MODEL SOLAR CAR

MATHEMATICAL SIMULATION

EXCEL VERSION 1.5 *Dec 2006*
TEXT REVISED *April 2017*

MODEL SOLAR CAR SIMULATOR INSTRUCTIONS

This mathematical model of a Model Solar Car is intended to be used by students as an aid to designing model solar cars. It allows students to vary characteristics of a proposed car and see what probable effect this has on the performance.
NOTE: The accuracy achieved depends on many things but particularly important is the accuracy of the coefficients used for air drag and rolling resistance (which need to be determined by the students experimentally) and the power output versus RPM data for the proposed motor. A power curve obtained from Dynamometer testing using a solar panel or a power supply with similar characteristics to a solar panel is essential for accuracy. Use of a battery or power supply without similar voltage & current characteristics to a solar panel will yield inaccurate results.

The model uses only basic mathematics and Newtonian Mechanics so students should be able to understand and modify it to suit their individual requirements. It is laid out on a standard EXCEL spreadsheet.

Remember this is only a simple model of a very complex system, only the main forces have been considered and simplifying assumptions have been made to keep the programme manageable. However it has given better than 95% correlation to the performance of the 3 cars we have tested. The results should prove to be very useful particularly when the simulation is used to determine what effect a change is likely to have, say car weight, streamlining, motor (type, power output or torque / RPM characteristics), gear ratio, or sun level changes.

ACCURATE INPUT DATA IS CRITICAL FOR OUTPUT ACCURACY!

SECTION 1

DEVELOPMENT OF THE MATHEMATICAL MODEL

Consider the main forces acting on the car, see sketch below.

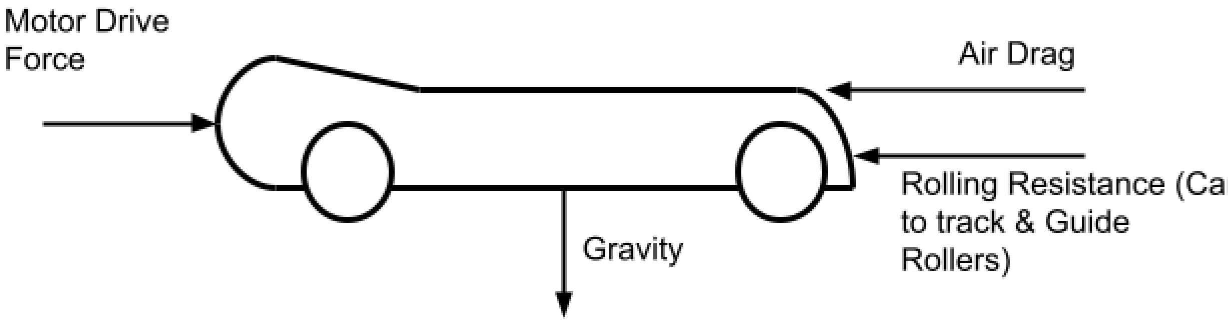


FIG 1

1 GRAVITY

Gravity acts vertically down, the gravity force in Newtons is determined by multiplying the Mass (M) of the object in Kilograms by the gravity constant 9.81 m/s/s. However when the car is on a slope a component of the gravity force will be acting down the slope. The magnitude of the gravity force component acting down the slope depends on the angle of the slope. This gravity component will provide a force accelerating the car down the slope. When the car is travelling down the slope this force will tend to speed it up, conversely if the car is going up the slope this force will tend to slow it down and may even stop the car if the car does not have sufficient speed or drive force to overcome this gravity component.

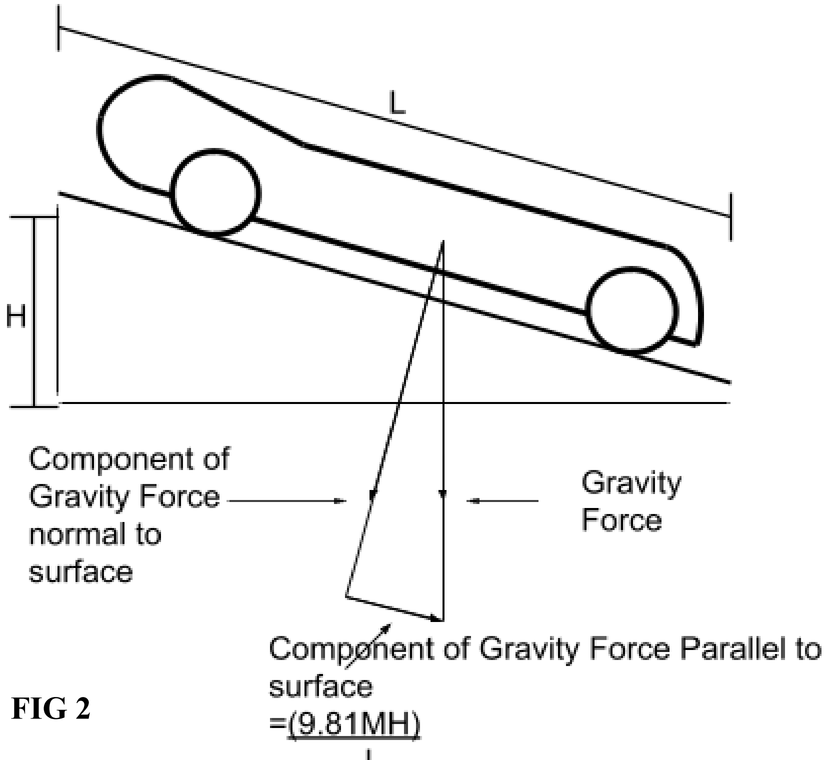


FIG 2

2 AIR DRAG

Air drag is due to the passage of air over the car, it can be due to the car moving through the air or air passing over the car such as a prevailing wind. This force acts parallel to the air flow and in the same direction as the air flow.

In this simulation we have ignored any prevailing wind, as the wind velocity is low close to the ground due to the drag effect of the ground surface and the many objects normally close to the ground which tend to block the wind eg. buildings, fences, trees, shrubs, etc. As the track is a figure 8 layout, any wind would be a tail wind for about the same time as it was a head wind and so the effects tend to cancel out.

For a complete explanation of air drag refer to standard fluid dynamics texts, but simply put:

$$\text{Air drag} = \tfrac{1}{2} \times \text{Air density} \times \text{Drag coefficient} \times \text{Frontal Area} \times \text{Velocity}^2.$$

Drag coefficient depends on the shape of the car, an aerofoil shape will have a drag coefficient many times lower than a flat plate. Wind tunnel testing is normally used to determine drag coefficients. For large items such as aircraft accurate scale models are normally used for wind tunnel testing.
Model solar cars are small enough to allow testing of the actual car, the coefficient we are using in our simulation is based on this assumption.

Consider the elements of the air drag formula:

Air density changes with temperature and pressure. As we are operating at sea level we will ignore the small changes that take place and treat density as a constant.
Frontal area is the projected area facing the air flow, since we are testing the actual car this is also constant
Drag coefficient is dependant on the shape of the car. Again as we are testing the actual car this remains constant.
Velocity is the only element that changes

Since we are testing our actual car, with air density, drag coefficient and frontal area all constant for simplicity we will combine them together into one constant which is called **Air Drag Coefficient** in the simulation.

So $$\text{Air Drag (Newtons)} = \text{Air Drag coefficient} \times \text{Velocity}^2 (\text{m/s}).$$

Therefore to obtain the air drag coefficient for a car perform wind tunnel tests on that car at a known air velocity and measure the drag force, transpose the above equation and use it to calculate the air drag coefficient to be used in the simulator for the car tested.

NOTE: You MUST do wind tunnel testing of your car to determine its air drag coefficient. (Values in the order of 0.03 for a flat plate of 200 cm square area to 0.003 for a low drag aerofoil shape of 200 cm square area would be typical.)

If you cannot perform wind tunnel testing you can make an estimation of air drag coefficient by taking the 0.03 drag coefficient for a flat plate of 200 cm square area and calculate the air drag coefficient for your car with a simple ratio calculation based on your cars frontal area compared to the 200 cm square.
This will give a worst case drag figure as it is based on a flat plate.

3 MOTOR DRIVE FORCE

As our motor performance data will be from Dynamometer tests, we will have torque and RPM data available.
See 5 DETERMINATION OF MOTOR TORQUE

Drive force is calculated from the motor torque as follows.

Motor torque × Gear ratio × Transmission efficiency = Wheel torque,

where:

Motor torque is the torque on the motor shaft.

Gear ratio is the ratio of motor RPM to wheel RPM. It is normally a reduction ratio (must be a reduction in this simulator) but does not have to be gears, it can be belts or any other form of reduction device. Note this simulation allows for a one shot gear change from an acceleration gear to a running gear.

Transmission efficiency allows for the losses in the reduction device. For a single step gear reduction 95% (0.95) would be about right. Testing will be required to determine the efficiency of your particular drive system.

Knowing the torque on the wheel and the wheel diameter you calculate the force on the wheel required to produce this torque.

Wheel drive force = Wheel torque ÷ Wheel radius

The motor torque measured in our dynamometer testing was in mNm so the wheel force in Newtons will become:

$$\text{Wheel drive force} = \frac{\text{Wheel Torque (mNm)} \times 2}{\text{Wheel Dia. (mm)}}$$

$$= \frac{\text{Motor torque (mNm)} \times \text{Gear ratio} \times \text{Efficiency} \times 2}{\text{Wheel Dia. (mm)}}$$

NOTE: The maximum force the wheel can transmit to the track before wheel spin occurs is limited by friction. When using an electronics system it is possible to have wheel spin for a short time during take off from the start line. Obviously when wheel spin is occurring the drive force accelerating the car is lower than calculated above.
The addition of WHEEL SLIP COEFFICIENT in the simulation takes care of this. You must measure the force required to cause wheel slip, use this force to calculate the wheel slip coefficient. Within the excel programme the Wheel Slip Coefficient is used to calculate the force required to cause wheel slip this is compared to the wheel drive force and the lower value used to calculate the cars acceleration.

4 WHEEL SLIP COEFFICIENT:

This was added to the simulator when it was observed that the 2232 Faulhaber Motor coupled to an Electronics unit could produce sufficient torque to spin an aluminium wheel on take off.
All we have done is written some logic that limits the drive force on the wheel to the slip value.
However you must determine the slip value for your particular car. This is easy just lock the drive wheel and measure the force required to drag the car along, this is the wheel slip force. (In Newtons)
To obtain the wheel slip coefficient use the following formula

Wheel Slip Force (N) = Wheel Slip Coefficient x Car Mass (kg)

NOTE: It will be different for a wheel with a tyre compared to a wheel without a tyre.
CAUTION: If you change the weight on the drive wheel the slip force will change.
To maintain the best accuracy if significant weight changes are made to the car retest it, if only minor changes are made and the C of G is not changed it will be all right.

5 DETERMINATION OF MOTOR TORQUE

The motor torque is determined by testing, see Dynamometer Testing. For a car using an electronic system testing is critical as the current multiplication the electronics provides greatly increases the available torque at lower RPM. Because of the difficulty in determining the formula to a curve, the curved graph of Torque vs RPM is arbitrarily broken down into 3 straight line sections. Coordinates defining these sections are entered in the simulator and the approximate Torque at the motor RPM we are considering is obtained by interpolation. See FIG 3.
(For a motor operating without an electronics system it is possible to calculate the torque RPM curve, you may wish to research this avenue.)
Refer to the typical straight line split up of a graph of torque vs RPM shown below.

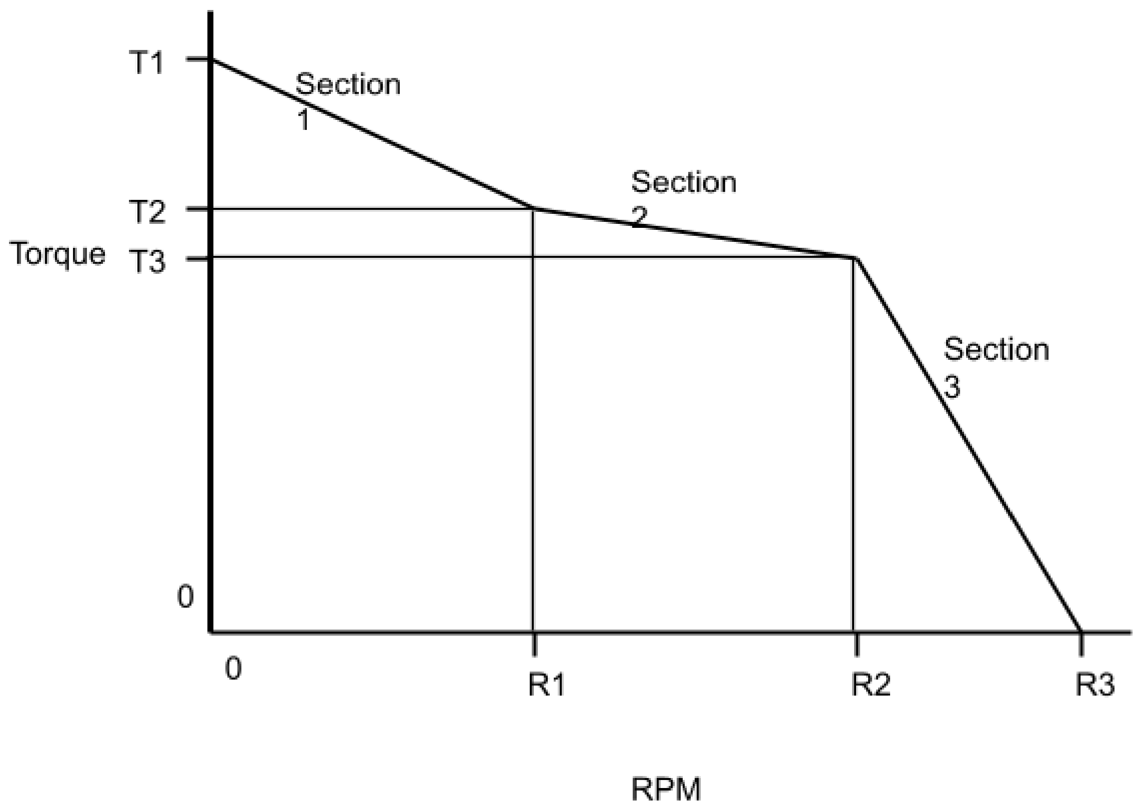


FIG 3

For section 1 of the graph the formula for calculating torque at a given RPM is

Torque = T1- (T1-T2 ÷ R1-0) × RPM

For section 2

Torque = T2-(T2-T3 ÷ R2-R1) × RPM

For section 3

Torque = T3-(T3-0 ÷ R3-R2) × RPM

These formulas are the equation to the straight line sections of the graph. In conjunction with logic statements to select which formula is to be used based on motor RPM they are used in EXCEL to calculate the torque at any given RPM.

(To enable realistic evaluation of this simulation some motor test data is included later in this section but also see Appendix J for more motor test results.)

If you have a power curve for your motor (graph of power vs RPM) it will be necessary to construct a torque vs RPM graph to allow you to input the data to the simulator. Torque can be calculated by transposing the formula

$$P = 2 \times \pi \times N \times T$$

N= Revs / Second
T= Torque Nm
P= power watts

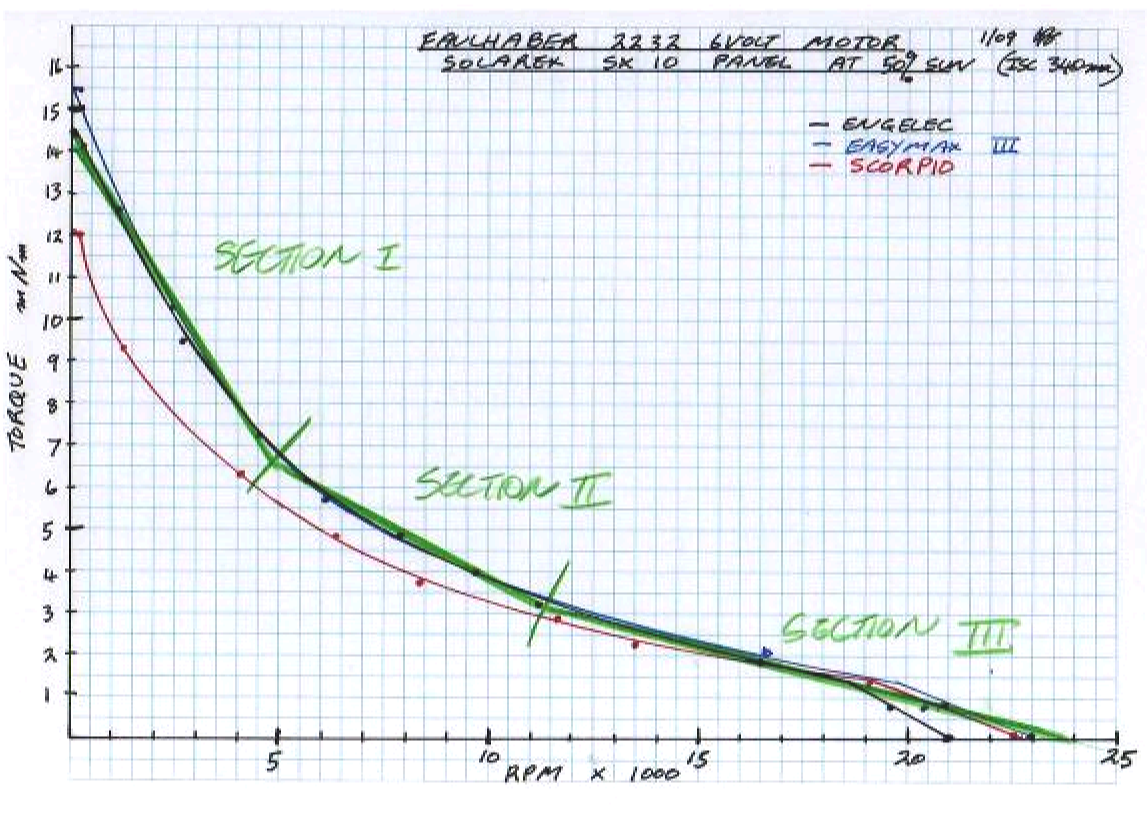
Into $$T = \frac{P}{2 \times \pi \times N}$$

Remember testing the motors at different sun levels is required as this is the only method provided for inputting different sun levels into this mathematical model.

HINT TO IMPROVE ACCURACY:
Using 3 straight line sections derived from a curved graph to input the data to the EXCEL model leads to inaccuracies. If you have good curve fitting software you could obtain the formula to the curve and input this formula into the EXCEL model. This would give virtually perfect results.

However sticking with the current 3 section method a significant improvement in accuracy can be easily obtained by extrapolating the graph section 2 to cross the axis thus effectively eliminating section 3. This allows an additional section to be inserted in the middle portion of the graph.

See the marked up copy of a real dynamometer test below showing how it is done. The important thing you MUST remember is that you cannot in fact operate in the extended area as it is imaginary. The chances of this are very remote.



Graph of torque vs RPM with modified third section to improve accuracy.
The new sections are shown in green. The imaginary section you must not allow car operation in is from 20000 RPM upwards.

5 ROLLING RESISTANCE

Rolling resistance in the case of our model solar car comes from 2 sources. One is the wheels the other is the guide rollers. It has been assumed that rollers of some sort are used for guiding as using a guiding system without rollers would have significantly higher friction due to rubbing on the guide rail.

Firstly consider the rolling resistance due to the wheels on the track. This is made up of two components, friction in the bearings, and the resistance to the wheels rolling on the track surface. The component due to the wheels is the most significant; it increases significantly for wheels with tyres or wheels that are running on a soft surface. The reason is that tyres when loaded will have a flat spot on the bottom causing an effect similar to running up a slight hill, while a soft track will effectively allow the wheel to sink into a hole making this up hill effect even greater – imagine this as riding a bicycle on sand. Both these effects mean your wheel is constantly trying to climb a small hill.

Additional weight on the wheel will increase the resistance due to this effect.
For the low loads we are working with the bearing friction is not expected to alter significantly with weight change so we expect the total resistance to be a small constant due to bearing friction plus the additional wheel to track resistance which varies with wheel load.

The coefficient for the simulator is obtained from testing of your car.
Testing is simple place the car on a flat level surface and measure how much force is required to just start it rolling. Repeat this test at different car weights (ie. Add weights to the car.) take care to place the weights over the cars centre of gravity to maintain the wheel and bearing loads in the same ratio. (motor disconnected from drive wheel we wish to measure rolling resistance due to wheels and bearings only)
Graph the results of your test, car weight on the X axis and force to roll on the Y axis.
The slope of this graph in Newton per kg is the Roll CoEf: in the simulator.
(NOTE: depending on tyres and bearings the graph may not pass through the zero point but cross the Y axis up from zero this is not common but the **Wheel Roll RS: in the simulator is this crossing value.**)

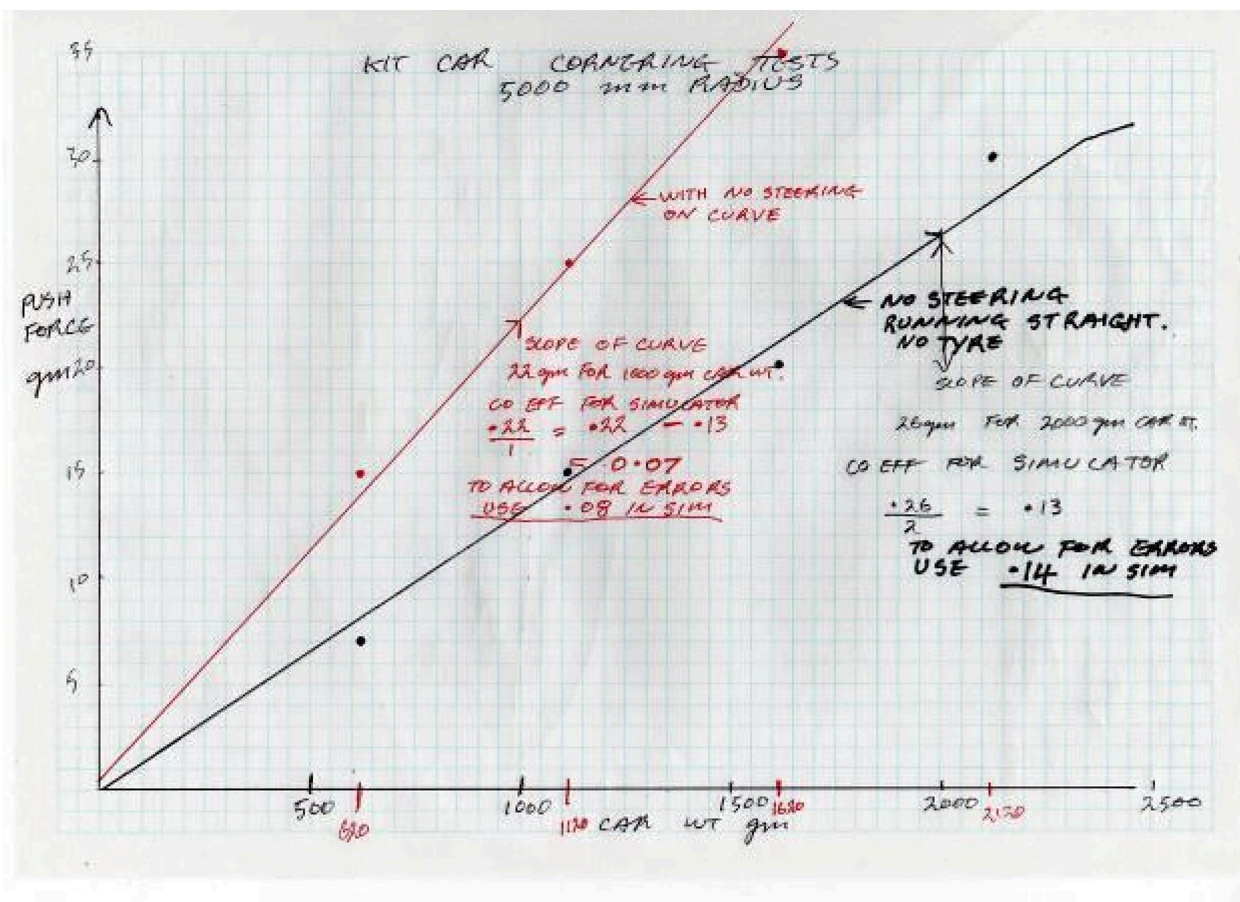
The Steering Drag , the additional drag which occurs when a car without steering is cornering (there is some side slip of wheels happening which increases the drag) is determined in the same way as the rolling resistance above except that the car is pushed around a corner of 5000 mm radius for the test.
Again graph the results on the same set of axes as the rolling resistance. **The difference between the slope of the graph for straight rolling resistance and the resistance around the curve is the Steering Drag: in the simulator again it is in Newton per kg.**

As a guide the results from testing the Sheridan Kit Car and associated graphs are shown below.

SHERIDAN KIT CAR ROLLING TEST RESULTS

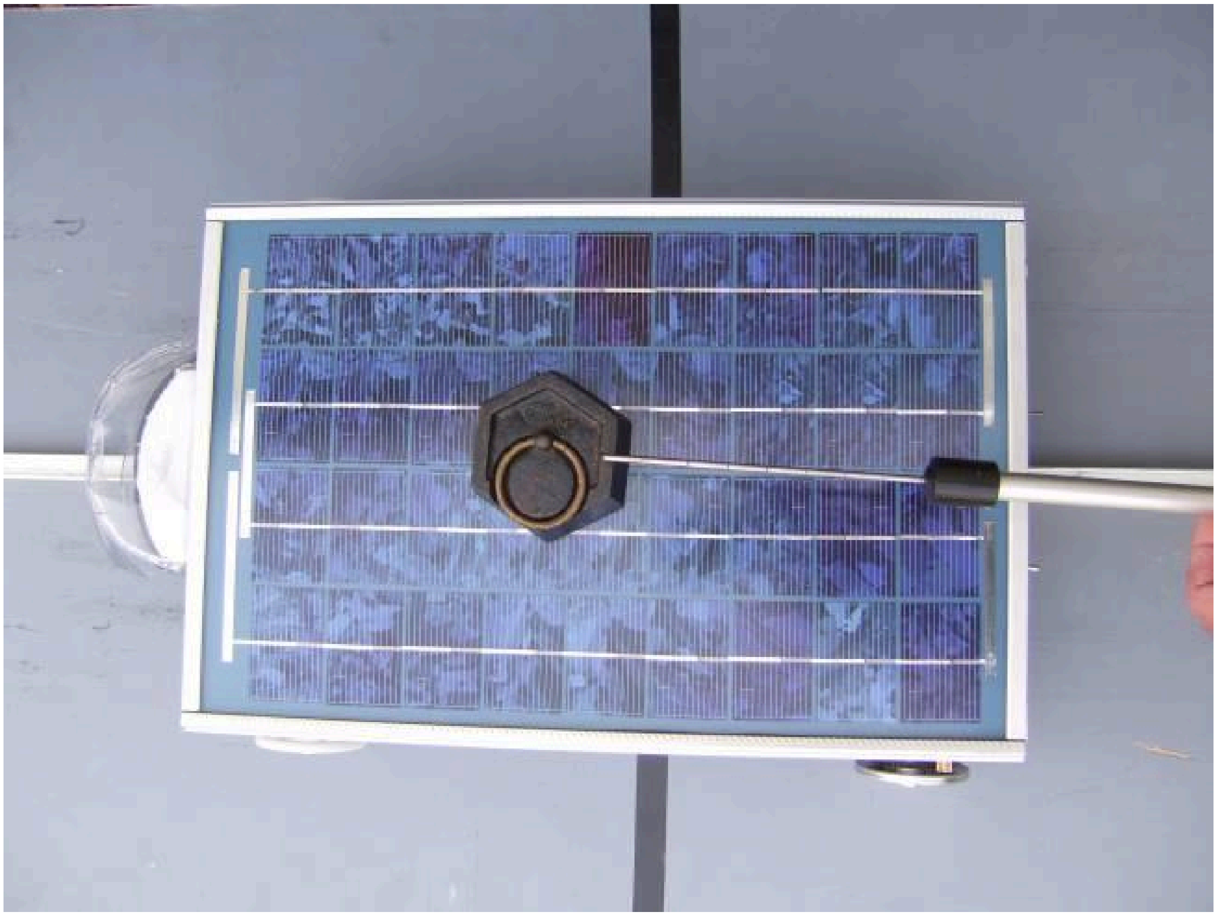
CAR WEIGHT gm.	FORCE TO ROLL gm. ON STRAIGHT	FORCE TO ROLL gm. AROUND CORNER
620	7	15
1120	15	25
1620	20	35
2120	30	40

GRAPHS OF THESE RESULTS ARE SHOWN IN GRAPH 2 BELOW.



GRAPH 2

To further assist understanding the photograph below shows testing set up on the car Photon Cruncher MK IV.



PHOTON CRUNCHER MK IV BEING PUSHED ON STRAIGHT TRACK SECTION NOTE ADDITIONAL WEIGHT ON SOLAR PANEL.

Determining the force to roll can be done with a spring balance, but take care that the balance you use maintains accuracy when horizontal. Otherwise a cord around a pulley to keep the spring balance vertical will be required. An option is tilting the surface the car is on, measuring the height it is lifted to just roll and calculating the force acting down the ramp due to gravity.

You should note that for this model we have assumed the wheel load to be constant as the car runs around the track. This is not exactly true. The wheel load is determined by the component of the gravity force which is normal to the track surface. This changes depending on position on the track – when the car is on a slope it is reduced slightly (see FIG 2). Since the hills are short compared to the track length and the slope fairly gentle we did not go to the trouble of including this change in the model.
There is also weight transfer to the outside wheels when cornering this too has been ignored.

The second portion of rolling resistance is due to the guide rollers on the guide rail. This force is acting mainly when the car is cornering, a well made car when running straight will have almost no contact with the guide rail.

Consequently we have considered this force to act only while the car is cornering.
The sideways force on the guide rollers can be quite high, we will assume the guide rollers take all the centrifugal force of cornering and none is taken by the wheels, (probably a reasonable assumption as the aluminium and plastic wheels have low friction on the track).

Centrifugal force (N) = Mass (kg) × angular velocity^2 (Radians) × Radius (m)

The force calculated above is the force acting on the guide rollers the force that is trying to slow the car down is due to the guide rollers rolling on the guide, just the same as wheels on the track. Except the force on the rollers is not just due to the cars weight the angular velocity around the corner together with the cars mass creates it .
Just as for the car on the track we will find the rolling coefficient of the guides on the guide rail and use it to calculate the retarding force.

Retarding Force = Coefficient × Mass × angular velocity^2 × Radius

Angular velocity is calculated from the velocity of the car and the radius of the curve.

$$\text{Angular velocity} = \frac{\text{Car velocity (m/s)}}{\text{Radius (m)}}$$

Substituting this angular velocity back into the previous formula the rolling resistance force due to the guide rollers on the guide rail becomes,

$$\text{Retarding Force (N)} = \frac{\text{Coefficient} \times \text{Mass (kg)} \times \text{Car Velocity}^2\text{ (m/s)}}{\text{Radius of curve (m)}}$$

This coefficient is determined in the same way as the rolling resistance of the car on the track except it is for the guide rollers not the wheels. Consequently the test needs to be somewhat different. The test is conducted with the car hanging on its guide rollers on a nearly vertical section of track, this removes most of the effect of wheels on the track and the small wheel to track force is ignored.
Again graph the force to roll against weight, the slope of this graph is the Guide Roll CoEf: in the simulator. (it is a dimensionless quantity in the simulator)

PHOTON CRUNCHER MK IV IN POSITION FOR GUIDE ROLLER COEFFICIENT TESTING.

The Total Rolling Resistance is obtained by adding the resistance for the car on the track, the steering and the guide rollers together.

SECTION 2

CALCULATING THE CAR'S PERFORMANCE

Having defined the main forces acting on the car, the performance can be calculated. By vector addition of the forces trying to drive the car forward and hold it back we obtain the resultant force acting in the direction of motion. This may be a positive force accelerating the car or a negative force decelerating the car.

This force is used in conjunction with the Newtonian Mechanics formulas to calculate the cars acceleration, velocity and distance travelled after a specified time. Remember the force acting varies with car velocity and position on the track, while the formulas used here assume the force is constant over the time interval chosen. Consequently our calculated results will be inaccurate, as the forces acting on the car are constantly changing, but for a short time interval the changes will be very slight. The inaccuracy will increase the longer the time interval used. We have chosen a short time interval of 0.05 seconds so reasonable accuracy is achieved.

At the end of each time interval the forces acting on the car are re-evaluated and used to calculate the performance for the next time interval. This iterative process is continued until the car has travelled the track length.

THE CALCULATIONS

The following method is used to calculate the car's performance.

1 DETERMINE THE RESULTANT FORCE ACTING ON THE CAR

Resultant force = Gravity + Air drag + Motor drive force + Rolling resistance
(the gravity force is the component acting up or down the hill see FIG 2)

NOTE: Standard Newtonian mechanics formulas are now used to calculate accelerations, velocities and distances travelled. Refer to standard texts for derivations and full explanations of their use.

2 CALCULATE THE ACCELERATION OF THE CAR

From Force (Newtons) = Mass (kg) × Acceleration (m/s²)
Transforming this we get

Acceleration = Force / Mass

3 CALCULATE THE DISTANCE TRAVELLED
(This is the distance travelled in the time interval.)

We now substitute the acceleration calculated into the formula for distance travelled.

Distance travelled = Initial velocity × Time + 0.5 × Acceleration × Time^2

4 CALCULATE THE FINAL VELOCITY OF THE CAR

(This is the velocity at the end of the time interval.)

Final velocity squared = Initial velocity squared + 2 × Acceleration × Distance travelled

5 CALCULATE MOTOR RPM

(RPM at the end of the time interval)

Using the final velocity obtained from above the motor RPM is calculated

$$\text{RPM} = \frac{\text{Velocity (m/s)} \times 60000 \times \text{Gear ratio}}{\pi \times \text{Wheel Diameter (mm)}}$$

6 CALCULATE MOTOR DRIVE FORCE

Using the motor RPM from above and the Torque vs RPM graph for the motor at the sun level being considered, determine the motor torque as detailed previously.
Use this torque to calculate motor drive force as detailed previously. NOTE: the drive force is limited to the value determined in wheel slip testing by comparing the wheel slip force to the motor drive force and using the lower value.

7 CALCULATE AIR DRAG

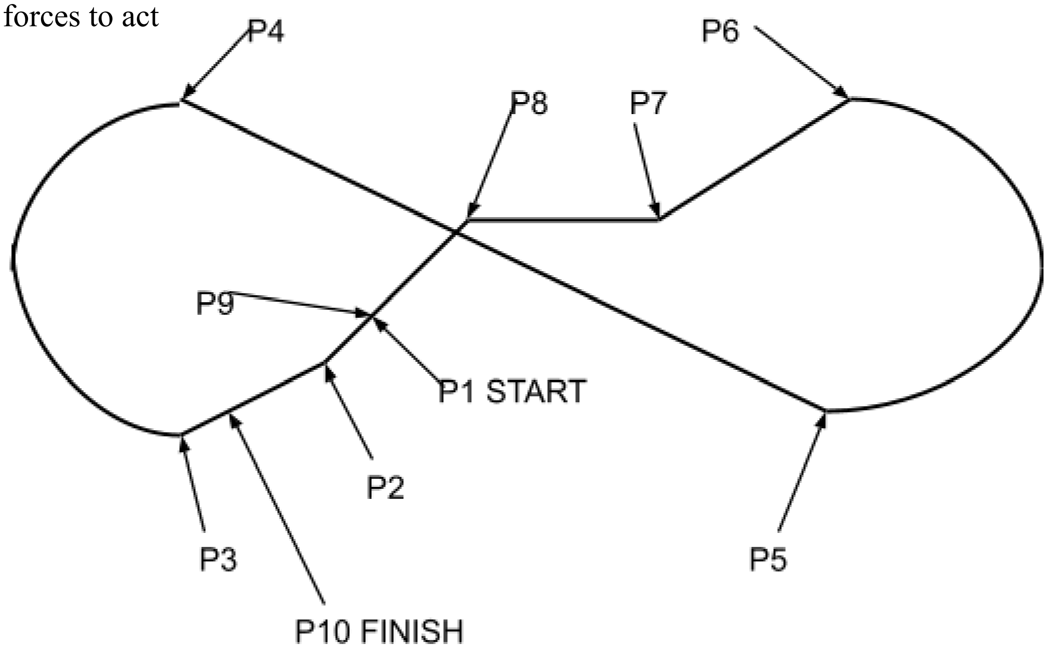
Use the final velocity to calculate the air drag as detailed previously.

8 REPEAT CALCULATIONS

Using the data calculated above, update the all the forces acting and re-evaluate the resultant force acting on the car. Repeat the calculations for the next specified time interval. Continue this cycle until the car has completed the course. By keeping a running total of time and distance travelled we know exactly where we are on the track at any time. Since the track is defined, logic statements based on distance are used to modify the gravity forces as we go up and down the hills and add the rolling resistances due to the corners. This process of calculating the conditions and position at the end of each short time interval is continued until the total distance travelled = track distance. The race is then over and the total of the time intervals is the time taken to complete the race.

TRACK LAYOUT

Below is a sketch of the track showing the distances over which we have allowed the variable forces to act



Position on track		Cumulative distance from start (Meter) LAP 1	LAP 2
P1	Start	0.0	
P2	Bottom of start ramp	6.7	
P3	Start of first corner	14.0	100.42
P4	Finish of first corner	3 7.0	123.42
P5	Start of second corner	49.0	135.42
P6	Finish of second corner	72.0	158.42
P7	Base of hill	76.72	163.14
P8	Top of hill	84.92	171.34
P9	Start position distance after I lap	86.42	172.84
P2	Bottom of start ramp	92.12	178.54
P10	Finish line	100.03	186.45

FIG 4

NOTE: From version 1.2 onwards modifications are included to make the slope on the hill reflect the track as it is now after the 2005 upgrade. For simplicity the hill has been assumed to be formed by two straight sections meeting at the crest where in fact there is radius (of approximately 3.625 Metre) over the top section. The height of the hill is 445mm and it is 8500mm long on both sides of the crest.

SECTION 3

CONVERTING THE MODEL INTO EXCEL

A standard Excel spreadsheet was created to perform the above calculations. Refer to the spreadsheet: we will now detail each column of calculations.
The formulas and calculations used in the spreadsheet are all detailed in the previous section. They have been transcribed into the format required by Excel and had the appropriate logic statements added to ensure the correct data is used in calculations.
The detailed formulas for each column can be viewed on the spreadsheet if desired.

Column A: A running total of elapsed time in 0.05 second intervals

```
=IF($B20>=100,A20,A20+0.05)
```

Column B: A running total of distance travelled in Meters

```
=IF(B20>100,B20,$B20+$C20*0.05+0.5*0.0025*$K20)
```

Column C: Velocity of car Meters / second

```
=SQRT($C20*$C20+2*$K20*($B21-$B20))
```

Column D: Motor RPM

```
=$C21/(3.1416*$B$10)*IF($L21>=1,$B$12,$B$11)*60000
```

Column E: Motor drive force Newtons. This section allows for 2 different gear ratios to be used – one lower ratio for initial acceleration then a change to a higher ratio at a nominated motor RPM. The logic statements in the Excel formula and the register column L allow this change to occur only once on initial rising motor RPM.
There is also a logic statement that limits the motor drive force to the value of the wheel slip force. (this added in Dec 06 see column M)

```
=$I21*2/$B$10*IF($L21>=1,$B$12,$B$11)*($B$13/100)
```

Column F: Air drag force Newtons

```
=B$9*$C21*$C21
```

Column G : Rolling resistance Newtons. This is the sum of car to track and guide roller resistance. It varies according to position on track ie. Guide roller resistance only operates during cornering. The effect of having steering active or not is included in this by adding the additional drag force which occurs during cornering when a steering system is not active.

```
=IF(OR(AND(B19>14,B19<37),AND(B19>49,B19<72)),$B$6*($B$7*C19*C19)/5+$B$8+$D$8*$B$7+IF($D$9="Yes",0,$D$10*$B$7),$B$8+$D$8*$B$7)
```

or the a two lap race a second sheet has been added, with logic statements to apply cornering resistance for the second lap at the appropriate distances, which is very similar to that shown above.

```
=IF(OR(AND(B2>100.42,B2<123.42),AND(B2>135.42,B2<158.42)),Sheet1!$B$6*(Sheet1!$B$7*C2*C2)/5+Sheet1!$B$8+Sheet1!$D$8*Sheet1!$B$7+IF(Sheet1!$D$9="Yes",0,Sheet1!$D$10*Sheet1!$B$7),Sheet1!$B$8+Sheet1!$D$8*Sheet1!$B$7)
```

Column H: Gravity force Newtons. This also varies according to position on track. It is positive while going down hill and negative when going up hill.

```
=IF(B20<6.7,0.445/8.5*B$7*9.81,IF(AND(B20>=6.7,B20<=76.72),0,IF(AND(B20>76.2,B20<84.92),0.445/8.5*B$7*-9.81,IF(AND(B20>=84.92,B20<=84.92),0,IF(AND(B20>84.92,B20<92.12),0.445/8.5*B$7*9.81,IF(B20>=92.12,0))))))
```

Similar to the rolling resistance formula this has been slightly modified for the second lap calculations and is shown below.

```
=IF(AND(B2>=92.12,B2<=163.14),0,IF(AND(B2>163.14,B2<171.34),0.445/8.5*Sheet1!B$7*-9.81,IF(AND(B2>=171.34,B2<=178.54),0.445/8.5*Sheet1!B$7*9.81,IF(B2>=178.54,0))))
```

Column I : Motor torque milli Newton meters. This is calculated from the data entered detailing the torque vs RPM graph (see previous section).

```
=IF($D21<=$B$15,$C$15-$D$15*$D21,IF($D21<=$B$16,$C$16-$D$16*($D21-$B$15),IF($D21<=$B$17,$C$17-$D$17*($D21-$B$16),IF($D21>=$B$17+1,0))))
```

Column J : Acceleration force Newtons. This is the resultant force acting on the car (the vector addition of the forces acting in the direction of motion). It will cause acceleration if positive or deceleration if negative.

= $M20+$H20-$F20-$G20

Column K: Acceleration in m/s/s this is the acceleration caused by the force above.

=$J20/$B$7

Column L : A shift register created to allow the logic statements to control only one change of gear ratio.

=IF($D20>=$D$11,1+L20,0+L20)

Column M: Wheel slip drive force, this is the force at which the drive wheel slips on the track we compare the motor drive force to this force and use the lower value in determining the acceleration force in column J.

=IF(E20>=($D$6*$B$7),($D$6*$B$7),(E20)

SECTION 4

USING THE MODEL

The model is simple to use. Just enter your car's characteristics in the Parameters section. The results will be displayed in the Results area. For details of the car's performance as the race progresses just scroll down the spreadsheet.

If you wish to use only one gear ratio set this ratio into both acceleration and run ratio areas.

When entering data to the motor torque and RPM section fill in all areas i.e. if you have a graph with only 2 straight line sections, divide one straight line section into 2 sections so you have data to enter into each area of the motor torque-RPM section.

You can customise the spread sheet to suit your own requirements. Full details of the calculations are detailed above which should allow you to perform modifications.

Below is a copy of the input output section of the simulator so you can see the layout, the data here is for a real car (PHOTON CRUNCHER MK IV) constructed from commercially available components.
Faulhaber motor, R&I Instrument and Gear Co. Gears, wheels ,guides, bearings and retaining components, Solarex SX10 Solar Panel and Engelec Electronics.
Full details of this car are published earlier in this document.

Model Solar Car Simulator

Parameters						Results	
Car Name:	PC IV MODIFIED FOR WHEEL SLIP					**1 LAP RACE**	
Sun Power:	88% Sun Solarex SX 10					**Time:**	19.5
Motor Type:	Faulhaber 2232 6Volt Engelec Electronics					**Velocity:**	6.897
Guide Roll CoEf:		0.015	**Wheel Slip Coeff**		0.9	**Mtr RPM:**	14694
Mass(kg):		2.1				**Air Drag**	0.333
Wheel Roll RS:		0	**Roll CoEf:**		0.097	**Rolling R:**	0.2037
Air Drag Coefficient:		0.007	**Steering(Yes/No):**		NO	**Mtr Torque:**	4.008
Wheel Diameter(mm):		64	**Steering Drag(N):**		0.13		
Acceleration Gear Ratio:		7.14	**Change RPM:**		0	**2 LAP RACE**	
Final Gear Ratio:		7.14				**Time:**	31.9
Transmission Effy:		92				**Velocity:**	7.373
Motor Tourque:	**Finish RPM:**		**Start T(mNm):**		**Formula**	**Mtr RPM:**	15710
Section 1:		5600		17.8	0.001429	**Air Drag**	0.381
Section 2:		10300		9.8	0.00083	**Rolling R:**	0.2037
Section 3:		24000		5.9	0.000431	**Mtr Torque:**	3.570

ABOVE IS SIMULATOR INPUT OUTPUT PANEL FOR PHOTON CRUNCHER MK IV USING AN ALUMINIUM DRIVE WHEEL, NO TYRE.

Model Solar Car Simulator

Parameters				Results	
Car Name:	PC IV MODIFIED FOR WHEEL SLIP			1 LAP RACE	
Sun Power:	88% Sun Solarex SX 10			Time:	19.1
Motor Type:	Faulhaber 2232 6Volt Engelec Electronics			Velocity:	6.851
Guide Roll CoEf:	0.015	Wheel Slip Coeff	1.67	Mtr RPM:	14597
Mass(kg):	2.1			Air Drag	0.329
Wheel Roll RS:	0	Roll CoEf:	0.11	Rolling R:	0.231
Air Drag Coefficient:	0.007	Steering(Yes/No):	NO	Mtr Torque:	4.049
Wheel Diameter(mm):	64	Steering Drag(N):	0.13		
Acceleration Gear Ratio:	7.14	Change RPM:	0	2 LAP RACE	
Final Gear Ratio:	7.14			Time:	31.55
Transmission Effy:	92			Velocity:	7.319
Motor Tourque:	Finish RPM:	Start T(mNm):	Formula	Mtr RPM:	15594
Section 1:	5600	17.8	0.001429	Air Drag	0.375
Section 2:	10300	9.8	0.00083	Rolling R:	0.231
Section 3:	24000	5.9	0.000431	Mtr Torque:	3.620

ABOVE IS SIMULATOR INPUT OUTPUT PANEL FOR PHOTON CRUNCHER MK IV USING AN ALUMINIUM DRIVE WHEEL WITH A TYRE.
(Tyre used is “O” ring BS032 fitted in a groove 0.050 inch deep)

DETAILS OF PARAMETERS ENTERED

Car Name, Sun Power, and Motor Type, identify the test conditions for future reference.

Guide Roll CoEf : this is the Coefficient determined empirically in Section 1 Part 4. Used to calculate the rolling resistance of the guide rollers.

Mass: The Mass of the car in kg.

Wheel Roll RS: Determined empirically see Section 1 Part 4 for details. Used to calculate the wheel rolling resistance on the track.

Roll CoEf Determined empirically see Section 1 Part 4 for details. Used to calculate the wheel rolling resistance on the track. (in conjunction with Wheel Roll RS above)

Air Drag Coefficient: Determined empirically see Section 1 Part 2 .Used to calculate the air drag on the car.

Wheel Diameter: The drive wheel diameter in mm.

Acceleration Gear Ratio: This gear ratio will be used in the calculations until the nominated motor RPM (Change RPM) is reached. The Final Gear Ratio is used thereafter. The ratio is a reduction ratio and only the reduction ratio number is entered. That is 9.5 to 1 reduction is simply entered as 9.5. If a gear change is not to be used this ratio must be set the same as the final gear ratio if best possible accuracy is to be obtained. (NOTE: even with the change RPM set at zero the first calculation will use the acceleration ratio.)

Change RPM: The motor RPM at which you nominate the gear change from the acceleration ratio to the Final Gear Ratio to take place. Once this change has occurred the car is locked into that ratio for the rest of the race simulation, no further gear changes are allowed for.

Final Gear Ratio: This is the gear ratio used for the remainder of the race after the change RPM has been reached. It is entered in the same format as the acceleration gear ratio.

Transmission Effy: The efficiency of your transmission system between the motor and the drive wheel an efficiency of 95% would be entered as 95. This efficiency must be measured by test if accuracy is to be achieved. Efficiencies in the order of 90% to 95% can be expected for a well adjusted single step gear reduction using precision gears.

Motor Torque: The torque vs RPM curve for the Faulhaber motors can be approximated to a graph with 3 straight line sections. The 3 Sections listed under this heading correspond to these sections. The RPM and Torque values entered allow the calculation of torque at any given RPM. Motor torque is used in calculating the motor drive force.

Wheel Slip Coefficient: Used in calculating the force at the wheel periphery at which the wheel slips on the track. IE. it is the maximum drive force the wheel can exert before wheel slip occurs. Determined by tow testing the car with the drive wheel locked and measuring the force required to cause the wheel to slip.
Caution it varies with wheel load, the calculations in the Simulator are based on the ratio of drive wheel load to total car weight remaining constant as car weight is changed.
(This feature was added to the simulator because the electronics systems in use can result in motor torque values which cause wheel spin with consequent loss of drive.)

Steering (Yes/No): This sets the additional drag force which occurs during cornering when there is no steering either on or off.

Steering Drag (N): The amount of additional drag force in Newtons which occurs during cornering when the car has no steering. The magnitude of this additional drag force must be determined for your car by testing.

DETAILS OF RESULTS DISPLAYED
Results are displayed for both a single and two lap race.

Time: The total time in seconds taken for the car to complete the course.

Velocity: The velocity of the car in Meters per Second as it crosses the finish line.

Mtr RPM: The motor RPM as the car crosses the finish line.

Air Drag: The air drag force in Newtons acting on the car as it crosses the finish line.

Rolling R: The rolling resistance in Newtons acting on the car as it crosses the finish line.

Mtr. Torque: The torque in mNm being produced by the motor as the car crosses the finish line.

All the above results are displayed for both a single lap and two lap race . Remember the final series of races are usually two lap.

DATA TO ENABLE YOU TO USE THE SIMULATOR FOR EVALUATION OF A CAR POWERED BY A SINGLE SCORPIO No.26 PANEL AS SUPPLIED FOR THE 2017 REGULATIONS.

The following graphs have been included to provide motor performance data when powered by a solar panel conforming to the 2017 regulations.
This data is intended to be used in the mathematical simulation to aid in car design evaluation.
The test results were carried out using a Scorpio No. 26 solar panel a Faulhaber 2232 6 volt motor, Automax and Scorpio electronics units, as these are the components most commonly used in car construction. Data for the motor without electronics is also included.

The tests were all conducted with the motor driving a "wheel" using R & I gears at a reduction of 4:1. Torque and RPM values were measured on this "wheel" then converted to the values on the motor shaft which were used to prepare the graphs.
The torque versus RPM graphs are the values on the motor shaft.
Consequently, **when using this data in the simulator you must insert the gear reduction ratio you are using but the transmission efficiency should be set at 100% as the gear losses are already included in these test results.**

Data from graph 1 below for Automax Electronics to be used in simulations:
Faulhaber 2232 6 volt Motor- on One Scorpio No.26 Panel 4:1 R & I reduction gears.

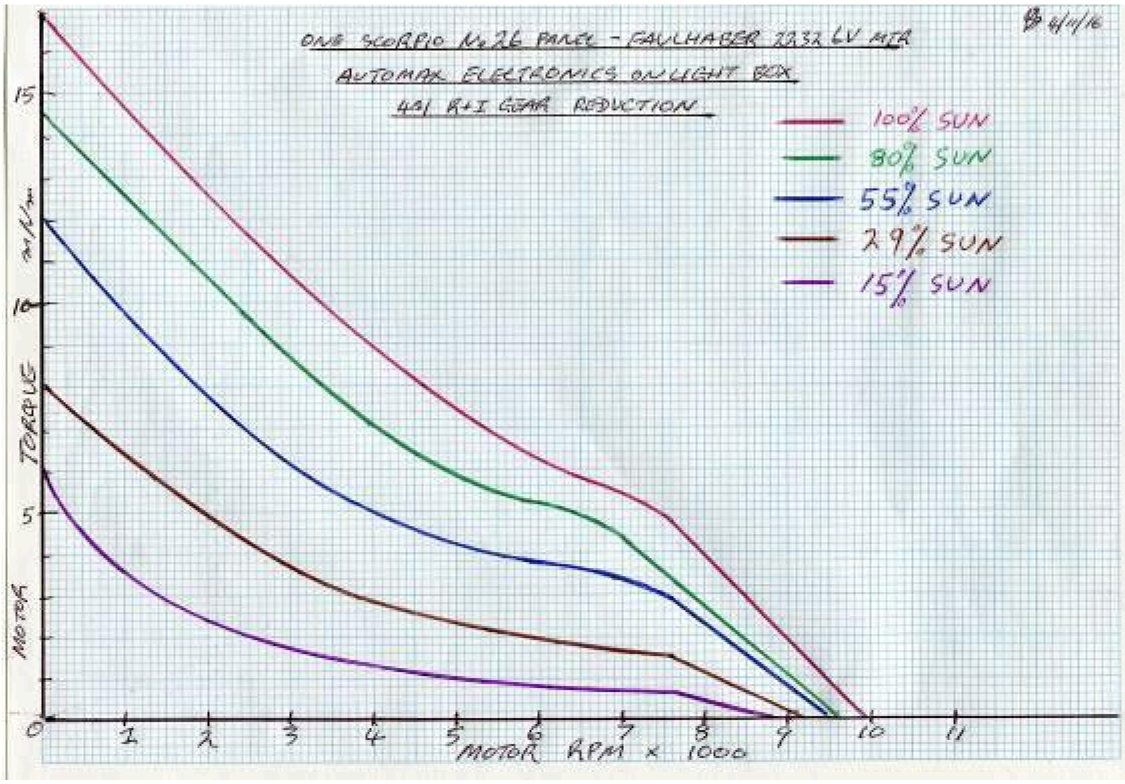
100% Sun	Finish RPM	Start Torque mNm
Section 1	4700	16.0
Section 2	7500	7.6
Section 3	10000	5.0

80% Sun	Finish RPM	Start Torque mNm
Section 1	4000	14.5
Section 2	7000	6.8
Section 3	9700	4.4

55% Sun	Finish RPM	Start Torque mNm
Section 1	3200	11.5
Section 2	7700	5.5
Section 3	9500	2.9

29% Sun	Finish RPM	Start Torque mNm
Section 1	3300	7.8
Section 2	7700	3.0
Section 3	9200	1.4

15% Sun	Finish RPM	Start Torque mNm
Section 1	2500	5.5
Section 2	7200	1.6
Section 3	8900	0.7



Graph 1 Automax electronics.

Data from graph 2 below for no electronics Panel connected in Series to be used in simulations:
Faulhaber 2232 6 volt Motor- on One Scorpio No.26 Panel 4:1 R & I reduction gears.

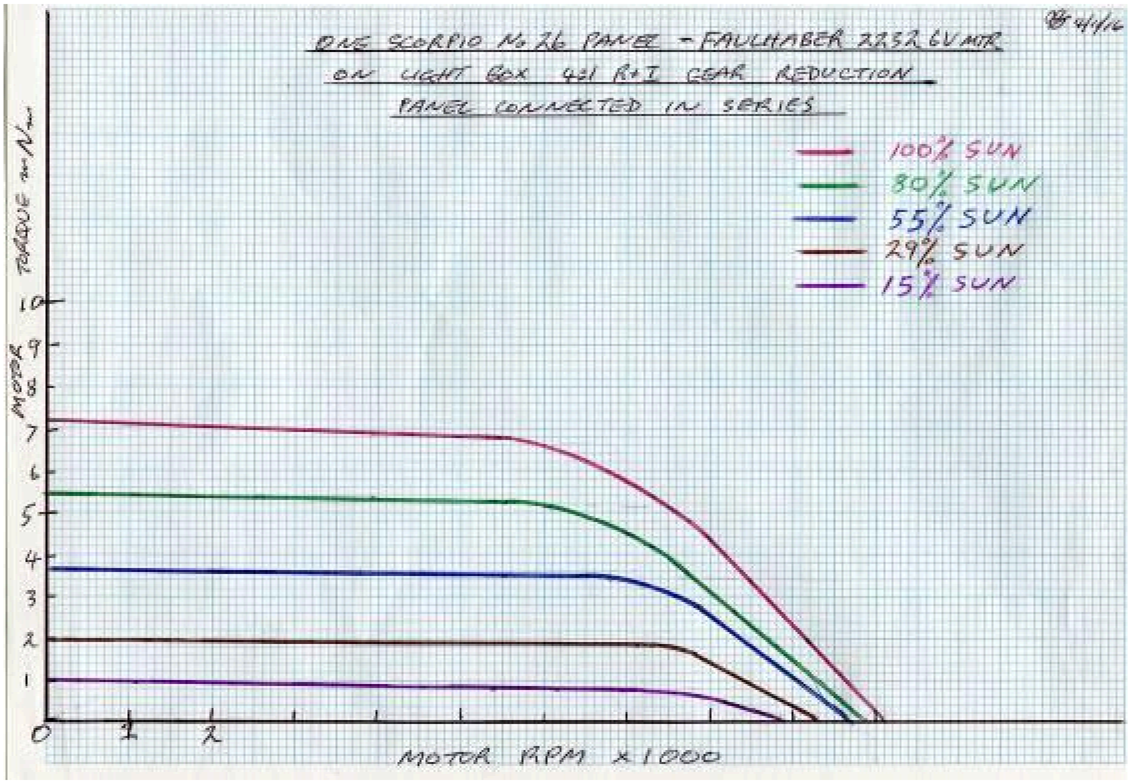
100% Sun	Finish RPM	Start Torque mNm
Section 1	5600	7.1
Section 2	7600	6.7
Section 3	10200	5.0

80% Sun	Finish RPM	Start Torque mNm
Section 1	5800	5.4
Section 2	7400	5.2
Section 3	9900	4.0

55% Sun	Finish RPM	Start Torque mNm
Section 1	6300	3.6
Section 2	7700	3.5
Section 3	9700	2.8

29% Sun	Finish RPM	Start Torque mNm
Section 1	4000	1.95
Section 2	7600	1.9
Section 3	9300	1.8

15% Sun	Finish RPM	Start Torque mNm
Section 1	4000	1.0
Section 2	7700	0.8
Section 3	8900	0.7



Graph 2 no electronics panel connected in series.

Data from graph 3 below for no electronics panel connected in parallel to be used in simulations:
Faulhaber 2232 6 volt Motor- on One Scorpio No.26 Panel 4:1 R & I reduction gears.

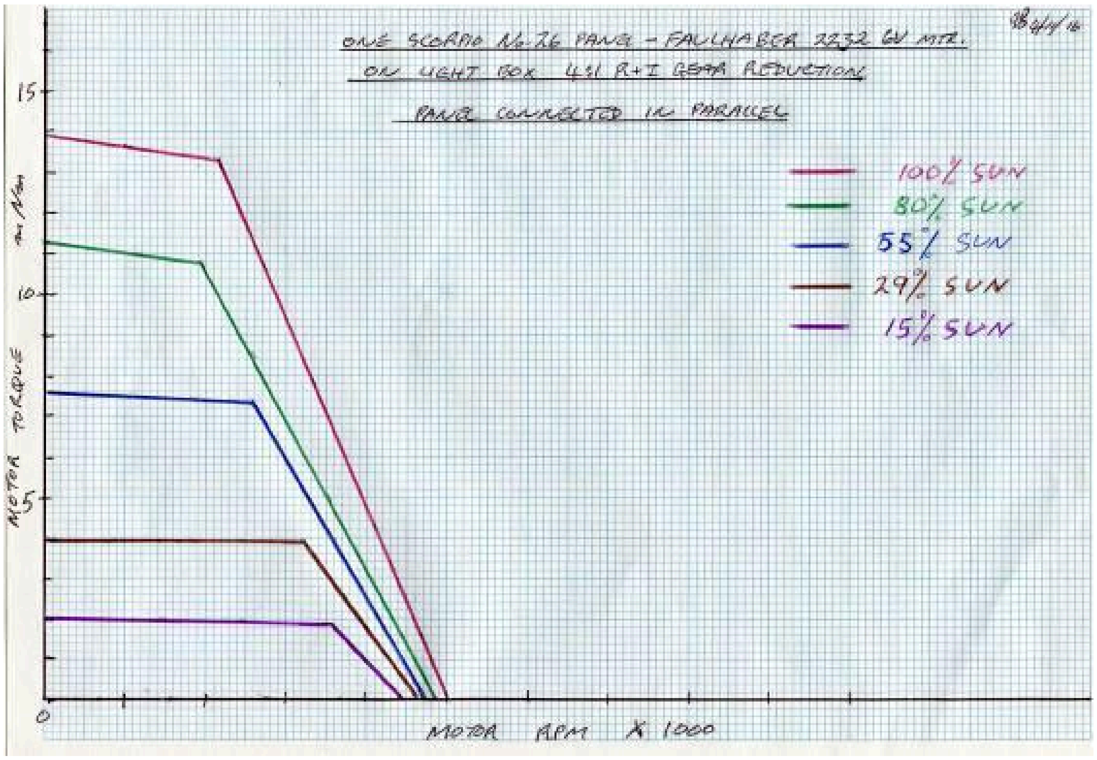
100% Sun	Finish RPM	Start Torque mNm
Section 1	2100	14.0
Section 2	2900	13.4
Section 3	5000	10.0

80% Sun	Finish RPM	Start Torque mNm
Section 1	2000	11.2
Section 2	3000	9.7
Section 3	4900	7.0

55% Sun	Finish RPM	Start Torque mNm
Section 1	2300	7.6
Section 2	2800	7.4
Section 3	4800	6.8

29% Sun	Finish RPM	Start Torque mNm
Section 1	2000	4.0
Section 2	3200	3.95
Section 3	4700	3.9

15% Sun	Finish RPM	Start Torque mNm
Section 1	2000	2.0
Section 2	3600	1.9
Section 3	4400	1.8



Graph 3 no electronics panel connected in parallel.

Data from graph 4 below for Scorpio Electronics to be used in simulations:
Faulhaber 2232 6 volt Motor- on One Scorpio No.26 Panel 4:1 R & I reduction gears.

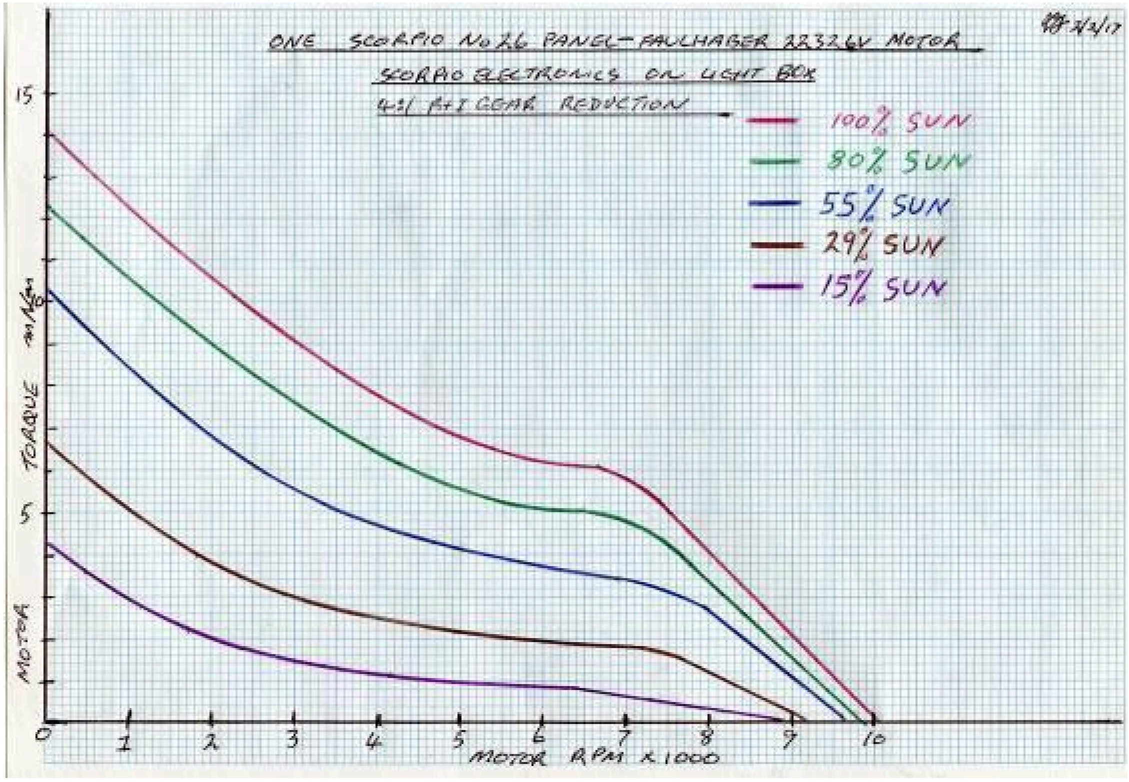
100% Sun	Finish RPM	Start Torque mNm
Section 1	4300	14.8
Section 2	7050	7.3
Section 3	10000	5.9

80% Sun	Finish RPM	Start Torque mNm
Section 1	4400	12.0
Section 2	7200	5.7
Section 3	9850	4.8

55% Sun	Finish RPM	Start Torque mNm
Section 1	3850	9.6
Section 2	7650	4.6
Section 3	9650	3.1

29% Sun	Finish RPM	Start Torque mNm
Section 1	3200	6.0
Section 2	7400	2.6
Section 3	9200	1.7

15% Sun	Finish RPM	Start Torque mNm
Section 1	2600	4.0
Section 2	6500	1.5
Section 3	9000	0.8



Graph 4 Scorpio electronics.

REVISIONS OF SIMULATOR AND DOCUMENTATION

Version 1.1: Steering option added
Version 1.2: Track parameters altered to reflect new shape hill after 2005 track upgrade.
Results now given for both a single and two lap race.
Version 1.3: Calculation time interval reduced from 0.1 sec to 0.05 sec.
Version 1.4 Modified to account for wheel spin.
Version 1.5 Additional mods for wheel spin. December 2006
January 08 Documentation revision (reflecting wheel slip coefficient changes)
April 2017 Added motor data for single Scorpio No 26 panel.

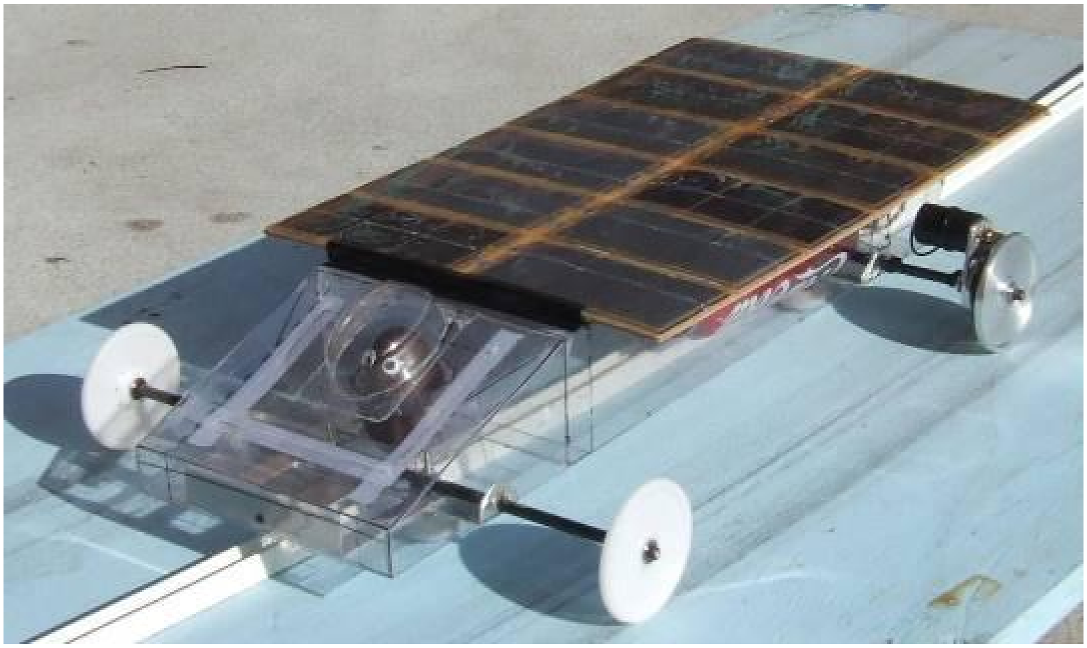
PHOTOS OF CARS & AIR DRAG COEFFICIENT

NOTE: You MUST do wind tunnel testing of your car to determine its drag coefficient. (Values in the order of 0.03 for a flat plate of 200 cm square to 0.003 for a low drag aerofoil shape of 200 cm square would be typical.)

If you cannot perform wind tunnel testing you can make an estimation of drag coefficient by taking the 0.03 drag coefficient for a flat plate of 200 cm square and calculate the drag coefficient for your car with a simple ratio calculation based on your cars frontal area compared to the 200 cm square.
This will give a worst case drag figure as it is based on a flat plate.
As a help to determining your drag ratios some drag ratios of actual cars that have been tested in a wind tunnel are given below.

CAUTION: The air drag coefficients listed here are not cd values or Drag Coefficient values as normally seen. They are derived from testing of a particular car and the coefficient includes cd values as well as frontal area and air density all rolled into the one coefficient. Consequently we cannot compare the aerodynamic performance of different cars without considering their frontal area.
(See section on air drag in Mathematical Simulator earlier in this document for more details)

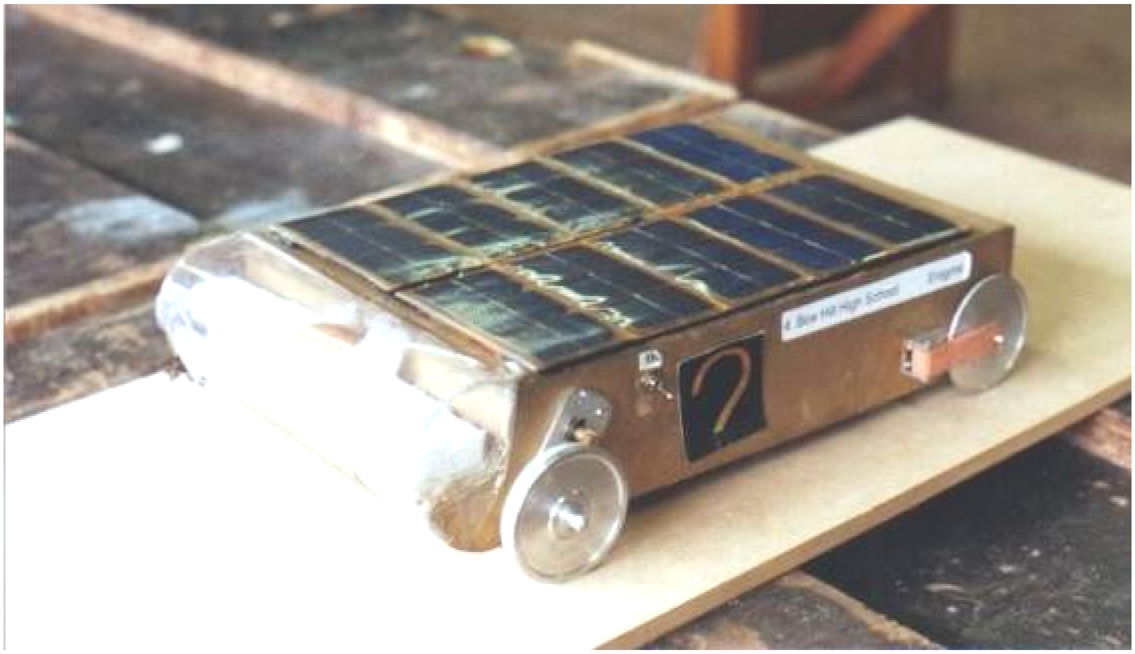
PHOTON CRUNCHER MK IV : SIMULATOR AIR DRAG COEFFICIENT 0.007



PHOTON CRUNCHER MK V: SIMULATOR AIR DRAG COEFFICIENT 0.0045

SYNDAL SOUTH 2006 CAR : SIMULATOR AIR DRAG COEFFICIENT 0.0045

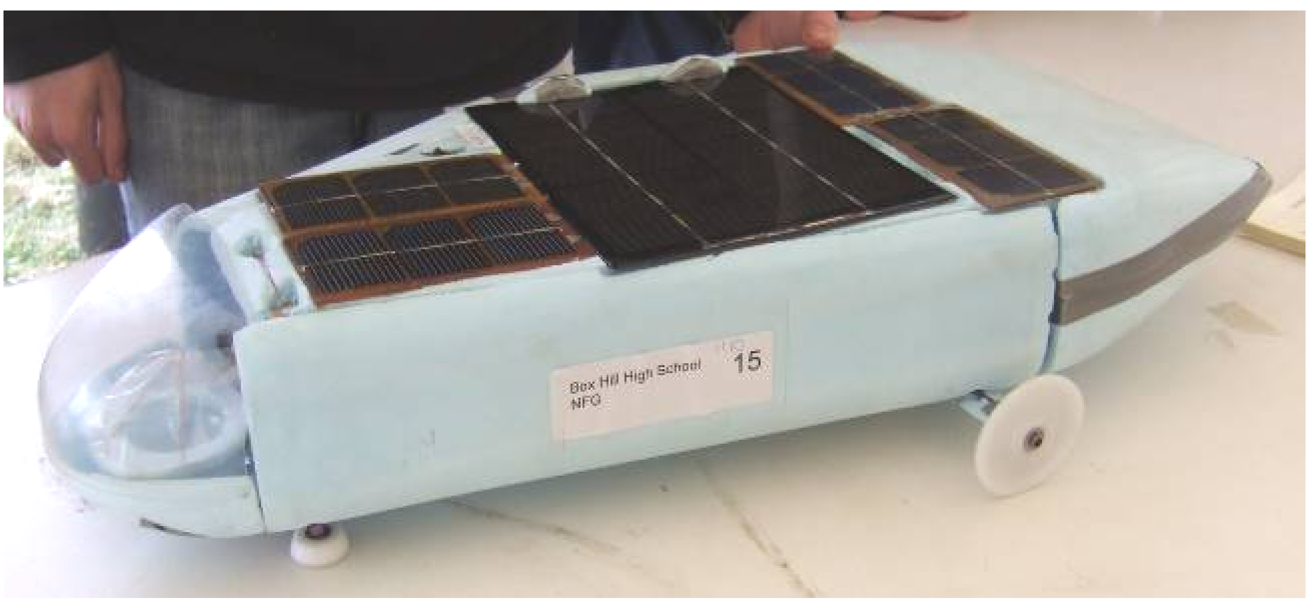
PHOTON CRUNCHER MK II: SIMULATOR AIR DRAG COEFFICIENT 0.012
(Note: This car designed to meet the 200 sq.cm. transverse panel requirement.)



ENIGMA: SIMULATOR AIR DRAG COEFFICIENT 0.012
(Note: This car designed to meet the 200 sq.cm. transverse panel requirement.)

HELIOS: SIMULATOR AIR DRAG COEFFICIENT 0.004
(Note: This car designed to meet the 200 sq.cm. transverse panel requirement.)

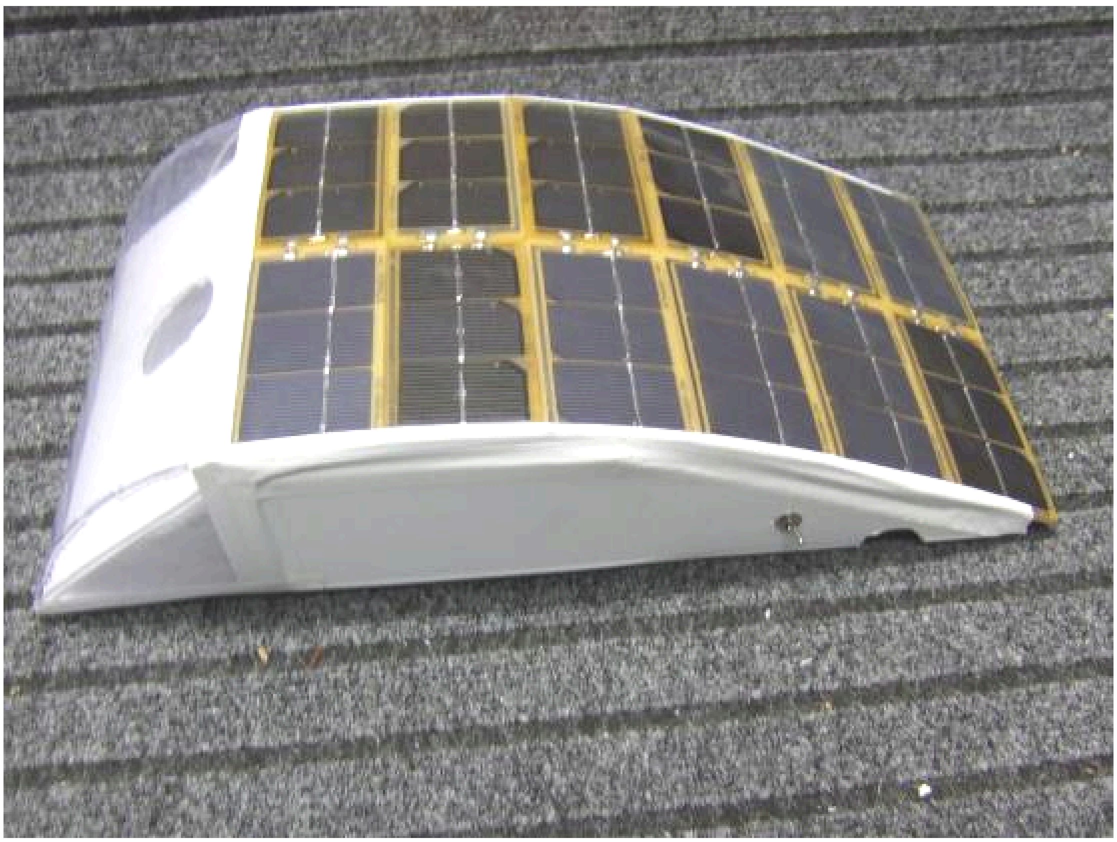
CARBO TRUDIS: SIMULATOR AIR DRAG COEFFICIENT 0.0039



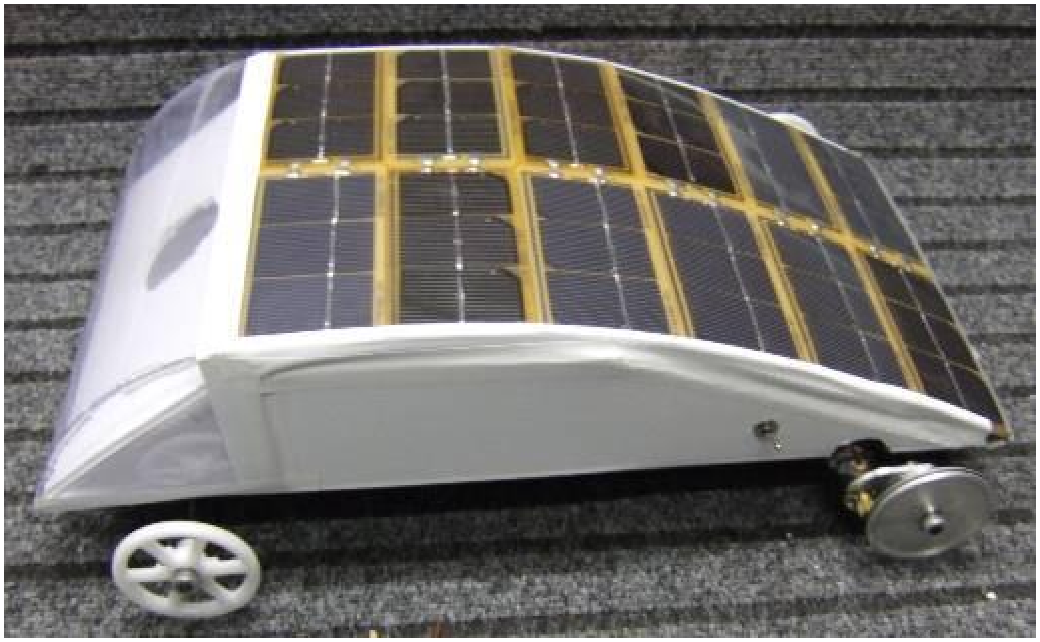
NFG: SIMULATOR AIR DRAG COEFFICIENT 0.007
(Note: This car won the 2008 National event. Designed for transverse milk carton.)

EFFECT OF WHEELS AND GUIDES ON DRAG

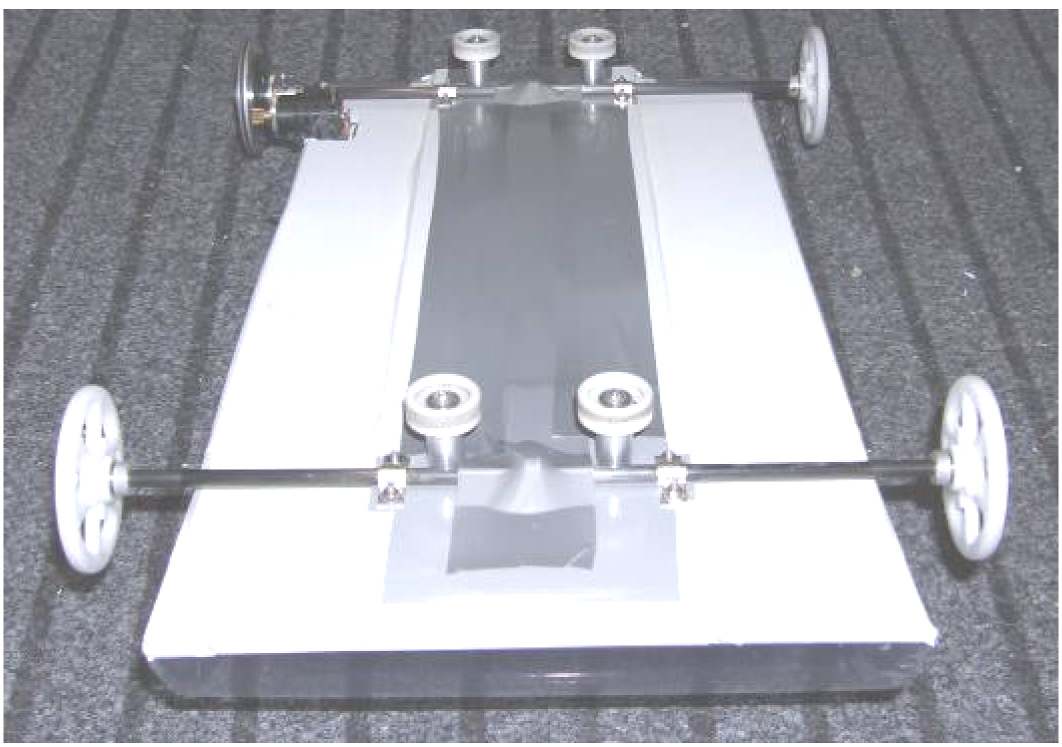
In order to show how important apparently small items can be when it comes to air drag, wind tunnel tests were carried out on a car to evaluate the effect exposed motor, wheels and guides has on air drag. A sample car made for workshop demonstrations was tested as a body only then as a complete car. Please note the chassis is that from PC IV so is shown in detail in the Design Hints.
NOTE: This car was designed to meet the transverse milk carton regulation.



BODY ONLY: SIMULATOR AIR DRAG COEFFICIENT 0.0035



COMPLETE CAR: SIMULATOR AIR DRAG COEFFICIENT 0.008



CHASSIS ONLY (SHOWN HERE STILL ATTACHED TO CAR)
: SIMULATOR AIR DRAG COEFFICIENT 0.0045