What you need to know about Electric Locos

When we first started building 5” gauge battery powered engines they used converted car dynamos as the motive power, this worked well but used a lot of power for the amount of work done. When Maxitrak started we had to use new motors on new locomotives and so found a 100 watt permanent magnet motor to do the job. This motor was later enlarged to 120 watt and continued in use on five inch gauge locomotives right up to a year or so ago.

The main reason for change the recent was to try and get a motor that would sit between the wheels so we could use a direct gear drive on to each wheel. The motor chosen is one of a new breed of small high efficiency permanent magnet motors as used in model boats, helicopters etc. In the last four years this motor has proved its worth to such an extent that is now used in multiple in even the largest engines in our range. We have been doing some experimentation to give some figures to back up the loadings quoted for these engines, and these make interesting reading later in the article.

There are odd occasions when an owner say, that his engine is not going as well as it was or it is not doing what was expected of it. This is a very difficult thing to pin down, so much of it is subjective and depends on the drivers impression of what the engine should be doing. There are occasions when I experience this driving my 1935 Austin Seven, when it is labouring on an easy looking hill the driver is forced to chose between the following options, either the hill is steeper than it looks or the car is “conking out”! To give the locomotive owner more positive figures to check the power against we have been taking some draw bar pull readings. At very least a simple draw bar pull test will show if the engine is performing and the problem lies with stiff rolling stock, passengers putting on weight or other external factors. Even if the drawbar pull is down the locomotive is not necessarily to blame as the battery needs to be holding a good charge.

Nine times out of ten the battery is the root cause of poor performance, a simple voltage test is not necessarily a good indication of the state of play and any battery that has had heavy use, been stored with no charge or is over a couple of years old should be looked on as suspect. Motors are quoted in Volts and Watts, as we learned in physics class Watts are Amps multiplied by Volts and are used to give an indication of the power of a particular motor. So far so good, except we are quoted the amount of electricity the motor will use, not the amount of power we can expect to get out of it. A motor running at 40% efficiency will give much less power from the same amount of electricity than a motor running at 80% efficiency.

To bring some real fact and understanding to all this we have compiled a set of facts and real test measurements obtained over the last year or so. We have broken it down into 3 section so you can absorb the facts slowly. In the battery section we have only considered lead acid batteries for the moment although we are looking into all modern developments, but at present they are all a bit expensive but we expect to be using them in the next year or two.

Section 1.	**The battery and actual Loco consumption.**
Section 2.	**Motors, Drive train, controllers, actual break tests and delivery of the available power.**
Section 3.	**Fault protection and over current protection.**

Lead Acid Batteries

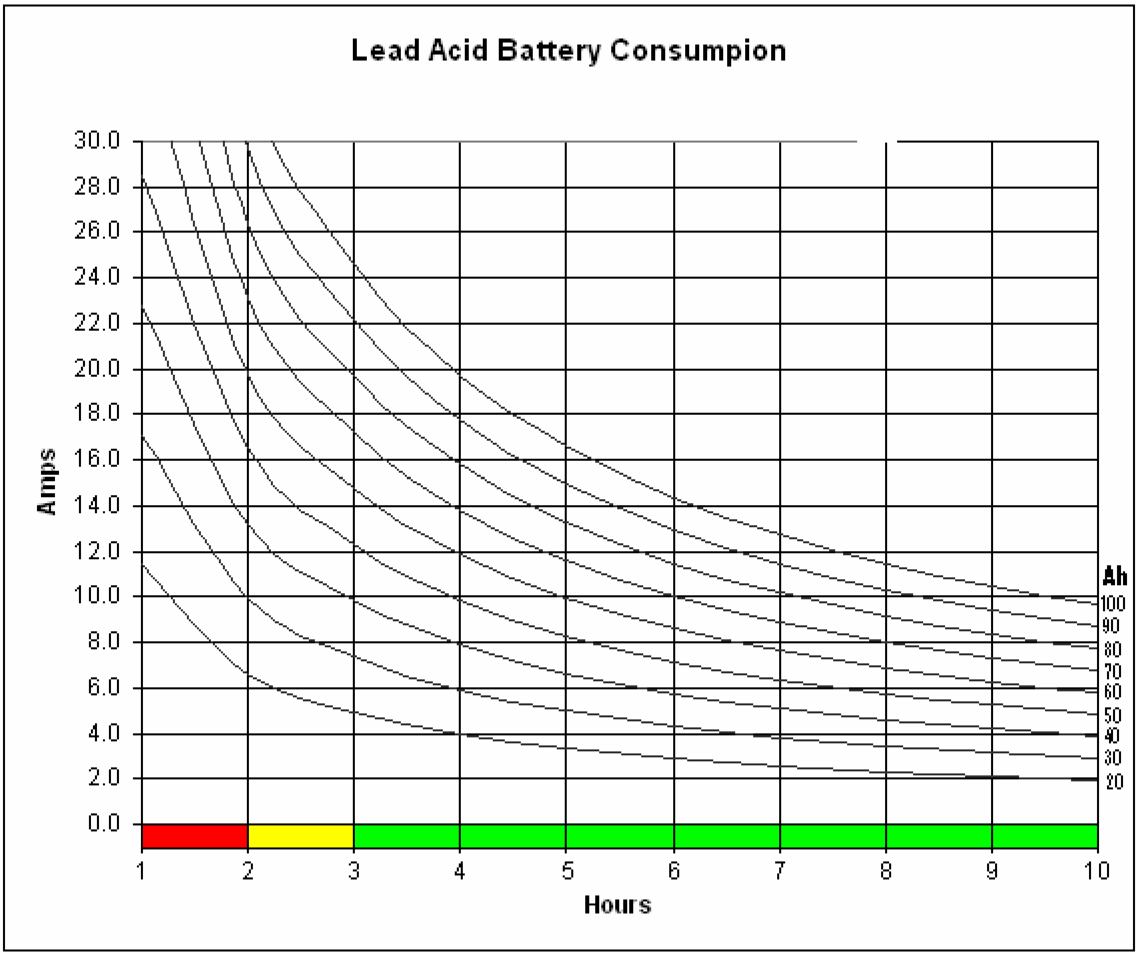
Ok then lets see if we can unwrap the mysteries of the lead acid battery. The facts and figures that follow represent usable averages of the different types of lead acid batteries:- eg flooded, gell, no maintenance, etc.

Current Consumption

This is not as simple as people think, we understand the battery capacity Ah (ampere hours) but most people don't understand that the actual capacity of the battery depends on how quickly you consume it. Batteries are quoted to give a guaranteed capacity of say 40Ah but consumed at a continuous rate over 20 hours; therefore it will supply 2 amps for 20 hrs. The capacity gets less and less as the consumption goes up, so for a 40 Ah battery consumption is as follows :-

Consumption over	% of Capacity	Continuous current	Actual Capacity
10 hrs	97%	3.88 amps	38.8 Ah
5 hrs	83%	6.64 amps	33.2 Ah
3 hrs	74%	9.86 amps	29.6 Ah
1 hrs	57%	22.8 amps	22.8 Ah

You don't want to consume the battery capacity in less than 3 hours as you may cause damage to the battery. As a rule of thumb, you don't want the battery terminal voltage to go below 11.4 volts when under load for long life.



The above figures are for continuous load consumption, so if we have periods of no consumption it will allow time for the battery to recover.

Actual Loco Consumption

To consider this we need to break it down into two parts

Average current consumption when running

Running not running ratio

Lets have a look at the "running not running ratio" first.

When driving your loco you run for a bit, stop for a bit, run for a bit, have a cup of tea, run for a bit, stop in the station, run for a bit etc. For example we run for 15 mins and stop for 10 mins. This would give a ratio of 15 / 25 = 0.6. If our average running current is 8 amps we can multiply it by 0.6 to give real requirement of 4.8 amps. Now looking at the previous graph we can see a 40Ah battery will give us 4 hours running, but after applying our ratio we can get 4.5 hours running on a 30Ah battery or 7 hours on the 40Ah battery. This will vary depending on the track you are running on, but well worth thinking about. So plenty of little stops could double the running time of your loco. I would think a value of 0.6 to 0.7 is easily obtainable.

Now lets consider the average current consumption when running.

This depends on the track you are running on, the loco you are running, the load you are pulling and the skill of the driver. If we are saying we have an average running current of 8 amps this will probably consist of pulling away at 20amps, up gradient 10amps, flat running 7amps, down gradient 2 amps etc. Driving skill has a large effect on this, if we pull away slowly we consume less current, if we plan for the gradient by raising our speed on the flat first we consume less current. This is something for you to think about and try and work out the average running current of your loco. Some of you might like to try this:- you remember in the old days of having a vacuum gauge on your old car, you could drive to this, the lower the vacuum the lower the petrol consumption. Well in battery consumption a volt meter across the battery terminals will give a very similar effect, eg the higher the voltage when driving, the lower the battery consumption is.

As a rule of thumb you should never let the voltage go below 11.4 volts when driving for best battery life and not below 11 volts if you don't want to permanently damage your battery.
If you are going below 11.4 volts this is a good sign that your battery has not got a big enough capacity or your battery is on its way out.

Charging Lead Acid Batteries

The life and performance of your battery depends on not discharging too quickly (don't let voltage under load go below 11 volts) and charging your battery in a multi – stage way.

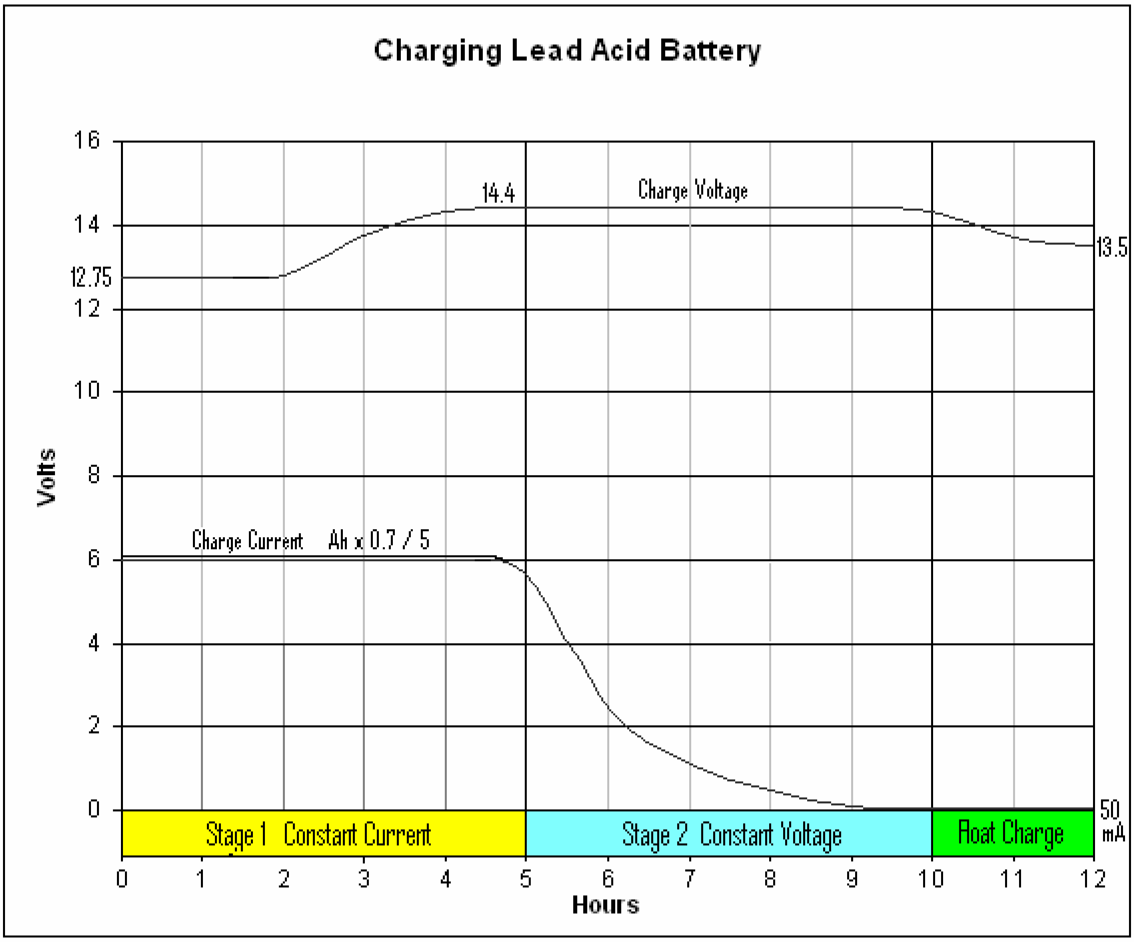
Charging is basically divided in to 3 sections

Constant Current   Constant Voltage   Float Charge

Stage 1 Constant Current Takes about 5 hours and consists of applying a constant current approximately equivalent to the batteries capacity Ah multiplied by 0.7 and divided by 5. This increases the terminal voltage to a preset value and gets the battery to a 70% charge condition.

Stage 2 Constant Voltage This stage also takes about 5 hours and applies a constant voltage of 14.4 volts, this causes the charging current to gradually reduce as the cells are being saturated. This section is essential for the well being of the battery. If omitted, the battery will eventually lose the ability to accept a full charge. Full charge is attained after the voltage has reached the threshold and the current has dropped to about 50 milli amps (will rise to around 100 milli amps when the battery is on it way out).

Stage 3 Float Charge This stage drops the charge voltage to 13.5 volts so the battery is not damaged. Float charge can be used at any time no mater how short or long a time it is applied.



Checking Battery Capacity by Terminal Voltage

This can only be done after the battery has been allowed to recover for 3 hours after charging or discharging.

12.65 volts = 100%
12.45 volts = 75%
12.24 volts = 50%
12.06 volts = 25%
11.4 volts = Discharged

These results assumes ambient temperature below 23° C. Never store your battery uncharged.

Motors, drive train and controller

Now let's have a look at motors, drive train and motor controller. This is how we get the energy stored in the battery (Ah) in to the track Torque Nm or drawbar pull N.

Ah (ampere hour's) Nm (Newton meter's) N (Newton's)

Delivering energy to the track

The easiest way to measure the work done puling a load, is to measure the draw bar pull. For this you can use a spring balance designed to measure weight in Kg kilograms. The energy used in Newton's is the weight multiplied by the effects of gravity 9.81 N/Kg.

Force = Weight or pull in Kg multiplied by 9.81 N/ Kg = Newton's.

This draw bar force is delivered through the wheel as an angular force which we call Torque, this is measured in Newton meters Nm and is the force or pull multiplied by the angular distance in meters.

Torque = Force or pull in Newton's multiplied by the angular distance in meters.

If we have a draw bar pull of 4 Kg delivered through a 75mm wheel the torque required :-

4 x 9.81 x 0.0375 = Kg x N/Kg x meters = Torque of 1.47 Nm.

The mechanical power will depend on the speed of rotation of the wheel and is calculated :-

$$\frac{\textbf{Torque x Pie x speed of rotation in rpm}}{\textbf{30}} = \textbf{Watts}$$ delivered or break

If we use the same pull of 4 Kg through 75mm wheel running at 339.5 rpm (3 mph), this would give a delivered mechanical power of :-

$$\frac{T \times \pi \times N}{30} = \frac{1.47 \times 3.14159 \times 339.5}{30} = \textbf{52.6 watts}$$ delivered to the track to pull 4Kg.

If we are travelling at 5 mph which is 566 rpm wheel speed, the power delivered would be :-

$$\frac{1.47 \times \pi\ 565.8}{30} = \textbf{87 watts}$$ mechanical power delivered. We call this break power or the power delivered in to the load.

This delivered power is provided from a motor through a gear train, so to find the actual power delivered by the motor we need to take into account the gear train and bearings, which probably work at an efficiency of around 90% in excellent condition but as low as 75% in poor condition. If we take our 4 kg pull at 3 mph this is a delivered power of 52.6 watts, if the gear train and bearings are 90% efficient then the motor needs to deliver :-

Good condition $\frac{52.2}{0.9}$ = **58 Watts** Poor condition $\frac{52.2}{0.75}$ = **69.6 Watts**

If we now want to know the torque at the motor we need to know the shaft speed which will be the wheel speed multiplied by the gear ratio which on our 75mm wheel is 6.5 to 1.

At 3 mph, wheel speed our motor shaft speed will be :- **339.5 x 6.5 = 2206.8 rpm**

Now to calculate the delivered torque at the motor shaft :- $\text{Watts} = \frac{\text{Torque} \times \pi \times \text{Speed}}{30}$

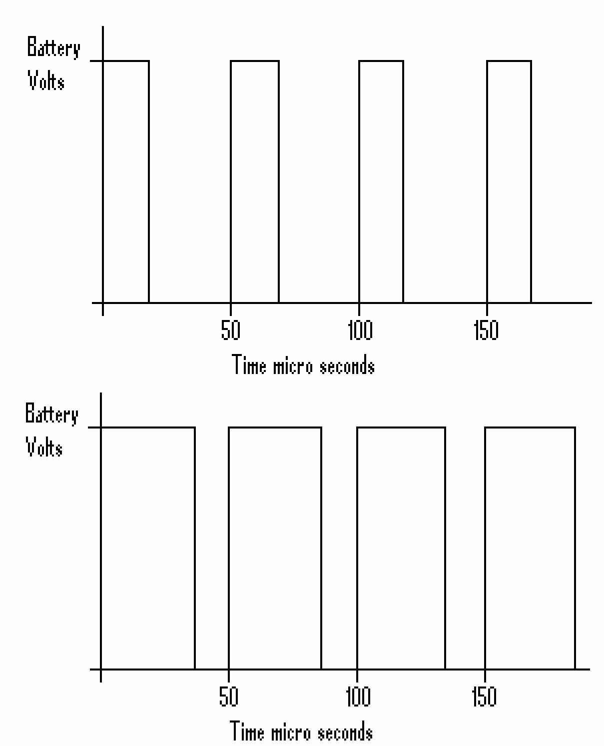
$$\frac{\textbf{Watts} \times \textbf{30}}{\textbf{Speed} \times \boldsymbol{\pi}} = \textbf{Torque} \qquad \frac{\textbf{58} \times \textbf{30}}{\textbf{2206.8} \times \boldsymbol{\pi}} = \textbf{0.25 Nm}$$ on a 6mm shaft

The force pulled by a string wound round the shaft would be :-

$$\frac{\textbf{0.25 Nm}}{\textbf{0.003 meters}} = \textbf{83.33 N} \quad \textbf{or} \quad \textbf{8.5 Kg pull.}$$

This has taken us from the output of the motor, through the gear train and bearings to the wheels. I have gone through this backwards as this is what we usually need to do, as the important point is what draw bar pull do we need.

Controller



Delivering the battery power to the motor in a controlled manner we use a controller, originally we would have controlled the voltage to give us speed control but in modern controllers we use PWM pulse width modulation this is far more efficient method of delivering power to the motor as used by Maxitrak on current Loco's.

PWM delivers the battery voltage to the motor in pulses at a frequency of around 20kHz and varies the width of the pulse from 0 to 100%, representing the power that is delivered to the motor and therefore its speed. As you can see from the above calculations as the speed rises the power required rises.

Delivering power in this manner is very efficient but is also very difficult to measure as the delivery is technically AC at 20k Hz and power from all the harmonics down to the 12 level will deliver power. Without using very expensive power measuring equipment it is not some thing we can do at home, so all the test results presented below show the voltage and current as measured by simple digital meters that you are likely to use, for this reason we will not go into efficiency calculations.

Actual Loco Tests

This section looks at actual motor test results. For this we have used Andy Probyn's garden 5 inch railway with standard Maxitrak Ruston and Jubilee loco's and actual break tests performed using

Maxitrak 5 inch driving axle with 75mm wheel, plain bearings, 6.5 to 1 nylon gearing and a Graupner Speed 900BB 12v motor per axle set. Andy's railway was used to get draw bar pull for flat running uphill and down hill running and averaged out at 4Kg on the flat and up to 8 Kg up hill.

The actual break Torque readings were taken from using a standard Maxitrak drive axle as described above with a Tufnell calliper break working round the diameter of the wheel pulling on a calibrated spring balance.

Actual readings of input power are for information only but can't be used to calculate efficiency as discussed above. The more useful reading of current is what you need to calculate the battery capacity required by your Loco.

6.5 to 1 75 mm Wheel	Draw Bar Pull	Output		Battery Input Power		
		Torque	Power			
	Kg	Nm	W	A	V	W
226 shaft rpm 2 mph	4	1.47	35	14.4	12.1	174
	3	1.1	26	10.8	12.2	132
	2	0.74	17	7.2	12.3	89
	1	0.37	9	3.6	12.5	45
340 shaft rpm 3 mph	4	1.47	52	16.4	12.1	198
	3	1.1	39	12.3	12.2	150
	2	0.74	26	8.2	12.3	101
	1	0.37	13	4.1	12.5	51
453 shaft rpm 4 mph	4	1.47	70	18.8	12.1	227
	3	1.1	52	14.1	12.2	172
	2	0.74	35	9.4	12.3	116
	1	0.37	17	4.7	12.5	59
566 shaft rpm 5 mph	4	1.47	87	20.8	12.1	252
	3	1.1	65	15.6	12.2	190
	2	0.74	44	10.4	12.3	128
	1	0.37	22	5.2	12.5	65

You can see that on a 12 volt Loco, depending on your speed you will expect to supply the displayed current for these draw bar pull's.

Pull Kg	**Amps Required**
2	7.2 and 10.4
3	10.8 and 15.6
4	14.4 and 20.8
5	18.0 and 26.0
6	21.6 and 31.2
7	25.2 and 36.4
8	28.8 and 41.6

The table below shows the same setup but with a 24 volt supply. You will be surprised to see that the input power is higher than the 12v setup for the same drawbar pull. This is due to the motor not working in its most efficient range. To get the same efficiency at 24 volt on this size of wheel 75mm we would need to increase the gear ratio from 6.5:1 to about 10:1.

6.5 to 1	Draw Bar	Output				
75 mm	Pull	Torque	Power	Battery Input Power		
Wheel	Kg	Nm	W	A	V	W
226 shaft rpm 2 mph	4	1.47	35	7.9	24.2	191
	3	1.1	26	6.2	24.4	152
	2	0.74	17	4.3	24.6	106
	1	0.37	9	2.3	25	58
340 shaft rpm 3 mph	4	1.47	52	9	24.2	218
	3	1.1	39	7.1	24.4	173
	2	0.74	26	4.9	24.6	121
	1	0.37	13	2.7	25	68
453 shaft rpm 4 mph	4	1.47	70	10.3	24.2	249
	3	1.1	52	8.1	24.4	198
	2	0.74	35	5.6	24.6	138
	1	0.37	17	3.1	25	78
566 shaft rpm 5 mph	4	1.47	87	11.4	24.2	276
	3	1.1	65	9	24.4	220
	2	0.74	44	6.3	24.6	155
	1	0.37	22	3.4	25	85

So using 24 volt supply on a modern motor, driven through a PWM controller dose not give you any particular advantage, in fact with the wrong gearing and small wheels it performs worse than 12 volt. The only real advantage is the reduction of current, making the use of smaller cables possible.

In simple terms there is no output power difference between 12 volt and 24 volt systems provided you are working in the efficient region of the motor speed range, the motor shaft speed needs to be higher on a 24 volt system to maintain efficiency and use the ability to have smaller cables. Its really down to size of loco 5 inch and small 7¼ inch loco using 6:1 to 8:1 gearing on 70mm to 100mm wheels are probably best on a 12 volt system and where you can get to above 100mm wheels and gear ratios 10:1 to 15:1 Larger loco's may benefit from 24 volt system.

It all really comes down to the motor specification, with the Graupner Speed 900BB motor Maxitrak uses and we have tested to near death, the shaft speed needs to be 3600 rpm for 5 mph running on 12 volt, peak efficiency is delivered at a consumption of 7 to 9 amps per motor at 12 volts. On a 24 volt system you need a shaft speed to be approximately 5500 rpm for 5mph.

Delivery of the available power

We can deliver power from the battery through the controller, gearing, bearings, axle and wheels to the track but if the loco weight is not right or distributed evenly over all driving axles then the wheels will slip. Having lots of driven axles sounds good but only works well if the loco weight is applied evenly across all axles, so very careful consideration to suspension and weight distribution is essential.

Generally our tests show that you need between 25 and 30 Kg loco weight on 2 driving axels' to pull 8 to 10 kg at the draw bar. It is generally best to have motors connected directly to the controller output and not connected in series across s axles as one slipping will reduce the performance of the other. You should only connect motors in series if they are driving the same axle.

Remember each driven wheel has a very small contact area to the track to deliver the power through (perhaps we should consider rubber coated wheel treads) so the state of the track is also very important. Not just leaves on the line but the track needs to be even, level across the track and secure not moving up and down.

Steel track can be misleading as the service starts to rust the surface is like a rail with sand on it giving good grip but as the rail pits because it oxidises unevenly and you polish the top during use that day the contact area can actually reduce due to the pitting. So it really comes down to good house keeping and how often do you use the track.

Fault and over current protection

Protection for fault currents like short circuit is best achieved by using a circuit breaker as this will disconnect within one second which is only one part of the protection, protecting against fire or melting cables, motors or controls. The second part of protection is for over current, the maximum current for the motor, controller and cabling for long term safe use. This is equally provided by circuit breaker of cartridge fuse.

The facts that most people do not realise is, that a circuit breaker dose not trip at its rated value, it will probably not trip at its rated value + 25%. The actual trip current and time to trip are displayed in the table below. The readings are for type B,C and D circuit breakers, and are continuous maximum currents. Your normal driving averages will fit well within these values.

Circuit Breaker	Current to trip in time				
Amps	3 Hr	1 Hr	10 Min	2 Min	40 Sec
10	13.5	13.8	16	21	29
16	22	22.5	25	33	47
20	28	29	32	42	60
25	35	36	41	52	72
32	44	47	52	68	92
40	56	57	65	85	101

To protect properly against over current :-

A 30 amp controller, you need to use a 10 amp circuit breaker.

A 60 amp controller, you need to use a 20 amp circuit breaker.

A 90 amp controller , you need to use a 32 amp circuit breaker.

Standard cartage fuses would give very similar results.

Well we hope this has been interesting and given you plenty to think about.