1994, when Mr. John Sheppard was teaching at The Hutchins School in Hobart. His students had just won the Tasmanian event and were trying to raise funds to go to the Nationals. As I have my own electronics company, I was targeted by the students for a donation. The accompanying letter explained a little about the event. Sufficient enough to whet our appetite so with eldest son Sturt at Clarence High the next year the die was cast.

We still had very little idea of what we were doing, probably a lot like most teams when they start, but a few phone calls later we had the basic concept. So, a car was built to the rules of the day, using a few sticks of balsa from an old kite, bits and pieces of old slot cars and wheels from a science lab block and tackle. The solar panel was hired from CSIROSEC in those days and an old hobby motor and gears were used. The car went, but slowly. John Sheppard volunteered the information about where to obtain precision motors and gears. The result was that the car swept all before it and won the 1995 Tasmanian event. The trip to Canberra for the Nationals was a real eye opener. To see what was happening in other states was invaluable. I still believe that you can learn more at one National event than from 5 years in state events. Sturt's car made it to the quarter finals and missed out on 4th place by less than a metre.

Sturt competed again in '96, coming 3rd behind 2 Sheffield High teams, and went to Adelaide for the Nationals. He experimented with 2 motors and using different sized wheels to alter the gearing. He competed again in '97, coming 2nd behind a Rosny College car and got to go to the Nationals in Surfer's Paradise. He went back to one motor and experimented with relays to change the panel voltage. Again he was the only Tasmanian car to make the finals, which he did all three years.

1998 saw Sturt retire from competition. Kent started at Clarence High and took up solar car racing. The old APSYS panels were starting to die so we purchased a Solarex MSX10. This panel weighed almost 1.4kg and was one heck of a penalty to carry around. We also started to play with electronics and the car made 3rd place in Tasmania behind 2 Woodbridge cars and then made the finals in Melbourne in the rain. Craig Lowndes did the presentations that year and eggs for drivers were introduced.

For '99 Kent stripped down the panel so it "only" weighed 1kg. The new rules required the cars to have proper bodies rather than a stick chassis and we redesigned the electronics to basically the circuit we use now. The car was just beaten into 2nd by Queechy High and went to the Adelaide Nationals. Kent experimented with a quick-change gearbox and we were able to spend quite a bit of time in Adelaide doing track testing. He made the finals again, even though the car kept lifting its drive wheel off the track.

2000 saw Ewen start at Clarence and also take up racing. Kent went for a radical streamlined car using 14 Dick Smith panels. A change in the rules had opened up a loophole that many teams exploited. Ewen opted for a more conventional car using the Solarex panel. Both cars used electronics. Kent experimented with fixed front wheels and tried tyred and non-tyred wheels. Kent easily came 1st, Queechy came 2nd and Ewen took 3rd so it was off to the Nationals in Sydney. Ewen changed to a 14 DSE panel and the question of steering and tyres was resolved. Kent again made the finals but Ewen's car fell foul of the disgusting National track and was eliminated before the finals. Some quick modifications to the guide system saw the car win all its repechage heats and take out the 2nd fasted lap of the day.

Further rule changes in 2001 saw both boys go for fairly basic but streamlined box shaped cars, again with 14 DSE panels and electronics. This time Ewen took 1st, Queechy 2nd and Kent 3rd. At the Nationals in Adelaide both Kent and Ewen made the finals, and Ewen shocked the organisers by taking out 4th place overall.

Another rule change and both boys were able to come up with totally radical designs for 2002 using two castering front wheels, a single castering rear drive wheel and offset guides. Both cars were ultra streamlined with Kent (now at Rosny College) going for a teardrop shape and Ewen a flying wedge. A bit of lateral thinking (and electronics) meant that both cars used only 10 DSE panels but totally demoralised the opposition. Ewen narrowly defeated Kent and both cars went to Sydney. They both experimented with suspension to overcome the rough National track. Kent had a suspension failure which saw his car T-boned when leading a race and it never ran quite as well afterwards. It still made the finals and took out 2nd fasted lap time. He won the Best Engineered Car award. Ewen was undefeated until the best of 5 grand final where he won the first 2 races and narrowly lost the next 3 to take out 2nd place overall. He recorded the fastest lap of the day. Both cars took ½ second of the old lap record.

In 2003 the boys tried to refine their cars again, Ewen sticking with the wedge and Kent going for a weird stealth shape. They reduced yet again to 9 DSE panels. Through the use of electronics, they were the only 2 cars to be able to reliably complete laps of the track in overcast and often rainy conditions, yet still be faster than all other cars in sunshine. This time Kent narrowly beat Ewen into 2nd so both went off to Adelaide. They both tried to further reduce the weight of their cars by using separate solar cells fixed to polystyrene panels but fell foul of the dubious power measuring system used at the Nationals and were required to carry an extra 400gms of ballast. Two weeks before the Nationals in Adelaide I ended up in hospital having a stent put in my heart and Ewen decided at the very last minute to make a new car from foam. It had never actually turned a wheel until it went on the Adelaide track. There were quite a few teething problems that were not all able to be eliminated, especially since it rained for most of Saturday. Still, despite the weight penalty, both cars made the finals and Ewen once again took out 4th place overall. Both cars were eliminated by the same extremely dubious car, which officially ran only 4 watts. Yeah, right.

Next year Kent finished school and started doing engineering at Uni, while Ewen, who could have competed for another 2 years, was totally cheesed off and retired, saying simply “they’ll never let us win anyhow”, a reference to the rather liberal interpretation of the rules by some of the more fancied teams.

To sum up, in 9 years of competing in the Tasmanian Model Solar Car Challenge, we entered a total of 13 different cars, took 3rd place 4 times, 2nd place 4 times and 1st place 5 times. We represented Tasmania at the Australian International Model Solar Car Challenge in every one of those years with 13, not always the same, cars and made the finals 12 times. For 7 of those years we were the only Tasmanian cars to make the finals. We made the quarter finals 10 times, took 4th place overall twice and 2nd place overall once. We had the fastest lap of the day twice and the second fastest lap four times. We held the lap record for 4 years.

In 2004 I went to Perth to represent the Tasmanian co-ordinator who was unable to go and ended up assisting with the scrutineering. I was involved in adding the ballast weight to every car and I was responsible for checking the weight of every car before it raced. Hence I got to see all the cars up close and personal. In general the standard of cars was quite low, compared to previous years. The track condition was ordinary to say the least, with the result that the best cars did not necessarily do well. Despite the brilliant sunshine the winning times were quite slow, the ‘successful’ cars were basic to say the least. I also saw first hand some of the things that we had suspected had been going on for years regarding dodgy solar panels and ‘performance enhancing’ practices. A couple of teams were not allowed to race.

For 2005 I was invited onto the National committee so I assisted with rewriting the rules to remove a lot of ambiguities and to try to remove avenues for ‘creative interpretation’. At the Nationals in Melbourne I was again involved in scrutineering and was responsible for checking the car and panel wiring and testing the panel power output, so I got to examine all the cars internals as well. In general the standard was much better than the previous year, although a few teams did try a couple of the old tricks, without success. . The most obvious thing was a complete change at the top There were still a few very ordinary cars, a lot of reasonable cars and a handful of very good cars. The top three cars all fitted into the latter category, I am pleased to say. The most exciting thing, from my point of view, was the fact that the top three cars were all built in the same basic configuration as our later cars.

Sydney 2007 was interesting for a number of reasons. Stan Woithe had to depart early to attend his son’s wedding so I got to play chief scrutineer. This gave me a really good look at all the cars. Once again there were a few very ordinary cars, a lot of well built but totally unimaginative designs, and, I was pleased to see, a fair few well thought out, well designed and well built cars. Also, the weather was rather variable, ranging from 90% sun down to 2% sun. This really tested the cars but one thing became even more obvious. Whether bright sunlight or total overcast, the best performing cars were all small, lightweight low loss designs. Tasmanian teams dominated the event, taking the top three places. Another Tasmanian car missed the finals due to an ill advised motor change but did a lap in 16.62 seconds in 90% sun when the proper motor was fitted. If you think that was impressive, the Queechy High (Tas) car that finished in second place did a lap in 16.24 seconds, also in 90% sun. That’s a full second off the old lap record. Yet, these cars, unchanged whatsoever, still ran around the track in less than 5% sun. Tasmanian took five cars to the Nationals, all based on our original concept. All five had run sub 18 second laps in the Tasmanian competition held in mid October.

If you reckon you won’t learn anything by reading on, then stop now, but don’t bother complaining later. It’s true what they say. You just can’t help some people.

Recommended reading. More than just a good idea.

I recommend that all solar car modellers read the book by Stan Woithe from the University of Adelaide, “Model Solar Cars: Optimising their Performance”, ISBN 0-7308-7620-9. Stan is on the National committee, one of the head rule makers and chief scrutineer. The book is a few years old now and a bit out of touch with a lot of the current regulations, but the laws of physics have not changed much in that time. It doesn’t say much about what makes a winning car, but it does cover the dos and don’ts of basic engineering I don’t intend rewriting Stan’s book but where he has gone right back to fundamentals I will simply say what we found out works and what doesn’t.

Bodies. Body building without using steroids.

Once upon a time, model solar cars used to be made from a couple of sticks. Sticks with wheels attached and a solar panel sitting on top. Then the organisers saw reason and brought in bodywork. You can still make your car from sticks but have you looked at how real cars are made? Once upon a time real cars had a rigid chassis with the motor and wheels attached and then the body sat on top. So were racing cars. Now real cars are monocoque construction. Monocoque means “single shell”. This means the body is also the chassis. So are racing cars, and aeroplanes. This is done to get maximum strength with minimum weight.

Fibreglass is just too heavy. Carbon fibre is very light and very strong but it also is very brittle. When it does break it shatters and is almost impossible to repair. It is difficult to work and join, needing special skills. It’s OK for a stick chassis but not for bodywork, unless of course you work for Ferrari or Lamborghini.

Aluminium is also strong and light but not as strong or light. It will bend before it breaks. Unless you can get aircraft grade aluminium it is not really worth using for bodywork. It is ideal for suspension bits and pieces and motor mounts as it is relatively easy to work yet mechanically sound.

Polystyrene blocks can be used to make complicated body shapes. It is messy to work and can only be glued with liquid nails. It has very little strength and you have to make up sub frames to attach suspension and motors, etc. You cannot use thin sections and it gets damaged very easily. It is also surprisingly heavy and you have to hollow it out. A car made from foam was actually heavier than the same car made from balsa sheets, but nowhere near as strong or robust. I must admit, in 2006 a couple of pretty successful cars were made by laminating thin foam with tissue paper on each side. The result was very strong and light, but they were extremely lucky that they didn’t suffer any damage as this construction is extremely brittle and repairs could have been almost impossible.

Good old balsa wood is very light and yet is stronger weight for weight than steel. It’s always difficult to beat nature. It does this because it is a maze of hollow cells of cellulose fibre. It is available in all sorts of shapes and sizes from 1mm thick sheets to 100mm square blocks. You can get sheets 100mm wide and 1000mm long. By carefully choosing you can get some that is extra flexible for bending around curves and some that is quite stiff for structural bits. For extra strength pieces like suspension mounts you can get beech, spruce and radiata from model shops.

You could use space frame construction covered in tissue paper or film as you would if you were building a model plane but you then have to be ultra careful when handling the car. Also, racing on the track is pretty rough on the machinery and this form of construction tends to not last the distance. Box construction using 1mm balsa sheets can be very light yet very strong. Use bulkheads to make a multiple boxes and put fillets in all corners.

Balsa can be cut to complicated shapes with simple tools and can be joined in minutes using a solvent based glue. You must use very sharp tools such as scalpels or Exacto knives. If it does get damaged repairs are quick and easy, as are urgent modifications. By applying two coats of aircraft dope to all surfaces even thin curved sheets become very rigid. If you don’t apply dope then don’t get balsa wood wet. It works like a sponge and becomes very heavy and soft. The only real drawback with balsa is that it is difficult to make compound curves, but it is possible.

Streamlining. Going with the flow.

When cars were made of sticks with a solar panel on top streamlining didn't matter much as these cars had a very low frontal area. When a minimum 200 square cm frontal area was introduced streamlining became essential for any reasonably fast car. Tests at Adelaide Uni found that, at 7 metres per second, a streamlined car had only 1.5 times the drag of a stick car while a non-streamlined car had over 7 times as much drag. Later rules reduced the frontal area for a while but streamlining was still useful.

For 2004, the single egg and the unspecified can carrying arrangement allowed for a very narrow body with wheels on sticks again, but streamlining was still a benefit. It is worth noting that in Melbourne 2005, the cars that came second and third both carried their cans end on and so had very narrow but fully streamlined bodies. The winning car had its can sideways but still had a beautifully streamlined balsa body. In 2006, one of the cans had to be carried sideways so the body had to be wider, making streamlining essential again. The successful cars were all very streamlined.

For 2007 the cans have been replaced with milk cartons so now the front of the car will have to be at least 235 mm wide and 75 mm high. Now, once again, streamlining is absolutely essential. Don't forget that your car will be doing over 25 kph on the straights and this is 7 metres per second.

Don't forget the floor area, either. You have to not only consider the shape looking from above but also looking from the side. For a couple of years you had to have a minimum of 400 sq. cm. floor, and combining this with the area of the solar panel you had a large potential wing. At the speeds a good car was going becoming airborne was a definite possibility. We saw, at first hand, how easy it is to hit a bad join in the track at full speed, get well and truly airborne and fly off the track. We cured our problem with little wings and front skirts, just like a full sized racing car, and nearly became Australian champions. This may not have been such a problem with the current weight penalty and a smaller front and floor, but a bit of aerodynamic down force is not hard to achieve. With the two milk cartons you are again looking at a floor area of over 350 sq. cm. This is a serious wing area so it will have to be taken into account when thinking about body shape. Get too much air under the front of the car and it could be all over till next year.

Wheels and tyres. On a roll.

First thing, how many wheels do you want, three or four? The obvious thing is to emulate a road car and use 4 wheels, but this is not the most efficient arrangement. Road cars are practical devices, we are building a specialised vehicle. Due to the rough nature of the track we found it almost impossible to keep all 4 wheels on the track at all times. Complicated suspension is just too heavy and introduces other problems, as we found to our peril, so you may often have your drive wheel off the track. Not a good idea. A tripod arrangement is inherently stable, normally keeping all wheels on the track. We do have photos of Ewen's three wheeler taking the corners on 2 wheels in Sydney '02, but the drive wheel was still on the track. The moral of the story is to use two wheels at one end and to drive through a single wheel at the other end.

For several years at the Nationals, all the most successful cars were 3 wheelers, some front wheel drive, others rear wheel drive. Changes to the rules meant a relapse to 4 wheeled stick cars for 2004, but, 2005 saw bodywork return. The cars that came 1, 2 and 3 at the 2005 and 2006 Nationals all had 2 wheels at the front and a single drive wheel at the rear. I haven't seen an arrangement of 2 wheels on one side like a motorbike and sidecar, but it might work. I don't think I'd bother, though. Also, just like a full size racing car, unless you have four wheel drive with viscous coupled power splitting differentials, rear wheel drive is the only way to go.

The regulations specify that all wheels must either be at least 1mm wide or 0.6mm radius. Why? Because of rolling resistance. The ideal wheel would have a hard, sharp rim but this causes serious damage to the track and is therefore banned. Racing bicycles use very thin tyres pumped up hard. Trains use steel wheels on steel rails. Even drag racing cars use narrow little front wheels. The next time you go for a long car ride get out and feel the tyres. They get hot from the friction in the rubber, so hot that in racing cars the rubber starts to melt, a property they can exploit, but we can't.

Tyres are only needed to get a road car around corners, for braking and accelerating. Model solar cars use a guide rail to get around the corners, don't have brakes and only accelerate through the drive wheel(s). So, don't use tyres when you don't need to. The rolling resistance may be small but it all adds up and is proportional to the overall car weight. Also, unless you are the world's best model maker, you will not get the wheels to track properly and they will spend a lot of the time being dragged sideways. You must use tyres on drive wheels though, unless you want to stay at the bottom of the hill. Small width O rings are ideal.

You can buy wheels or make your own very easily from 3mm PVC sheet in a lathe. About 50mm diameter seems to work OK. For non-drive wheels turn the edge down to about 1.2mm leaving a central hub to hold the bearing. For drive wheels turn a groove into the rim to take the O ring then turn out the body of the wheel if you like, leaving about 3mm at the rim and a hub for the bearing. Don't drill holes to lighten the wheels as the wind drag more than offsets any gain. You also have to bore a hole in the centre for the bearing. The bearings must be a press fit and a bit of Loctite is a good idea. Don't get Loctite in the bearings, though. It doesn't matter if the wheels wobble a little bit, as long as they spin freely and they are round.

Guides. Keeping it on the island.

Solar cars are guided around the track by an extruded plastic channel. The track builders have finally woken up to the fact that the joins in the track and guide were far from perfect. Now they place strips inside the channel to align the joins. This means you cannot run a guide pin down the middle of the channel. No serious cars ever did, anyway. Now you must use a guide each side of the channel. The new National track is extremely smooth and well aligned at the moment, but that probably won't last as the rigours of weather and transportation take their toll.

If you think about how fast your car will be going then you have to use wheels running on the sides of the channel for guides. These wheels need to have sufficient diameter to cope with the bad joins in the channel and must be fitted with bearings. They will be turning faster than the road wheels and will have quite a load on them to get the car around the bends at full speed, especially if you don't have steering front wheels.

You could just use ball bearings running on the channel but it is easy to make some PVC wheels. We used 6mm PVC and made top hat shaped wheels. This is to get the rim closer to the track yet raise the screw that goes through the bearing. Don't bother with tyres. They just add weight and rolling resistance, and who cares about the noise. Our wheels were 25mm diameter and fitted with the same bearings as the road wheels, the rim was 1.5mm thick.

Make sure that you use good solid mounts for your guide wheels as they will take quite a pounding. I have seen cars with long thin bolts extending down with bearings on the bottom. They invariably fail. This is not the area to save weight at the expense of strength. Remember, a good car is still going to weigh around 1kg and the guides have to push it around the corners at 25kph or more.

You are required to have guides at the front of the car. Position these just behind the front road wheels. This is to cope with the badly lined up track. If the guides are just behind the wheels then the wheels will lift the guides up over the bad joins. The alternative can be disastrous.

If you have a very badly designed car you don't need guides at the rear. If it is overcast you don't need rear guides. If you have F1 racing slicks on your car you don't need rear guides. Otherwise you do need rear guides. At any reasonable speed the car will want to slide out. Without guides either the car will spin out or at best it will drag its rear wheels or worse, its drive gear, along the guide channel. Either is a disaster. All you have to do is decide how far apart they are going to be.

If you have fixed rear wheels you must have the guides wide enough apart to let the rear of the car track in on the corners at low speed. Dragging wheels around corners is hard work. At any reasonable speed though, the back of the car will slide out on corners. Setting the guides so the back wheels now point straight ahead will give the best high speed performance. But there are better ways.

Bearings. Putting a spin on things.

You must use good quality ball bearings. Using good bearings means you only need one for each wheel. The smallest readily obtainable industrial ball bearing is 10mm outside diameter, 4mm wide with a 3mm inside diameter. They are available from any industrial bearing supplier. Bearings come in several versions. The open type have low friction and are easy to clean out but pick up dirt easily as well. Those fitted with rubber seals to keep dirt out cannot have the grease cleaned out easily and also have high friction levels. Those fitted with shields can be easily cleaned out, have low friction levels and keep out most dirt. They can have shields fitted to both sides and this is what we want. The bearings we used were type 623-2Z.

Before you use them in you solar car you must wash out all the grease using white spirit or dry cleaning fluid. It takes several goes to get all the grease out. Don't use petrol as it leaves a residue and never use WD-40 or similar as they intentionally leave behind an oily residue. Once the bearings are clean you must wrap them up and keep them dry because they will rust. They may make a lot of noise but they should spin freely. They must be washed out on a regular basis, especially after use on the track, but it is worth it. You should wash them out, dry them and then use a little sewing machine oil before long storage, washing again before racing. It can be worth having several sets of wheels with bearings fitted so they can be quickly changed between races if needed. Every time your car comes off the track you must check out the bearings and a wet track is a real worry. Methylated spirits will remove water.

Steering. Going around the bends without going around the bend.

Even with smooth front wheels, unless they steer, your car will not get around the corners in low light. This also means that even in high light you are still wasting energy. The problem is even worse if you use front wheel drive because you must use a tyre and if the drive wheel is not pointing straight down the road you are wasting lots of energy. Front wheels must steer into the corners. This can be achieved using complicated guide systems with tie rods etc., but it is almost impossible to get them to track absolutely correctly. The simplest way is to allow the front wheels to caster like shopping trolley wheels. Very simple, very low weight, very effective.

Under the subject of guides I talked about dragging the rear wheel across the track with close guides or allowing the rear to slide at speed. Dragging is to be avoided at all costs. If you have rear wheel drive and the back of the car is sliding then you are already getting wheel spin and loosing drive potential, even if you do have a tyre fitted. So the resistance has gone up but the drive has gone down. There is a simple way around all these problems. Use close guides at the rear as well and allow any rear wheels to caster.

The cars that came 1st and 3rd in 2005 had two castering front wheels and a single castering rear drive wheel. The car that came 2nd also ran two front wheels and a single rear drive wheel but all wheels were on fixed axles. The 1st and 2nd cars both cars used the same 10 Dick Smith Electronics panels. The 2nd car had a better motor and was noticeably faster in a straight line, but the 1st car actually overtook it around the outside of the last corner, due in no small part to the lower drag of the caster wheels. I rest my case.

A word of warning. If you use a castering rear drive wheel you must either offset the drive wheel or offset the guides to prevent the wheel running into the guide track. Either method is OK but we always preferred to offset the guides as this kept the car better balanced.

Another word of warning. I have lost track of how many cars I have seen fitted with casters where no effort has been made to correctly align the wheels. It is absolutely critical that the wheel is directly in line with the pivot pin.

Motors. Speaking motivationally.

Are you serious about this competition? Anyone (well, almost anyone) can build a car that will go around the track in bright sunlight. Not fast, but it will go. Just attach a cheap hobby motor to your solar panel and it will go, maybe, if the sun's bright. A lot of people have used motors recovered from VCRs etc. but you don't know anything about them and they tend to be built for long, smooth, silent operation rather than efficiency. If you want to compete seriously and win races you must use a precision motor. These motors use very powerful magnets, precious metal brushes and precision wound ironless rotors. They are actually built inside out compared to normal motors. They are designed for industrial applications which call for small size, low weight, high efficiency and predictable performance.

Probably the most used motor for solar cars is the Faulhaber Minimotor. Full motor data is available for download from www.minimotor.ch.

Without going into too much detail the pick of the motors used to be the Type 2233, either 4.5 or 6 volt. I preferred the 4.5 volt version because it has a lower DC resistance, a slightly higher efficiency and a slightly higher power rating. You must ask for the 2mm shaft because this fits the pinion gear that you should use. They cost about $100 each. Even though it is only rated at 3.9 watts you can safely connect it to up to 10 watts of panel because it will last for thousands of hours at 3.9 watts and probably several hundreds of hours at 10 watts. Each race is much less than 30 seconds so that's a lot of races. (A good race is under 20 seconds.) Don't even think about using the brushless motors.

Now, without a shadow of a doubt, there is a better motor. It is Type 2232 6 volt. This is basically the same motor as the 2233 but fitted with rare earth magnets. It boasts a power rating of 11 watts, has an even lower resistance so has an efficiency of 87%. More importantly it has three times the torque. It has a lower speed constant (revs per volt) so it was thought that the gearing may need changing, but this hasn't seemed to be the case. This is the motor used by the 2nd car in 2005 and explains its performance despite non-steering wheels. Of course, it costs more but it is worth having. I simply replaced the 2233 in one of our old 2002 cars with a 2232. The results were simply amazing. This old car was 1metre faster than the 2005 National champion car! When one of these motors was fitted to the champ car it was now 1 metre in front! Needless to say, all Tasmanian cars ran these motors. If you don't use one of these motors, save your money and stay at home.

The next question is, do we use one or two motors? Easy, just the one. No two motors are exactly the same, even the precision ones. Even if you buy lots of motors and do lots of testing to get two almost the same they will still fight each other and you will not get twice the value. You will have twice the weight, twice the gear losses, twice the cost, but slightly less power. If you connect them in parallel they will have the same voltage applied but it is highly unlikely that they will want to run at exactly the same speed, so one will get dragged down by the other. If you put a motor on each side of the car then when it goes around a corner the wheels will try to go at different speeds but the motors will try to go at the same speed. It just doesn't work. If you wire them in series then you will need twice the voltage. They will operate a bit like a differential and let the wheels go at different speeds around corners but you still have twice the weight and losses, and you will need a 20 volt panel.

Anyway, why would you bother? If you had a 10 watt panel and two 4 watt 80% efficient motors you would have 8 mechanical watts to play with. If you only use one 4 watt motor you will still have 8 mechanical watts to play with. Electric motors do not create energy, they simply convert the electrical energy to mechanical energy. The motor just won't last as long, that's all. The only advantage of two motors and two drive wheels is that it can reduce torque steering, but that's another story.

Gears. Setting the wheels in motion.

It would be possible to fix a wheel straight on to the motor shaft but our motors spin too fast for this to be successful. If we were using a stepping motor or a pancake motor then it would be possible but we're not. You need to use something to reduce the speed. This also increases the available torque and therefore the tractive force. Like all things in real life you get nothing for free so you are going to loose a bit of the available power in the process. What we have to do is keep this to a minimum.

I have seen it all. Rubber bands and O rings used as belts, Lego chain drives, Lego gears, rubber idler wheels running on the road wheels, idler wheels running on the top of the guide channel, you think it up it's probably been tried. A high quality, micro-miniature roller chain and sprockets would probably work OK. However, unless you are very rich you're not likely to get one.

By far the most efficient and the simplest form of transmission is a single set of straight cut spur gears. Bevel and bevel cut gears are too inefficient. Two and three stage gearboxes are also too inefficient. Don't play around with cheap gears. You must use good quality gears as this is still a source of losses. You can get instrument quality precision moulded plastic gears from Purgon in Melbourne or Farnel Electronic Components in Sydney.
The ones to use are 0.5mm pitch and come in sizes from 12 to 80 teeth. The 12 and 15 teeth have a 2mm bore to press fit onto the motor shaft. (Remember to get a 2mm motor shaft). A drop of glue helps to keep the gear on but makes it hard if you have to replace it. You can come up with all sorts of methods to work out what size of gears you need but if you start with a 12 tooth and a 72 tooth you can go from there.

These gears are made from a fancy plastic and are self lubricating so the worst thing you can do is to oil them. This only makes them pick up dust and that quickly wears them out. You must allow a bit of play in the gears, they must never mesh tightly. You can attach the big gear straight to the drive wheel but you must be accurate. We have always fitted a separate bearing into the gear to allow the gears to be meshed properly before fitting the road wheel. This also allows for quickly changing the gear or the wheel if needed.

It is most important to use a good solid mounting for the motor and wheel. The motors have threaded holes for 2mm screws in the end plate and that is how they should be mounted. Dick Smith sells packs of 2mm screws Any movement will chew out the gears and you might as well go home. If you have the misfortune of having the gears come out of mesh while running they will quickly destroy each other and must be replaced. You can practice with damaged gears but don't bother racing with them. Bear this in mind if you go gluing gears onto shafts, etc. A spare set of gears is a must.

Solar Panels. You've got the power.

When this competition first started there where no suitable panels available so a company in Melbourne made the 8 watt APSYS panels. These provided 4 rows of 3 volts each that could be connected as desired. Everyone used them but they started to break down after a couple of years. Solar car racing is pretty hard on the equipment.

The only readily obtainable alternatives were the BP Solar 12 watt and the Solarex 10 watt. These were both expensive and very heavy as they were intended for a long life out in the elements. We chose a Solarex at this time, even though it weighed 1.4kg and you weren't allowed to modify the panel in any way. Next year you were allowed to remove the frame as the required weight was calculated from the surface area. The Solarex still weighed almost 1kg but needed more ballast.

One of the WA Colleges had imported some small panels from the USA and convinced the powers that be to allow measuring each individual panel when calculating the weight. We exploited this by using 14 Dick Smith panels which produced more power than the old APSYS panel but were required to weigh considerably less.

Never to be outdone, the committee changed the rules to require the power of the panel be measured and the weight calculated according to the formula: Weight = (Power in watts – 4) x 220gm. This meant our 14 DSE panels had to weigh about 970gm.

If you take car weights (all up and including the egg but not including the solar panel) from 250gm to 600gm and then use panel powers from 4 watts to 12 watts, you can calculate the overall power to weight ratio for the car. You can do this manually or use Excel to plot graphs. Either way you would discover that the best power to weight was with a 4 watt panel. Unfortunately you cannot make a panel with zero weight. Using 9 DSE panels meant the panel was over weight and 10 DSE panels required a small amount of ballast. This equates to a bit over 6 watts.

To get closer to the ideal next year we trimmed all the excess off the panels and glued them to balsa wood. This way we found 8 DSE panels to be overweight and 9 DSE to be just underweight. We used these in the Tasmanian races, but, to get even closer we imported bare solar cells from the USA and used double-sided sticky tape to attach them to 20mm polystyrene sheet. We had panels that weighed less than 50gm. However, the National committee didn't agree with our power figures and we had to carry 400gm of lead in each car. We should have removed cells and had them re-assessed, but if you'd seen the circus that was National scrutineering you'd understand why we didn't. The car that beat Ewen out of 3rd place supposedly had only 4 watts, but the panel size and the car speed told a different story.

From 2004 they changed the rules yet again. The formula now is:

Panel Weight = (Power in watts – 6) x 175 + 600gm,with the proviso that the minimum panel weight shall be 600gm.

This is interesting. Now doing the calculations for power to weight shows that for an all up car weight of 450gm (no panel) the power to weight is constant for any panel power above 6 watts. If your car weighs less than 450gm then a 6 watt panel gives the best power to weight. If your car weighs more than 450gm then the more power the better, you're going to need it, hauling all that unnecessary bulk around. Or is it? With a 6 watt panel you will always get a bigger gain for any reduction in car weight. Then there is the extra friction in wheel bearings and the increased rolling resistance from carrying all that weight around. Don't even think about going below 6 watts as you will still have to carry the same weight as if you had 6 watts. 6 watts is easy to get. Just use 10 DSE panels. These are relatively cheap, are quite robust and easy to attach.

There have been a number of successful panels made up this way. We used a narrow PCB to which we attached the panels using their own bolts, then ran tape around the edges, taking care not to cover the cells, This has proved to be very reliable. Other teams have simply used corflute sheeting or balsa or polystyrene and wired the panels together. Whatever fits your car is the best for you, just make sure you have good connections. Do not try soldering directly to the panels as you will melt the solder inside and you cannot fix it. Also, don't over tighten the nuts as you can turn the bolts, fracturing the tracks inside, also unrepairable. As in all things, a little care required.

A number of teams who purchased the APPSYS panels years ago have been stripping them down but as they produce over 8 watts they have to carry far too much dead weight ballast. The only advantage is that they can put the ballast lower down and where they want to. Also, a number of teams have been persisting with using the full 12 watts allowed, but the all up car weight is just too much.

Car Weight and Performance. Anorexia on wheels.

Tests by Adelaide Uni also show where the power goes in a solar car. For the car tested, from the total power developed by the solar panel, 15% was lost in the motor, 3% in the gears, 13% in rolling resistance, 11% in air resistance and 58% in accelerating the car.

We have chosen the most efficient motor and we have perfectly meshing gears. We have clean bearings in our three narrow wheels fitted to casters. Our body is beautifully aerodynamic. How can we further improve the performance?

As in any vehicle, the biggest power consumer is simply accelerating the car. To get up to speed, to go around corners and to go up the hills you have to accelerate the car. Power is time rate of doing work. Work is applying a force through a distance. Force is accelerating a mass. The mass in this case is the mass of the car. Doctor Who may be able to change time and distance but we can't. What we can change is the mass of the car.

Now you might see why I mentioned power to weight calculations when discussing solar panels. You can decide the solar array weight and you can reduce the car weight. (Weight is the force exerted by gravity acting on a mass.) Reducing mass has the biggest gain in performance of anything you do to your car. If your complete car, without its solar array and ballast, but including the egg, weighs more than 500gm then you simply aren't trying hard enough. 300gm and you are getting really serious.

The best cars in 2005 and 2006 weighed between 1000 and 1100 grams all up in racing trim.

Power Maximisers. Things that go bump in the night.

There has been a lot said about the use of electronics in model solar car racing. The simple fact of the matter is that it works. It is true to say that, if you build the perfect car, for the conditions prevailing at the time, because of the small losses, you will go faster without electronics than with electronics.

Some of the well funded teams turn up at the Nationals with an array of components that has to be seen to be believed. They have a choice of 4 or 5 different motors and a choice of 20 or more gears to play with. Plus they have years of test data at their disposal. Provided the conditions don't change during the course of a race they can be very hard to beat, but it is possible, as we have proved. If conditions change during a race, as when a cloud crosses the sun, then these cars can be in real trouble.

Over the years we have always had to keep the cost to a minimum, being fully self-funded. Running 2 teams meant doubling up on everything and buying lots of motors was out of the question. We have also had very limited access to a track to do serious testing. Usually our cars have only been run across the driveway at home before going on to take out the Tasmanian race and shake up the Nationals. Testing gear ratios at the Nationals is normally not possible. Kent did get to try his quick-change gearbox in Adelaide one year and this proved to be invaluable.

Why does anyone need to change motors and gears? In simple terms you have to match the source of energy, in our case the solar panel, to the load, in our case the car. There is a thing called The Maximum Power Transfer Theorem which students of electronics will learn about, but, trust me, it applies to everything.

Electrical power is found by multiplying the voltage and the current. A solar panel not connected to anything except a voltmeter develops an open circuit voltage. There is no power being produced because there is no current flowing. An ammeter connected directly across the panel will cause the panel to produce a short circuit current but again no power is being produced because there is no voltage. (Any power being produced is all being lost in heating up the panel). We know that the panel does supply power in between these two points, but in varying quantities. Somewhere in there is the voltage at which the panel supplies the maximum power possible to the load.

An electric motor has unusual properties. In its simplest form it can be likened to a resistor in series with an adjustable battery. The resistor value is the resistance of the windings and brushes, etc. The battery voltage varies directly in proportion to the RPM of the motor and is created by the motor acting as a generator when it is turned. It is generally referred to as the back EMF, or electro-motive force.

Ohm's Law states that the voltage across a resistor is directly proportional to the value of the resistance and the current flowing through the resistor, V=IR. So, if we connect a battery to a motor the current drawn will be limited only by the resistance of the motor. This will be quite a high value and is known as the starting current, or stall current. This high current through the windings will produce a high force in the rotor so the motor will try to accelerate quickly.

As the motor speeds up it will generate an increasing back EMF. This opposes the applied battery voltage so the current will decrease. This will continue until the difference between the battery voltage and the back EMF causes just enough current to flow to overcome the losses in the motor. This is the no-load current. These losses include bearing friction, brush friction and wind resistance. The biggest loss is called the I^2R loss, or the loss due to the winding resistance. This is why a motor gets hot. A perfect motor would have zero resistance, maybe by using superconductors.

If a load is now connected to the motor then it will slow down and the current will increase until it is sufficient to supply the losses and the load. The combined losses are what determines the overall efficiency of the motor. The motor we have chosen has very low bearing friction, very low brush friction and virtually no wind resistance. It also has a very low winding resistance and is therefore the most efficient that is affordable.

All this means that the motor presents a very complex and changing load to the solar panel as the car changes speed going around the track and up and down the hills. That is, the voltage across it varies continuously. However, the solar panel produces maximum power at only one particular voltage.

Back in the olden days teams tried connecting their panels in series/parallel to get different voltages. Different motors have different voltage/speed characteristics and different gear ratios will also alter the back EMF. As I said, this is all great just as long as conditions don't change. What we need is something to automatically change the parameters of the motor and gears so they match what the panel would like.

Changing the motor and gears during a race is beyond most of our capabilities. A mechanical variable ratio drive would be far too inefficient. By using an electronic circuit between the solar panel and the motor we can make the solar panel think that the motor is a near perfect match, all the way from stalled at the start to going at several times its rated speed. It can never be a perfect match because of this thing called entropy, which basically means you never get anything for free. You will still never beat the perfectly set up car and occasionally the opposition will fluke it. However, most of the time you will get a big advantage.

Basically, all maximisers/optimisers, whatever, work the same way. They switch the motor on and off at a high frequency to maintain the correct maximum power voltage on the solar panel. The switching is usually done with a MOSFET and the energy stored in a small toroidal inductor. How they do it varies from simple circuits using operational amplifiers to those using micro-controllers. I have tested some of these circuits and found that they all work to some extent but have drawbacks. Simple op-amp circuits tend to be free running so the frequency varies greatly with load. Also, they tend to switch too slowly between on and off and so can be quite inefficient. They are easy to set up and adjust, though. Most micro controller circuits are extremely efficient, but, they are definitely overkill and do not lend themselves to simple adjustment. Besides, these circuits are yet to achieve ultimate success.

We have developed our own design which uses a dedicated switch mode power supply integrated circuit and a high speed driver stage. It is extremely easy to set up. It is so effective that the cars will spin their drive wheels at the starting gate. The circuit allows for a micro switch to be placed at the front of the car to inhibit the operation when the gate is down, then accelerate smoothly away. It also allows for dynamic braking at the end of the race. Cars fitted with these maximisers will operate in fully overcast and rainy conditions at less than 5% sun and still do full laps of the track, yet when the sun is shining do a standing lap in well under a 17 seconds. This equates to an average speed of well over 20kph with a finishing speed of well over 25kph. No changes need be made to the cars to go between these two extremes. These cars may still be beaten by cars perfectly set up for either of the two extremes but we didn't have to change our cars between races, ever.

I am pleased to say that in 2005 the first three cars in Melbourne all used these maximisers. I can now add that the top three cars in Sydney 2006 also used them. I think the case for maximisers has been settled, once and for all.

Calculations. Additional things.

What motor do I use?
This one's easy. You must use a precision motor, like the Faulhaber Minimotor. The most efficient one used to be the 2233 series 4.5 volt. It is 86% efficient. This is still a good motor but the newer 2232 6 volt is 87% efficient and has 3 times the torque while retaining the low series resistance. This is now the only motor to use.

How many watts do I use?
Sit down and work out the power to weight ratio for panel powers from 6 to 12 watts and car weights from 300gm to 600gm.

Panel power	6	7	8	9	10	11	12
Panel weight	600	775	950	1125	1300	1475	1650
300gm car wt	900	1075	1250	1425	1600	1775	1950
Power/weight	6.67	6.51	6.4	6.32	6.25	6.2	6.15
400gm car wt	1000	1175	1350	1525	1700	1875	2050
Power/weight	6.0	5.96	5.93	5.9	5.88	5.87	5.85
450gm car wt	1050	1225	1400	1575	1750	1925	2100
Power/weight	5.71	5.71	5.71	5.71	5.71	5.71	5.71
500gm car wt	1100	1275	1450	1625	1800	1975	2150
Power/weight	5.45	5.49	5.52	5.54	5.56	5.57	5.58
600gm car wt	1200	1375	1550	1725	1900	2075	2250
Power/weight	5.00	5.09	5.16	5.22	5.26	5.30	5.33

If your car, complete with all running gear and egg but without solar panel and ballast, weighs less than 450gm then use as close as you can get to, but not less than, 6 watts. If it weighs more than 450gm then use whatever you like, I think history proves it's way too heavy to be a serious contender.

What panel voltage do I use?
You will need at least twice the rated motor voltage and perhaps not more than three times the rated voltage. A lower voltage will give you more current for hill climbing and low light operation while a higher voltage will give you more high light speed. If you are using a maximiser you want 2-3 times the voltage and the maximiser will compensate for all conditions.

What size wheels do I use?
You have to compromise between getting enough ground clearance and not making the car unstable. You need at least 25mm under the middle to clear the guide channel when you go over the bridge and if you have an overhang at the front or back you will need about the same. Also, your drive wheel has to be bigger than the drive gear. Basically. 30mm is getting too small and 100mm is way too big. We originally used 65mm wheels because we had them but when we made our own we made them 50mm because it seemed like a good size. The tyre made the drive wheel 52mm. A number of fast cars in 2006 used narrow commercial 65mm wheels. The wheel size will combine with your gear ratio to determine the overall final drive ratio so you could have fixed gears and change wheel sizes but this also affects ride height so then you would also have to adjust the height of your rear guides.

What gear ratio do I need?
This is tied into the motor you are using, your panel voltage, the diameter of your drive wheel and the weight of your car. It may be anywhere from 3:1 to 10:1. We tried them all, even using a quick change gearbox one year. We found that using a maximiser the gear ratio isn't as critical. We settled on 6:1 many years ago. That is a 12 tooth motor gear driving a 72 tooth wheel gear. If you use the new motor the ratio may need to be different, but I suspect not. Hobart College tried from 6:1 to 5:1 with very little effect. Queechy ran 6:1 with a 65mm wheel and took second place but smashed the track record. . Someone with access to a test track will probably come up with a different ratio

Conclusions. The sum of all fears.

To be a really serious contender your car will need to be able to do a 100 metre lap in much less than 20 seconds. The top cars are now taking not much more than 16 seconds. An 18 second lap means an average speed of 20kph but the finishing speed is more likely 25 or even 30kph. A 50mm wheel has a circumference of 314mm. To do 25kph the wheel has to turn 25,000,000/60/314 per minute, or 1327rpm. With 6:1 gears the motor must do 7962rpm. With 6 volts applied your 2232 motor has a no load speed of 7100rpm. You need 8000rpm at full load, so you need to have at least 13.5 volts available. To have the best power to weight you will use a 6 watt panel. At 13.5 volts this is 444mA and you will have trouble getting a solar panel to suit. 10 DSE panels produce something over 6 watts at about 15 volts and about 400mA, so you could change the gear ratio or the wheel size to suit, and it might even work. Or use a maximiser like everyone else. With the 2232 motor it might be worth going for perhaps a 5:1 gear ratio. This means a motor speed of 6635rpm and an applied voltage of a bit under 12 volts.

Your complete car will weigh in at around 1kg on the track, less if possible. This allows for about 6.5 watts plus a sub 400gm car.

If you think this is all too difficult, have a look at the top three cars for the last two years. Different schools, different constructors, but all based on our original concept. It can be done, it's not that hard.

Otherwise, happy racing, you too are going to upset a lot of people.

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