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The 1998 World Solar Rallye: Akita, Japan

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Abstract

In early August 1998, 81 solar/electric vehicles participated in a three day endurance race in Japan. The objective was to complete as many laps of the 31 km circuit as possible. Some of the cars used state-of-the-art motors, batteries, chassis, solar cells and tyres to produce vehicles which could travel at speeds of 70–80 km/h on about 1 kW of input power. With only 20 kg of battery, some solar cars were travelling around 450 km a day. This paper tells the story of the race and the technological developments behind the successful vehicles. © 1999 Elsevier Science S.A. All rights reserved.

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1. Introduction

In 1983, Hans Tholstrup crossed Australia in a solar powered vehicle called Quiet Achiever. He believed that a sustainable alternative to the combustion engine was needed and thought solar energy could be a means of powering future vehicles [1]. He founded the World Solar Challenge to help promote the design and development of solar vehicles. The event started in 1987 and runs every 3 years. It involves solar powered vehicles racing from Darwin in the North of Australia to Adelaide in the South, a distance of about 3000 km. The winner of the first race, the GM Sunraycer, was designed with aerodynamics as the main consideration. This significance of this feat was expressed thus by Hans Tholstrup: ‘‘The GM Sunraycer's performance in the inaugural World Solar Challenge is as important as man's first flight. GM has done for energy efficiency what Kennedy did for the space program. It is a little awesome. GM has proved ... that electric cars are now feasible. Every automotive engineer in the world will realise the implications of this mind-boggling performance [2].''

As he had hoped, the performance of the vehicles improved rapidly with average speeds increasing from 42 km/h in 1987 to 76 km/h in 1996. The average speeds of the first six cars from 1987 to 1996 inclusive are shown in Table 1.

One of the main areas of concern with the fastest solar cars is the cost to produce them. Cars which average over 70 km/h have so far cost in excess of £1,000,000 to produce. The main area of expense is the top grade solar cells which are produced in small batches in laboratories and can cost up to £750,000 for an array of 8 m^2. Such vehicles are specialised racing cars which are not intended for production. The skills learned by the designers are, however, employed in the design of efficient electric vehicles. An area investigated in this paper is the performance that a solar racing car can achieve with currently available mass produced components. Using such technology at South Bank University, a budget of £20,000 was made available to build a solar racing car for entry in the 1996 World Solar Challenge. The objective was to produce a vehicle to travel the 3000 km course within the 10 day time limit.

The 1996 solar car (Mad Dog 1) was produced using: commercial solar cells, flooded plate lead–acid batteries, bicycle wheels and tyres, brushed motor, carbon-fibre/PVC core chassis with fibreglass nose cone and side panels. The car, shown in Fig. 1, successfully completed the 1996 race and on good days averaged 43 km/h and travelled 369 km. Although much slower than the leading

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Table 1
Solar car performances

Year	Average speed(km/h)
1987	42
1990	46
1993	73
1996	76

cars, Mad Dog 1 showed that a reasonable performance could be achieved for little expense.

2. Solar car development

The team felt that an even faster car was possible with only a small increase in cost, building on the knowledge gained when developing the first car. A survey of other solar cars highlighted several areas which could be improved at low cost but achieve significant improvements in performance.

2.1. Brushless instead of brushed motor

Some solar racing cars have in-hub brushless motors to eliminate transmission losses. These can be purchased from New Generation Motors (NGM) for about £10,000 and are 93% efficient with the controller. CSIRO in Australia offer a 98.2% efficient motor without controller for about £30,000. Both motors were too expensive for the new solar car (Mad Dog 2). A Lillington T-Flux 406 motor and controller was used with a toothed belt drive to the rear wheel. The peak efficiency was given as 95% yet the cost was £3000. The brushed motor system on the first car was estimated to give an average efficiency of 82%.

2.2. Genesis valve-regulated battery instead of flooded plate type

It was expected that the replacement of the flooded plate batteries with the genesis would give between 5 and 10% improvement in charging efficiency and eliminate maintenance.

2.3. A greater area of solar cell array

The commercial solar cells are pseudo square, being cut from round, single crystal, silicon rods. To eliminate the gaps this creates between the cells they were all laser cut into rectangles. This improved the active area from 86 to 93%.

2.4. Better aerodynamics

The frontal area of the new car is 0.8 m^2 compared to 1.0 m^2 for Mad Dog 1. An aerofoil section is used for the main body to give a lower drag coefficient (C_d). C_d values can only be estimated; for the old car a value of 0.2 was considered reasonable and for the new car 0.16.

2.5. Lighter chassis

The new car uses ‘pre-preg’ carbon fibre with Nomex Honeycomb core supplied by Hexcel. The old car had a mass of 320 kg including driver and batteries compared to 260 kg for Mad Dog 2.

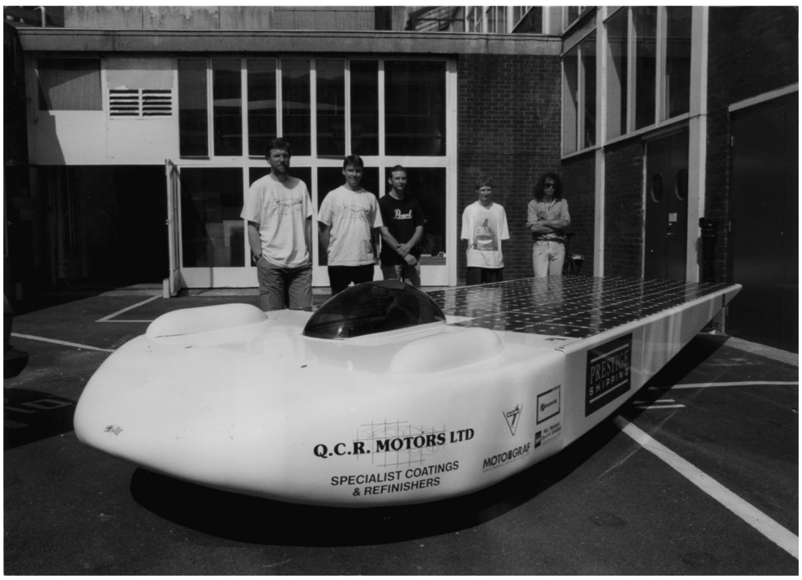

Fig. 1. Mad Dog I.

2.6. Michelin solar tyres instead of bicycle tyres

The new car uses Michelin tyres. The rolling resistance of a bicycle tyre is typically 6 kg/ton (0.006). Michelin's solar racing car tyre is 2 kg/ton (0.002).

3. Performance of Mad Dog 2

The overall performance of the new car can be compared to the old by employing the power equation (Eq. (1)). The two forces that have to be overcome when moving a vehicle are aerodynamic drag and rolling resistance, assuming a level road with no head wind.

$$\mathrm{IP} = \left(mgR_r v + \frac{1}{2} C_d A \rho v^3 \right) \frac{1}{\eta_e} \cdot \frac{1}{\eta_m} \cdot \frac{1}{\eta_T} \tag{1}$$

where IP means input power (W), m is the mass (kg), g is the acceleration due to gravity (m s^{-2}), R_r is the rolling resistance (no units), v is the speed (m s^{-1}), C_d is the drag coefficient (no units), A is the frontal area (m^2), ρ is the density of air (kg m^{-3}), η_e is the electrical efficiency, η_m is the motor efficiency and η_T is the transmission efficiency.

Table 2 shows the relevant variables for the old car, the new car, the Honda Dream solar car and a conventional vehicle.

The above figures show that a theoretical improvement in speed of about 25 km/h can be achieved with the new car compared to the old. As speed increases the main factor to consider is aerodynamic drag. The power required to overcome this increases as a cubic function of speed. A low frontal area and C_d are essential for any low powered vehicle which is intended to cruise at speeds of 60 km/h and above. The Honda Dream could cruise all day at over 90 km/h. To achieve such speeds, the Honda engineers paid great attention to aerodynamics.

These results are given graphically in Fig. 2 which shows plots of the power vs. speed for the three solar cars. The steepest power curve is for Mad Dog I and the shallowest is for Honda Dream. The cruising speed is found from the intersection of the power curve with the array power which is shown as a horizontal line, with Honda Dream the highest and Mad Dog I the lowest.

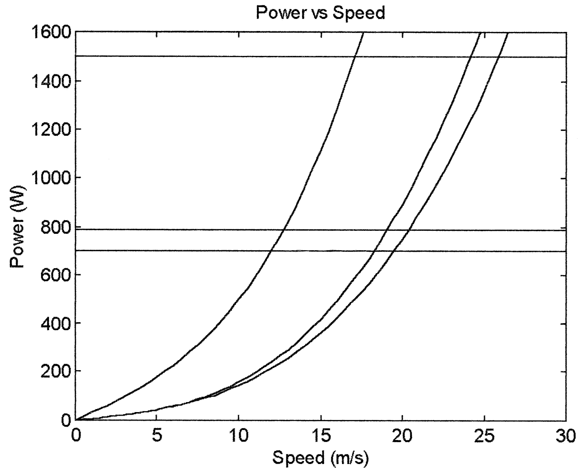

Fig. 2. Theoretical power (W) against speed (m/s) curves for Mad Dog I, Mad Dog II and Honda Dream.

Compared to a combustion engine vehicle, the Honda Dream, while carrying two people, only required 1500 W input power to maintain a speed of 93 km/h. A typical combustion engine vehicle would need about 60 kW input power to achieve the same speed. The energy efficient solar cars show that reasonable performance is possible within the space of a typical passenger road vehicle. It is suggested that electric vehicle designers learn from the experience gained by solar car engineers and to design vehicles which inherently require less power to propel them.

4. Comparisons of battery systems for solar cars

Another major decision in solar car design is the selection of battery type. It is clear that the lighter the battery and the greater its capacity, the greater the advantage one car will have over another. This is why teams with large or seemingly unlimited budgets opt for zinc/silver oxide batteries with their high energy densities. With such cells, the compromise between total battery capacity and increased mass becomes less significant. For this reason, the regulations of solar races restrict the battery capacity to 5 kW h. Teams using zinc/silver oxide and other battery

Table 2
Speed and power for solar and conventional cars

	IP (W)	m (kg)	R_r	ρ (kg/m^3)	C_d	A (m^2)	η_m	η_e	η_T	V (km/h)
Mad Dog 1	700	320	0.006	1.2	0.2	1.0	0.82	0.8	0.94	43
Mad Dog 2	786	260	0.002	1.2	0.16	0.8	0.92	0.9	0.97	68
Honda Dream	1500	327[a]	0.002	1.2	0.12	1.0	0.96	0.98	1.0	93
Normal Car	60000	1200	0.02	1.2	0.35	2.0	0.22	1.0	1.0	93

[a]The Honda Dream is a two-seat vehicle.
Driver mass: 160 kg (80 kg × 2).

Table 3
Battery weight limits and usage in the 1996 World Solar Challenge

Cell type	Limit (kg)	No. of entries
Lead–acid (Pb/acid)	125	25
Silver/zinc (Ag/Zn)	40	13
Nickel/zinc (Ni/Zn)	70	5
Nickel/cadmium (Ni/Cd)	100	2
Lithium-ion (Li-ion)	40	1
Nickel/iron (Ni/Fe)	100	0

Table 5
Battery characteristics

	Weight (kg)	kW h	W h/kg	V
All cars	68	3.27	62.9	101
Lead–acid	81	2.85	35.8	101
Silver/zinc	39	4.5	115	97
Lithium-ion	36	3.09	106.2	101
Nickel/cadmium	57	2.51	44.65	136
Nickel/zinc	41	2.51	60.86	101

types still at the development stage have a clear mass advantage over the teams using lead–acid. Races are subdivided into classes so that teams using comparable technology can be assessed against each other. It is not just the cost of zinc/silver oxide batteries that prohibits their use by most teams. The problems of maintenance and short cycle-life makes their use too demanding for teams with small numbers of personnel.

Total battery size is also restricted by weight, with the limit being set by the type of cell used (see Table 3).

Table 4 lists the top 10 finishers of the 1996 World Solar Challenge, along with details of cell type, number of cells, total battery voltage, battery pack weight, capacity and energy density. The result of the entry from the University of Queensland demonstrates that cars using lead–acid batteries can compete with the big budget teams.

Some of the most important characteristics in battery selection for a solar racing car are listed below.

(a) Weight: increased weight increases rolling resistance and the power required to climb gradients. Entries ranged from a very small 12.5 kg battery up to the maximum limit of a 125 kg battery pack.

(b) Capacity: a large capacity is not necessarily a good idea over a long distance unless there is sufficient solar energy to fully charge the batteries during periods of rest. Teams using zinc/silver oxide used most of the allowable capacity, whereas the average capacity for lead–acid was only 2.85 kW h out of the possible 5 kW h. The reasoning behind these decisions is discussed later.

(c) Energy density: this measurement encapsulates the first two. The higher the energy density, the better for solar racing.

(d) Voltage: the choice of total battery voltage must be made early in the design stage as this must suit the output of the photovoltaic array and the operating voltage of the electric motor and controller. The 120 and 72 V systems are popular but the maximum used in Australia was 240 V.

Table 5 lists the averages of these characteristics for the entire field and then for each battery type.

5. Modelling a solar racing day

A racing day starts as soon as the sun rises and there is sufficient solar power to charge the battery pack. Insolation data was collected during the first five days of the World Solar Challenge 1996. Fig. 3 shows a plot of the insolation as measured at hourly intervals during the race day. Apart from 1 day of variable conditions (day 1), there is a clear trend. The second plot is the average insolation over the five days and this is shown with a second order polynomial fit. Although taken from a limited sample at a particular time of year in Australia, the data shows a clear

Table 4

Team	Cell type	No. of cells	Voltage (V)	Weight (kg)	Capacity (kW h)	Energy density (W h/kg)
(1) Honda	Ag/Zn	72	108	38.52	3.34	84.1
(2) Schooler	Ag/Zn	82	123	39.03	4.92	126.1
(3) Aisin Seikei	Ag/Zn	52	78	39.42	3.9	98.9
(4) Mitsubishi Materials	Ag/Zn	67	100.5	39.87	4.824	121
(5) Univ. Queensland	Pb/acid	60	120	81.5	2.88	35.3
(6) Waseda	Ag/Zn	56	84	39.2	4.2	107.1
(7) NTU	Ag/Zn	33	49.5	38.87	4.95	127.3
(8) Simon	Ni/Zn	204	115.6	70.89	4.162	58.7
(9) UNSW	Pb/acid	58	116	98.6	3.016	31.1
(10) Tokyo Salesian Poly	Li-ion	896	100.8	35.84	3.086	106.2

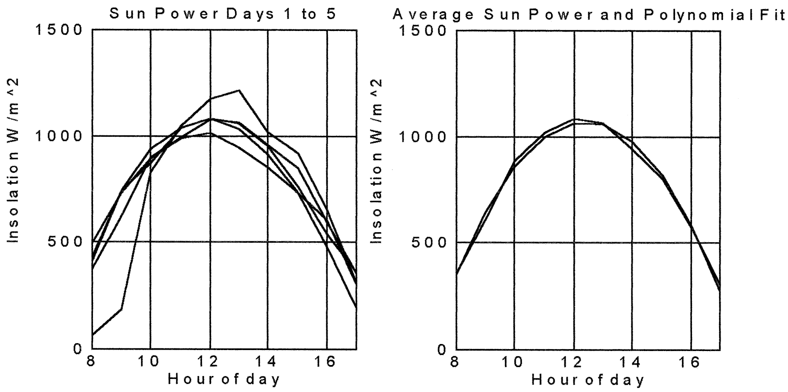

Fig. 3. (a and b) Insolation (W m^{-2}) data from 1996 WSC.

trend that can form the basis for modelling conditions. This curve can be adjusted to suit local conditions.

Before the Akita race, it was believed that the available sun power was only 60% of that recorded in Australia. This was based on hearsay but also backed up by inspecting the results from the 1997 World Solar Rallye in Akita, which indicated low average speeds for teams that had performed well in Australia the previous year. On this basis, it was estimated that the average insolation could be as low as 500 W m^{-2}, which would translate to an array power of 600 W for Mad Dog II. This value can be used in Eq. (1) to calculate a value for a constant speed strategy. This works out to be 12.5 m/s or 45 km/h.

When a constant speed has been selected or calculated, the car's gearing must then be set up to match it to the optimum motor speed. The car had originally been designed for a speed of 70 km/h and if this gearing was used the motor would not be running efficiently at 65% of its design speed. No measured data for the motor was available other than calculations based on quoted motor parameters. These predicted that the motor would be only 85% efficient if the car was driven at 12.5 m/s when the gearing was set up for 19.5 m/s.

Fig. 4 is a simulation block diagram used to test out strategies based on driving and weather conditions. This assumes a constant speed and uses models of sun power, array conversion and car power demand. The simulation starts at 0800 h and uses the time of day to calculate the available solar power using a polynomial similar to that shown in Fig. 3. Another function represents the efficiency and parameters of the solar array and calculates the electrical power input. Against this, the power demand is modelled using Eq. (1) and the sum is used to give the net current from the battery pack. Figs. 5 and 6 below show a typical plot from this simulation.

This has assumed a constant speed of 12.5 m/s with the sun power at 60% of the Australian data. This shows that under these conditions the battery has not been charged up (apart from a period between 1200 and 1400 h) but is being used to supply energy during the early and latter parts of the race when the sun power is low. At the end of this day's racing, a net total of 1 kW h has been used, most

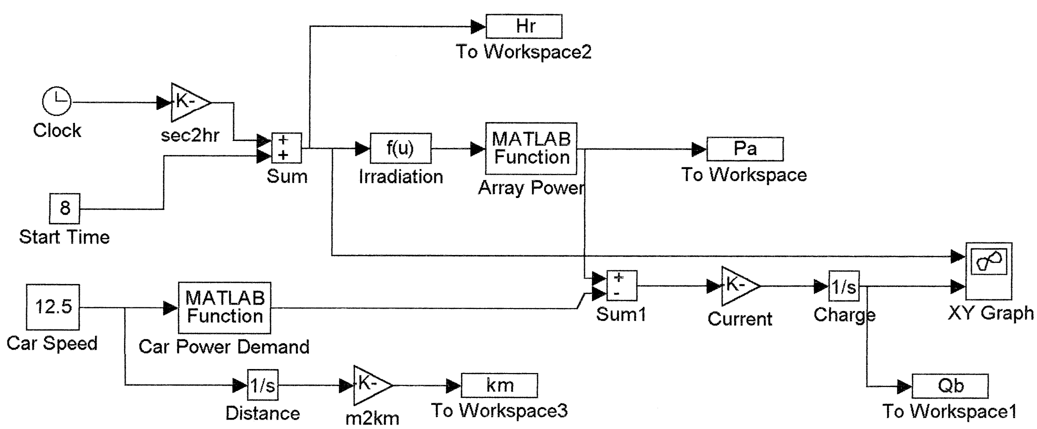

Fig. 4. Simulation for race strategy.

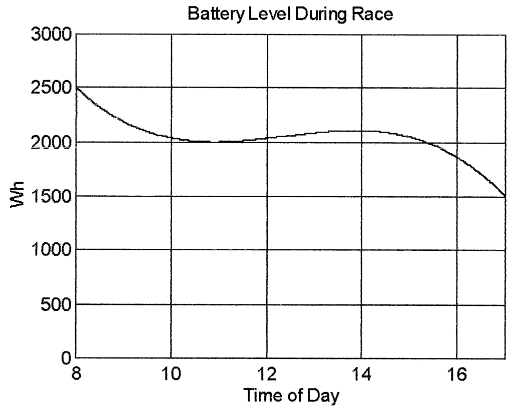

Fig. 5. Race simulation output, state of charge (W h) against time of day.

of which could be regained in the recharging periods in the early evening and next morning.

6. The race in Akita

Mad Dog II (Fig. 7) was finally put through its paces in August 1998 at the World Solar Rallye in Akita, Japan. The race attracts the most entrants of any solar car race and reached a record of 81 cars that year. The vast majority of the solar cars are Japanese, a staggering 76 as opposed to only five from overseas. The race attracts all types of entrants, from large organisations such as Mitsubishi to small clubs of three or four enthusiasts. The USA had its two best teams, MIT and Minnesota University, competing and the Australians had two cars from Northern Territory University (NTU) and Canberra. NTU's car is recognised as one of the fastest solar cars in the world and was hoping to beat the record set by the Honda Dream. South Bank's new car was untested and it was difficult to say how well the predicted performance would compare to the realities of racing. However, a lot had been learned from Mad Dog I, so it was hoped the car would at least be competitive.

To make things fairer for all the entrants, there are various classes for different types of car. The top class is called 'Free', which basically means that there is no limitation on the types of batteries and solar cells that these cars can use. This of course means that cars in this class have better components and should go faster. For example, NTU's car Desert Rose used batteries costing nearly £10,000. The biggest class is 'Stock' which had 37 entries of which Mad Dog II was one, and was also the only foreign entry. To qualify for this class, all the cars have lead–acid batteries and commercially available solar cells.

A team of 10 (three staffs and seven students) set out for Japan in July. The solar car with all the required equipment was delivered to the race track in the same container that it left Felixstowe and thankfully arrived undamaged. There was about 1 week of race preparation for the car, during which numerous faults were found and subsequently remedied. The car was now running very smoothly and the team made the final preparations for inspection and qualification. After some trouble with the brakes the solar car passed a rigorous technical inspection and finished 18th in the qualification speed trial. This is just like a motor racing grand prix, with the grid position being determined by qualification results. The next day, all of the 81 solar cars lined up two by two on the race track with the all teams making final adjustments and getting their drivers ready.

The race track is the longest closed circuit in the world (31 km) and is built on a poulder near a village called Ogata-Mura. The flat land and good quality road surface make it ideal for solar car racing. The race lasts for 3 days (8 h a day) and the winner is the car which can complete the most laps. The record is held by Honda with 45 laps (over 1200 km). It soon became apparent that the weather for the 1998 race would be much worse and that Honda's record would be safe.

6.1. Day 1

When the race started, the sky was blue and all the solar cars sped away. The team had decided to drive conservatively and save battery charge because the weather forecast for the next 2 days was bad. Many cars overtook Mad Dog as it cruised round at 50–60 km/h. The team kept in contact with the driver by mobile phone. The driver relayed information back to the team and the strategist then informed the driver whether to speed up or slow down. As day 1 came to a close and the sunlight started to weaken, Mad Dog overtook many of the cars which had passed it earlier. The final position was 18th overall and 4th in

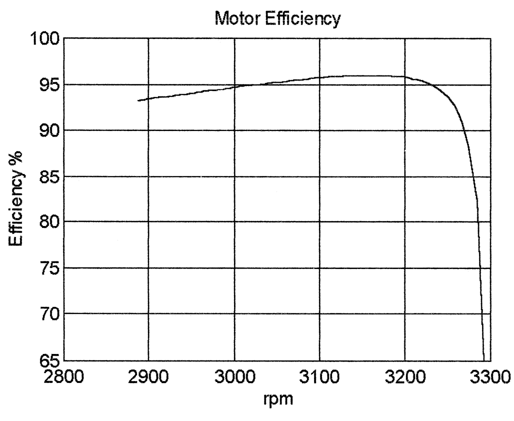

Fig. 6. Motor efficiency (%) curve.

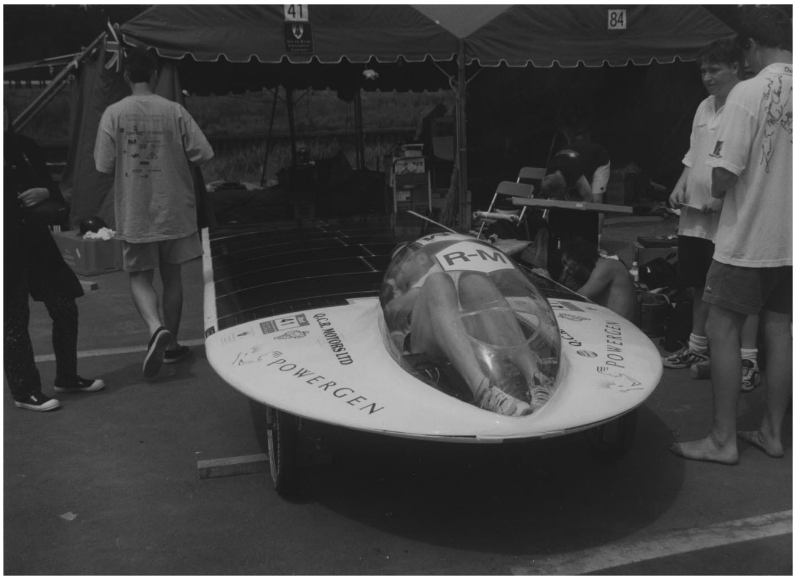

Fig. 7. Mad Dog II.

class. The team were happy to have regained their starting position and more importantly had plenty of energy left in the batteries. That evening was spent re-adjusting the car ready for the next day.

6.2. Day 2

Day 2 was cloudy, leaving Mad Dog in a strong position as it still had plenty of energy in the batteries. In ‘Stock’ class, everyone started the race going much slower than day one except for Mad Dog. As the day progressed, the cars in front were picked off one-by-one. By late afternoon, Kira Kira III, the local favourite and leader was passed, leaving Mad Dog head of its class.

6.3. Day 3

The weather on day 3 was so bad that the race was postponed. A storm had hit North Japan and with the circuit flooded the race was postponed until midday. When the race was eventually started the track was still very wet and all the cars drove very slowly. The South Bank team decided to just do enough to win their class. All the cars behind Mad Dog were monitored to make sure they did not catch up. By mid-afternoon the strategist had calculated that it was impossible for any car in ‘Stock’ class to beat Mad Dog. The decision was made to bring the car into the pits and end the race. If the car had continued racing and broken down on the circuit, the penalty was 60 min and one lap. This would undoubtedly have cost the team its class win and was not considered worth the risk.

When the race officially ended, South Bank was pronounced winners of ‘Stock’ class, beating 36 other cars, and received a gold plaque at the award ceremony. Overall, the team finished 15th.

7. Conclusions and further developments

Although great fun, solar car racing has serious implications for the development of electric vehicles. It raises interesting research topics, is of great educational value for students and helps to raise the profile of energy issues in the public domain. Improvements in solar racing cars rely on improvements in solar cell technology, motor efficiency, lightweight construction techniques, battery efficiency and weight.

It is believed that Mad Dog II could have achieved even more if time had been available to test the car thoroughly and learn the characteristics of the electric system. More knowledge is required to understand how best to charge and discharge the batteries efficiently. A cautious approach was adopted in the latter stages of the race because the car had never been driven with the batteries taken very low. This is an area where the team require assistance due to the problems associated with testing vehicles in the inner city.

Mad Dog 3 has been designed and construction will have started in January 1999 in preparation for that year’s World Solar Challenge. This car will have improved suspension design, employ simpler construction techniques, increased driver comfort and feature more instrumentation to improve strategy management and collection of data for evaluation of performance. Lead–acid batteries have proved very robust and reliable. It is envisaged that they will be used again.

Acknowledgements

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