

# Model Solar Racing Car Design for Dummies.

## 2009 upgrade.

or

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

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**History.** Where I'm coming from.

**As a competitor.** The early years.

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 well and truly cast.

We 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. To this day 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 4<sup>th</sup> place by less than a metre.

Sturt competed again in '96, coming 3<sup>rd</sup> 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 2<sup>nd</sup> 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 in 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 despite the huge weight penalty the car made 3<sup>rd</sup> 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 just a stick chassis and we redesigned the electronics to basically the circuit we use now. The car was just beaten into 2<sup>nd</sup> by Queechy High and went to the Adelaide Nationals. Kent experimented with a quick-change gearbox and we were lucky enough to be 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 at high speed and the front casters got the death wobbles.

2000 saw Ewen start at Clarence and also take up racing. Kent went for a radical looking 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 and some of Sturt's old running gear. Both cars used electronics. Kent experimented with fixed front wheels and tried tyred and non-tyred wheels. Kent easily came 1<sup>st</sup>, Queechy came 2<sup>nd</sup>

and Ewen took 3<sup>rd</sup> 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 once and for all. Kent again made the finals but Ewen's car fell foul of the atrocious National track and was eliminated before the finals. However, some quick modifications to the guide system saw the car win all its repechage heats and take out the 2<sup>nd</sup> fastest 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 1<sup>st</sup>, Queechy 2<sup>nd</sup> and Kent 3<sup>rd</sup>. At the Nationals in Adelaide both Kent and Ewen made the finals, and Ewen shocked the organisers by taking out 4<sup>th</sup> place overall.

Yet another rule change for 2002 but the boys were able to come up with totally radical, and still often controversial, designs 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, but 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, took out 2<sup>nd</sup> fastest lap time and won the Best Engineered Car award. Ewen won 32 races in a row and was undefeated until the best of 5 grand final where he won the first 2 races before the other car suddenly received an amazing and mysterious performance boost and narrowly won the next 3. So Ewen had to settle for 2<sup>nd</sup> place overall. He had already recorded the fastest lap of the day, both of our cars taking over 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 cut down 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 2<sup>nd</sup> so both went off to Adelaide. They both tried to further reduce the weight of their cars by using separate bare solar cells fixed to polystyrene panels but fell foul of the dubious power measuring system being used at the Nationals. Reducing the size of the panels was not an easy option so they both 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 that and the weight penalty, both cars made the finals and Ewen once again took out 4<sup>th</sup> place overall. Both cars were eliminated by the same extremely dubious NSW 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. He now takes his frustrations out as a heavy metal drummer.

P.S. He still really has a soft spot for solar cars and did return to help out at the 2008 Nationals in Hobart.

To sum up:- In 9 years of competing in the Tasmanian Model Solar Car Challenge, we entered a total of 12 different cars, took 3<sup>rd</sup> place 4 times, 2<sup>nd</sup> place 4 times and 1<sup>st</sup> place 5 times. We represented Tasmania at the Australian International Model Solar Car Challenge in every one of those years with 12 (not always the same) cars and made the finals 11 times. For 7 of those years we were the only Tasmanian cars to make the finals. We made the quarter finals 11 times, took 4<sup>th</sup> place overall twice and 2<sup>nd</sup> 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. If only we had come from a 'better' school in a different state....

**As an administrator.** The later 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 calculating the ballast weight for each 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, and 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, but some teams seemed to get away with just about anything because “so and so teacher is a good guy and everyone knows that he wouldn’t cheat!!!!” Who did they ask? The Tooth Fairy or Santa Claus?

For 2005 I was invited onto the National committee so I got involved with rewriting the rules to remove a lot of ambiguities and to try (not always successfully) 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, with less 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 2006 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. Tasmania took five cars to the Nationals, all based on our original design concept. All five had run sub 18 second laps in the Tasmanian competition held in mid October.

P.S. I have since discovered that, despite being very smooth, the new NSW track is not 100 metres but only about 94 metres long, so our old lap record times stand up pretty well.

Adelaide 2007, what can I say. This was the Atlanta Olympics of solar car nationals. If you are too young to know what I am talking about, don’t worry. I won’t elaborate too much, but... The track was late arriving so no-one got to practice. In the middle of a drought the weather sucked for most of the time, especially on Saturday, and then was all over the place on Sunday. Why is it that it always seems to rain when we go to Adelaide? And they have the hide to make comments about Tasmania. The Saturday time trials were farcical to say the least and the ‘seedings’ saw the two top Tasmanian cars race each other in the first elimination round on Sunday while other races had two cars that hardly crawled around the track. This trend, and the variable weather, continued all day so the finals were in no way a true indication of the standard of the cars. Given any other weekend I suggest that the final four would have been completely different. For example, the car that was placed fourth did not make the finals in Tasmania and was taken at last minute as a wild card to make up the numbers. Not to say it wasn’t a good car, it’s just that other cars were better. Once again I was involved in measuring the power of the panels and calculating the weights so I saw all the cars first hand. The car that was awarded first place was very ordinary but by virtue of an anomaly in the rules was able to gain a huge advantage in low light conditions. This effect is now fully understood and I will have more to say later. Probably one of the best cars was from Winthrop Baptist College in WA. This was a small, lightweight car built from this help file by a new school, and, despite some teething troubles and a bad draw, turned in a 16.3 second lap yet was eliminated. The ‘winners’ didn’t crack 19 seconds all weekend. You work it out, I can’t.

Hobart 2008 has been declared a success by all who attended. Possibly this was due to the fact that we coerced the National champs from 2005 and 2006 to run the event, with help from yours truly and other long sufferers. Despite the fact that it rained every night it did not actually rain on the event. One of the boys had written a seeding programme that took the light level into account and it worked out pretty well spot on. As well we measured all the panels at 50% Sun then doubled it to greatly reduce any advantage from low Fill Factor panels. This caught a few teams by surprise even though it was written into the regs so there was a bit of panel shuffling going on. This won’t be allowed any more, you will now have to stick with what you first bring to scrutineering. As a result a number of the ‘fancied’ teams didn’t perform very well. Most of the cars were pretty ordinary to say the least, with only a few stand outs design and construction wise. The Victorian car that won broke lots of the accepted design norms but won due to meticulous preparation and attention to detail. A well deserved win. There was a bit of inventive interpretation of some of the regs, including by the winning car, but this has been tidied up for 2009. Despite the 2<sup>nd</sup> placed Velox doing 16.18 seconds in 122% Sun (due to the clean dry Hobart air) none of the other cars were particularly fast, unless you count the 3 wheeler built to the 2008 rules by the 2005/6 winner which went 15.75 seconds in a demonstration time trial in 108% Sun. Shows what can happen if you build your car properly in the first place.

So then, if you reckon you already know everything that there is to know about model solar car racing and you couldn't possibly learn anything new by reading on, stop now. It's true what they say, you just can't help some people.

**Recommended reading.** More than just a good idea.

I used to 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 also on the National committee, one of the rule makers and is Chief Scrutineer. However, the book is a few years old now and fairly out of touch with the current regulations. Despite that 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 a lot of 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. Ian Gardner (Victorian committee) has also written a lot of useful stuff but, again, it tends to be pretty technical so is more aimed at the more experienced constructor. Check it out on the Victorian and Tasmanian websites.

**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 all cars had a separate chassis with the motor and wheels attached and then the body sat on top. So did racing cars. So did trucks. Now all 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. A tin can, a milk carton, a soft drink bottle and an egg are all examples of monocoque construction. Trucks and four wheel drives (read small trucks) still use a separate chassis. What are you going to build?

Fibreglass is very strong but just too heavy. Carbon fibre is even lighter and even stronger but it also is very brittle. When it does break it shatters and is almost impossible to repair. It is also fairly 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 nowhere near as light. It will bend before it breaks. Unless you can get aircraft grade aluminium and all the fancy gear required to work it, 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 while still relatively light.

Polystyrene blocks can be used to make complicated body shapes. It is messy to work and can only be glued with things like liquid nails. It has very little structural strength and you have to have a separate chassis or at least 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 so you have to hollow it out. A 2003 car we made from foam was actually heavier than the same car made from balsa sheets, but nowhere near as strong or robust, requiring a separate chassis. I must admit, in 2006 and 2007 a couple of pretty successful Tasmanian cars were made by laminating thin foam with tissue paper on each side. The result was fairly strong and light, but they were extremely lucky that they didn't suffer any damage as this construction is extremely brittle and repairs would have been almost impossible. Also, both years were fairly overcast, so, who knows what damage high speed action might have wrought. They didn't do as well in 2008, for some reason.

Good old balsa wood is very light and yet is stronger weight for weight than steel. It does this because it is a maze of hollow cells of cellulose fibre. Cotton and linen are also cellulose fibre and look how strong they can be. It's always difficult to beat nature. Now, if only we can work out how to use spider web! Balsa is readily 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 the same 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 as stiffeners and put fillets in all corners. Properly designed and built balsa cars can weigh under 300gm with all running gear except the solar panel and ballast installed.

Balsa can be cut to complicated shapes with simple tools and can be joined in minutes using 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 as you have effectively made a sandwich. If you don't apply dope then don't get balsa wood wet. It works like a sponge and quickly becomes very heavy and soft. The only real drawback with balsa is that it is difficult to make compound curves, but even that is possible by using a steamer. And anyway, you really don't need to.

### **Streamlining.** Going with the flow.

When cars were made of sticks with a solar panel on top streamlining didn't matter as these cars had a very low frontal area. Back 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 have modified the frontal area several times but it can be shown that even at fairly low speeds streamlining remains absolutely essential.

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 as terminal speeds had gone up. 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 actually 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.

In 2007 the cans were replaced with milk cartons so now the front of the car had to be at least 235 mm wide and 75 mm high. Once again, streamlining was absolutely essential. The 2007 winner didn't actually ever go fast enough to need streamlining, but the fastest laps (low 16s) were done by fully streamlined monocoque cars. The 2008 winner and runner up both used extensive streamlining, although they both bent the interpretation of the rules somewhat in the process. Interestingly, a number of cars went to great trouble using various methods to reduce the weight but had square box shapes. They didn't go very fast. Perhaps someone told them that the sun never comes out in Tasmania?

The 2009 rules call for a 2 litre milk bottle so the car will be at least 100mm high. You can have the bottle end on or sideways, so the body could be 100mm or 260mm wide. Both ways do have merit. Don't forget that in full sun your car should 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 the cars had to have a floor with a minimum of 400 sq. cm. 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 right off the track. We cured our problem with little wings and front skirts, just like a full sized racing car. This may not have been such a problem with a smaller front and floor, but a bit of aerodynamic down force is not hard to achieve. More importantly, you can still get a lot of lift if you are not careful! With the milk bottle you are still looking at a minimum floor area of around 300 sq. cm. This is definitely a serious wing area so it should 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 until next year. Think seriously about where and how you want to arrange the milk bottle to minimise both drag and lift. Unless like a lot of teams your car isn't going to be particularly fast, of course.

Lastly, draw a line between where all the wheels contact the track. Any weight outside this line will increase instability and must be minimised so think about how you are going to arrange things like the solar panel and the ballast weight.

### **Wheels and tyres.** On a roll.

First thing to decide is 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 but we are building a specialised vehicle. Due to the rough and uneven 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 wheeled car taking the corners in Sydney in 2002 while up on 2 wheels, but the drive wheel was still firmly 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.

If you still don't believe me, anyone who has been in Adelaide for the finish of the Darwin to Adelaide solar race will have noticed one glaring detail common to all the cars. Without exception, they all have three skinny wheels.

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 somehow created a relapse to 4 wheeled stick cars for 2004, but, 2005 saw sense and 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 limited slip differentials, rear wheel drive is the only way to go. All serious sports cars are rear wheel drive. Could you imagine a F1 car putting 1000HP onto the track through the front wheels? You'd need to be The Governator to steer it! True, the first and second placed cars in 2007 were four wheelers, but, for various reasons which I'm not allowed to talk about, they didn't actually get to race in anything like full sun, and, also for various reasons some of which I have mentioned, they didn't get to race against any serious three wheelers. I am also not allowed to mention the inappropriate panel weight carried by some of them. The race times still show that the three wheelers were up to 3 seconds faster than the four wheelers, but they didn't necessarily get the chance to show their potential. The 2008 winner was again a 3 wheeler.

P.S. I have since seen photos of a stunning looking sidecar arrangement model solar car built in Portugal. I have no idea of its performance, but it looked fantastic.

The regulations specify that all wheels must either be at least 1mm wide or 0.6mm radius. Why? It's called rolling resistance. The ideal wheel would have a hard, very narrow rim but this causes serious damage to the track and is therefore banned. Racing bicycles use very thin tyres pumped up very 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 in fact that in racing cars the rubber starts to melt and stick to the track, a property they can exploit, but we can't. The power to heat the tyres comes from the car engine, and since we have so little power to start with we simply cannot afford to waste any, no matter how small.

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 probably not get the wheels to track properly and they will spend a lot of the time being dragged sideways. You must use something on drive wheels though, unless you want to stay at the start gate or at the bottom of the hill. Very narrow O rings are ideal, but you must glue them to the wheel or they may fly off at high speed. Another option employed by some teams is to use an aluminium wheel with a serrated rim. This may actually work better on a wet track, but I don't know.

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 extra wind drag more than offsets any weight loss. I have seen a number of teams drill out their wheels and then place film on each side. This seems to be a reasonable idea, although how much weight is saved is debatable. 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. It was pretty obvious in Hobart that the track is starting to distort as some scalloping was fairly evident.

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 any bad joins in the channel and must be fitted with bearings. They probably 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 was 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, even 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 should at least be able to hold the whole car up by any one of the guide wheels.

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 any bad track joins. If the guides are just behind the wheels then the wheels will lift the guides up over the bad joins. The alternative can often be disastrous yet quite spectacular.

If you have a 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. It is called momentum. The car wants to keep going in a straight line. Without rear 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, that is, the car is pointing tangentially down the track, will give the best high speed performance, especially if you have rear wheel drive. 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 are low in friction and are easy to clean out but they also pick up dirt easily. Those fitted with rubber seals to keep dirt out cannot have the grease cleaned out easily and also have relatively high friction levels. Those fitted with shields can be fairly easily cleaned out, have low friction levels yet also 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. The '2Z' (or sometimes 'ZZ') means shields both sides. Only use first quality reputable brand name bearings as they will last for many years even without lubrication.

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 can 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 and dirt once all the grease and oil have been removed.

P.S. We have our old 2002 cars that still get dragged out for demonstrations. The bearings cost about \$10 each but have not been looked at, oiled or cleaned for several years. They can still beat all but the best new cars.

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

Even with smooth front wheels, unless they steer, your car might 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 probably need 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. Simple, low weight, 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 have already broken traction and are losing drive potential, even if you do have a tyre fitted. It's called limiting friction. So the resistance has gone up and the drive has gone down. A lose-lose situation. 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 1<sup>st</sup> and 3<sup>rd</sup> in 2005 had two castering front wheels and a single castering rear drive wheel. The car that came 2<sup>nd</sup> also ran two front wheels and a single rear drive wheel but all wheels were on fixed axles. The 1<sup>st</sup> and 2<sup>nd</sup> cars both used the same 10 Dick Smith Electronics panels and the same Engelec maximiser. The 2<sup>nd</sup> car had the better motor and was noticeably faster in a straight line, but the 1<sup>st</sup> car actually overtook it around the outside of the last corner, due no doubt to the much lower drag of the caster wheels. I rest my case.

A big 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 or worse, the drive gear, running into the guide track. Either method is OK but we always preferred to offset the guides as this kept the car better balanced.

An even bigger 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 wheels are directly in line with their pivots. Haven't any of you ever pushed a supermarket trolley with a bent or misaligned caster? If you don't align all the wheels then don't bother, stay home.

**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 is 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. These are the things they use for medical tools and space exploration.

Probably the most successful motor for solar cars is the Faulhaber Minimotor. Full motor data is available for download from <[www.minimotor.ch](http://www.minimotor.ch)>. No, that's not Chile, it's Switzerland.

Without going into too much detail the pick of the motors used to be the Type 2233, either 4.5 or 6 volt. We always used the 4.5 volt version because it had 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 brushless motors.

Now, however, without a shadow of a doubt, there is a better motor. It is the Type 2232 6 volt. This is almost 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 2<sup>nd</sup> car in 2005 and explains its performance despite the non-steering wheels. Of course, it costs more but it is worth having. I simply replaced the 2233 in Kent's old 2002 cars with a 2232. The results were amazing. This very tired old car was 1 metre faster than the 2005 National champion car! When one of these motors was then fitted to the champ car it was now 1 metre in front! Needless to say, all 2006, 2007 and 2008 Tasmanian cars ran these motors. In Sydney 2006 at least the top 4 cars used this motor. In Adelaide 2007, the top 14 cars all used this motor. Hobart 2008, apart from the 2 Taiwanese entries, 28 cars ran this motor. If you don't want to use one of these motors, then save your money and stay at home. The other 2 cars ran a Maxon 118740 motor. This motor is supposed to be very good but it also is very big, very heavy and very expensive.

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 want to go at different speeds but the motors will try to go at about 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 now need a 30 volt panel.

Anyway, why would you bother? If you had a 10 watt panel and two 3.9 watt 86% efficient motors you would have 8.6 mechanical watts to play with, not 7.8 watts. If you only use one 3.9 watt motor you will still have 8.6 mechanical watts to play with, not 3.9 watts. 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. Anyway, the motor that we are all going to use now is rated at 11 watts. End of story. By the way, using an 11 watt motor doesn't mean we need an 11 watt panel. It just means that if we use less than 11 watts it will last for more races than you can possibly comprehend. The only advantage of two motors and two drive wheels is that it can reduce torque steering, but that's yet 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 could 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 and acceleration. Like all things in real life you get nothing for free so you are going to lose 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. Leonardo da Vinci knew that hundreds of years ago. 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 can still be a serious 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. Do not get glue on the teeth! 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. Make sure the small gear doesn't rub on the wheel. We have always fitted a separate bearing into the gear to allow the gears to be meshed properly before fitting the road wheel. We put pins through the gear to loosely engage holes in the wheel. This allowed for quickly changing either 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. Make sure you use screws that are the correct length. 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.

P.S. Hobart Nationals, 2008, one team dared to be different. They used a Maxon 118740 motor with direct drive to the wheel. This required a wheel around 30mm diameter to clear the motor so the motor still ran quite slowly, around 4400rpm for 25kph. The data for this motor shows that it has a speed constant of 1200rpm/V, or it does 5360rpm at 4.5

volts This meant that the motor voltage was always relatively low and, as a consequence, the current high. This can be a problem with higher maximiser losses at low output voltages. Also, the side loading on the motor shaft may be too high. Whether this offsets the 3% gear loss is debatable.

**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. There are still a few of these being used and while some are almost as new, most are well past their use by date.

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 the active area of 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:  $\text{Weight} = (\text{Power in watts} - 4) \times 220\text{gm}$ . 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 quickly 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 equated to a bit over 6 watts, using the DSE panels of the time. This car took 2<sup>nd</sup> place and held the lap record for the next 4 years. The car that beat it used imported cells and chicanery.

Next year, 2003, to get closer to the ideal, 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 3<sup>rd</sup> place supposedly had only 4 watts, but the panel size and the car speed told a different story and in fact, this car and panel were not allowed to race in Perth the next year.

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

Panel Weight =  $(\text{Power in watts} - 6) \times 175 + 600\text{gm}$ , 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 was easy to get. We just used 10 DSE panels. These were relatively cheap, are quite robust and easy to attach. However, they have changed the design so the present ones produce more current but they are also much larger and heavier.

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, fitted balsa sheets beside the PCB and then ran tape around the edges, taking care not to cover the cells. This has proved to be very reliable and we have panels many years old. 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 probably 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. Once you've made it, don't fiddle. I repeat, we have home made panels many years old. We don't touch them. Ever.

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. I know of one 11 watt powered car that has a habit of breaking wheels. Not recommended.

Don't forget that since 2008 you are not allowed to have anything on your panel. That includes the On/Off switch and series/parallelling switches.

I have found that there are at least four different solar cells sold by DSE. The original dark blue monocrystalline that produced around 550mA, a blue polycrystalline that also produces around 550mA, a grey monocrystalline that can produce over 660mA and a light blue polycrystalline that only produces 430mA. All four styles deliver the same voltage, but, you must be aware that they will produce vastly different power figures. As I said earlier, now they sell a bigger version. Also, you should never, never, never, ever mix up different cells in a panel.

Jaycar are advertising that they sell the same panels as the old DSE but still do not have any. The latest date offered is March 2009. I am exploring obtaining these in large quantities and reselling them at a much lower price, providing that they are a suitable device. Watch the various web sites for updates.

The other cell worthy of comment is that obtained from the Tech Ed centre. There seems to be a huge variety of cells from this source, also of widely varying performance. Many of these seem to be either reject or surplus cells. There appears to be some that have an unusually low and normally unacceptable Fill Factor. The Fill Factor is the ratio of the maximum power to the product of the open circuit voltage and the short circuit current. It is an indication of the quality of the cell. The laws of the universe limit the maximum FF to about 0.85 and normally commercial viability limits the useful minimum to about 0.7. It seems that at least one batch of cells from Tech Ed have a FF of around 0.5. These cells give normal open circuit voltage and short circuit current but the maximum power and the maximum power voltage are both well below what you would expect. A panel made from these cells will seriously under perform. However, it can be shown that the loss of output is much less at lower light levels and it is easy to build a large panel that only registers around 6 watts when measured on a light box, yet performs the same as a 10 watt (or more) panel in 50% light. This can give a huge boost in car performance in anything below 100% sunlight, as observed by everyone in Adelaide in 2007. The 2009 rules have been amended to take this into account. Also, it is extremely easy to artificially create this effect in any panel and this practice has been outlawed as well.

P.S. I have since learnt that in actual fact panels can be intentionally produced with a FF as low as 0.2 and a FF of 0.4 is commonly used in Northern Europe because they perform better in very low light levels. (We know!)

Note. There will be a 20% increase in the required panel weight from 2009 if you chose to use electronics. This will change nothing in the overall scheme of things since the only 2 cars without electronics in Hobart came from Taiwan and they would have fitted electronics on the spot except that their panels did not produce a high enough voltage. Personally, I see it as just a further complication for the scrutineers. Also, the break even weight for your car will go up from 450gms to 540gms. (See later for calculations.) I also see this as a totally retrograde step as it allows an even slacker approach to car design and construction. Mediocrity wins again.

### **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.

A quick lesson in some basic physics.

No God yet invented has anything to do with model solar car racing. Science rules.

Force is accelerating a mass.  $F = ma$ .

Work is applying a force through a distance.  $W = Fs = mas$

Power is the time rate of doing work.  $P = W/t = Fs/t = mas/t$

The mass in this case is the mass of the car. We have to accelerate it up to speed, around the bends and up the hill. We have to do this over the length of the track. The time we take determines how much power we use. Perhaps now you see why power to weight is so important?

Doctor Who may be able to change time and distance but we can't. What we can do is change 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 power (and therefore weight) and you can reduce the car weight. Weight is the force exerted by gravity trying to accelerate a mass. Reducing the mass (weight) has the biggest gain in performance of anything you can do to your car. If your complete car, without its solar array and ballast, but including the egg, weighs more than 500gm then you just simply aren't trying hard enough. 300gm and you are getting really serious. Yes, it can and has been done, many times. The best performing cars in 2005, 2006 and 2007 all weighed less than 1100 grams all up in racing trim. I already know of at least 1 car built to the 2009 regs that weighs around 250gms complete except for the panel. Luckily for you the builder is too old to compete.

**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 could build the perfect car, for the conditions prevailing at the time, because of the smaller losses, you will go faster without electronics than with electronics.

Some of the well funded teams used to turn up at the Nationals with an array of components that had to be seen to be believed. They'd have a choice of 4 or 5 different motors and a choice of 20 or more gears to play with. Plus they had years of test data at their disposal. Provided the conditions didn't change during the course of a race they were very hard to beat, but it was possible, as we have proved. If conditions change during a race, such 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. In simple terms this states that, for maximum power to be transferred from the source (solar panel) to the load (motor) the impedance (resistance) of the load must be the same as that of the source.

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 point 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. This is found in motor data sheets as the voltage constant.

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 determine 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. At all other times it produces a current proportional to the light level and the motor then determines what the voltage will be.

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, for most of the time you will get a big advantage.

Basically, all maximisers/optimisers, whatever, work the same way. They switch the current 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 inductor. Capacitors smooth out the switching pulses. 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 often seem to be overkill and often do not lend themselves to simple adjustment. Some also have been shown to have potential problems at low light levels and they can stop working for no apparent reason.

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 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 the first three cars in Melbourne in 2005 all used these maximisers and the top three cars in Sydney 2006 also used them. The top 4 cars in Adelaide 2007 all used maximisers, although not all mine. In 2008 only

2 cars out of 32 did not use a maximiser of some sort. There were at least 5 different designs used. 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. It does however rotate slower because, as I said, you get nothing for free. Despite that this is now the only motor to use. I have been assured that the Maxon is also a good motor but it costs over twice as much and weighs bucket loads more.

How many watts do I use?

First you have to decide whether you are going to use electronics or not. Don't ask me, you know what my answer will be. 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. If you are not using electronics it looks like this.

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 that, in a fair fight, it will be way too heavy to be a serious contender.

With the new 2009 rules there is a complication. If you decide to use electronics the required solar array weight will be increased by 20%. The formula becomes  $Weight = [(Power - 6) \times 175 + 600] \times 1.2$  so the table now looks like this.

Panel power	6	7	8	9	10	11	12
Panel weight	720	930	1140	1350	1560	1770	1980
300gm car wt	1020	1230	1440	1650	1860	2070	2280
Power/weight	5.88	5.69	5.56	5.45	5.38	5.31	5.26
400gm car wt	1120	1330	1540	1750	1960	2170	2380
Power/weight	5.36	5.26	5.19	5.14	5.10	5.07	5.04
500gm car wt	1220	1430	1640	1850	2060	2270	2480
Power/weight	4.92	4.90	4.88	4.86	4.85	4.85	4.84
540gm car wt	1260	1470	1680	1890	2100	2310	2520
Power/weight	4.76	4.76	4.76	4.76	4.76	4.76	4.76
600gm car wt	1320	1530	1740	1950	2160	2370	2580
Power/weight	4.55	4.58	4.6	4.62	4.63	4.64	4.65

Obviously the power to weight ratio was going to be lower for all car weights and panel powers but it is not the full 20%. In fact the loss is much less and it is not the same for all weights and powers.

Car weight	300gm	400gm	500gm	600gm
6 watt panel	-11%	-10.67%	-9.7%	-9%
12 watt panel	-14%	-13.85%	-12.65%	-12.75%

This indicates that the bigger panels will be even further disadvantaged and further advances the case for small light weight low powered cars. Play with the figures however you like. Provided your car weighs less than (now) 540gm, you will still get the best power to weight with a 6 watt panel. If you can't get below 540gm what the heck are you doing?

What panel voltage do I use?

Experience shows that 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 rated motor voltage and the maximiser will compensate for all conditions. (See below for calculations.) With a maximiser you will probably want at least 10 volts to ensure the circuit works properly, especially in low light 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 and a 52mm wheel. If you use the new motor the ratio may need to be different. 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 also smashed the track record.

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. A 16 second lap means an average speed of 22.5kph but the finishing speed is more likely 25 or even 30kph. A 50mm wheel has a circumference of 157mm. To do 25kph the wheel has to turn  $25,000,000/60/157$  per minute, or 2655rpm. With 6:1 gears the motor must do 15,930rpm. With 6 volts applied your 2232 motor has a no load speed of 7,100rpm. So, to do 15,930rpm at full load, you need to have over 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, 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 would mean a motor speed of 13,275rpm and an applied voltage of over 11.2 volts. To get closer to 30kph may need a lower gear ratio or a bigger wheel or a higher voltage. Also, I haven't included the IR losses. That is, the voltage drop due to the current flowing in the motor resistance. What you have to do is make sure that at top speed the motor voltage is at, or, if you have a maximiser, just below, the maximum power voltage of your panel. Obviously, if you are not running the panel at its maximum power point then your car could be going faster. This is where maximisers come into their own.

**Conclusions.** The sum of all fears.

Basic four wheel stick cars are easy, anyone can build them. And a well built one usually goes fairly well. Three wheeled monocoque cars can be harder to build and even harder to build properly, but the results are well worth while. And they look better and give you a much greater sense of achievement. They win a lot of Best Engineered Car awards as well.

If you think this is all too difficult, have a look at the top three cars for 2005 and 2006, and the fastest cars from 2007 and 2008. Different schools, different constructors, but all based on our original three wheel concept. It can be done, it's not that hard. I can name several schools that have never competed before but have followed this line of thinking and made it to the Nationals on their first attempt.

Why didn't they win in 2007 and 2008? Simple, forget 2007, it was a total furfy. The seeding was a nightmare and enough has been said about the winning car. Three wheelers still came 3 and 4 and totally creamed the fastest lap when they were given their chance. The 2008 winner was also a 3 wheeler and although not completely to this formula it won simply because of the meticulous way it was prepared and maintained and the unfortunate lack of serious well designed and built competition.

So, happy racing, you too are going to upset a lot of people. Believe me, rattling cages is contagious.

Oh, one last thing. In case you didn't know, the new grey track is not 100 metres long. It is in fact only 85 metres for a lap with 9 metres more to the finish line, a total of 94 metres. This means that Ewen's old lap time of 17.5 seconds for 100 metres on the rough old track and with the old motor set in 2002 still stands up pretty well against the new motors doing 16.3 seconds on the new smooth 94 metre short course track.

See you in Melbourne.

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