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Electric locomotives

This document was written by John Conry and was originally published by Frimley and Ascot Locomotive Club between November 2022 and July 2023.

What you need to know about Electric Locos

Section 1

There are odd occasions when an owner thinks 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 driver's impression of what the engine should be doing.

To give the locomotive owner more positive figures to check the power against I have been taking some drawbar pull readings. At very least a simple drawbar 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 and the motor working at optimum efficiency.

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 quoting 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 I have compiled a set of facts and real test measurements obtained over the past 10 years or so. I have broken it down into three sections so you can absorb the facts slowly. In the battery section I have only considered lead acid batteries for the moment although I am 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. This information has been put together by Ken Delaforce who made the test equipment and carried out all the testing, using locomotive motors provided by Maxitrak. I have over the past few years made many electric Loco's from small 5in to large 7¼in gauge. This is my latest, an interpretation of a Japanese hybrid works loco 'Nozomi', It can silent run on battery or normal on petrol. It has on-board a 200 amp welding generator, 6.5KV 230v or 115v generator, winch, short lifting crane on the back and 3.5cfm compressor. It has four 1hp motors direct drive to axles through 90deg gearboxes two on each bogie. Breaking is fully regenerative.

Section 1. The battery and actual loco consumption.

Section 2. Motors, drive train, controllers, actual brake tests and delivery of the available power.

Section 3. Fault protection and over-current protection.



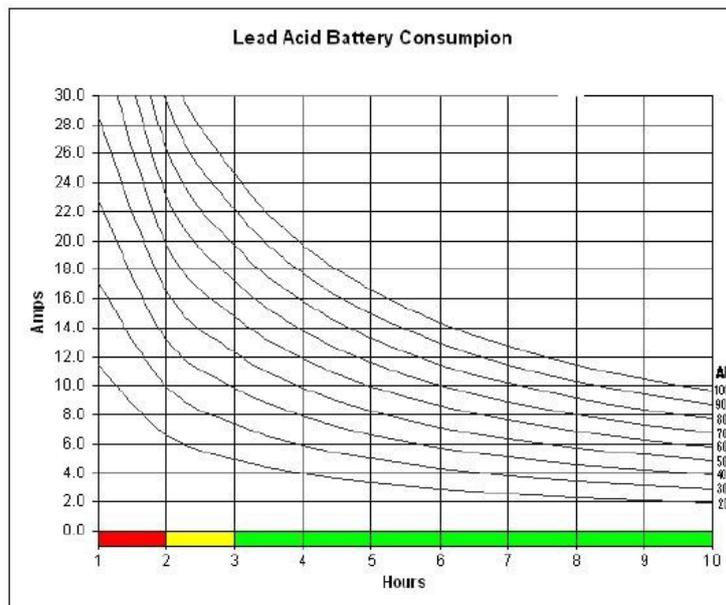
Lead Acid Batteries

Let us 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: 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:

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

Let's 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 let's 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 to 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.

In battery consumption a volt meter across the battery terminals will give a very similar effect, e.g. 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

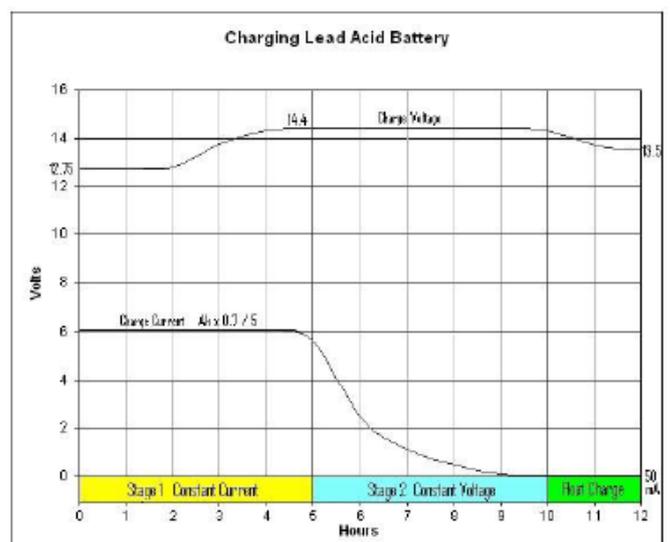
The life and performance of your battery depends on not discharging too quickly (don't let voltage under load go below 11 volts) and charging your battery in a multi-stage way.

Charging is basically divided in to three sections

Stage 1 Constant Current: Takes about five 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 its 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 matter how short or long a time it is applied.



Section 2

Checking Battery Capacity by Terminal Voltage

This can only be done after the battery has been allowed to recover for three 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 assume ambient temperature below 23deg. 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 pulling 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:

$4 \times 9.81 \times 0.0375 = \text{Kg} \times \text{N/Kg} \times \text{meters} = \text{Torque of } 1.47 \text{ Nm.}$

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

Torque x Pi x speed of rotation in rpm = Watts delivered or break

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

T x pi x N = 1.47 x 3.14159 x 339.5 = 52.6 watts delivered to the track

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

1.47 x pi x 565.8 = 87 watts mechanical power delivered.

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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 4kg 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: $52.2/0.9 = 58 \text{ Watts}$

Poor condition: $52.2/0.75 = 69.6 \text{ Watts}$

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:

$339.5 \times 6.5 = 2206.8 \text{ rpm.}$

Now to calculate the delivered torque at the motor shaft:

Watts = Torque x pi x Speed

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Watts x 30 = Torque = 58 x 30 = 0.25 Nm on a 6mm shaft.

Speed x pi 2206.8 x pi

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

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

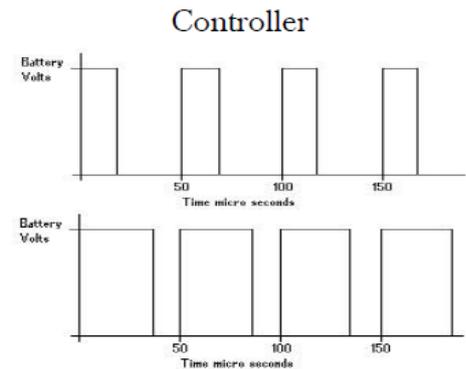
This has taken us from the output of the motor, through the gear train and bearings to the wheels. I have gone through this backwards as this is what we usually need to do, as the important point is what draw bar pull do we need.

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 locomotives.

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 something 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.



Section 3

Actual Loco Tests

This section looks at actual motor test results. For this we have used 5 inch driving axle with 75mm wheel, plain bearings, 6.5 to 1 nylon gearing and one 12v motor per axle set. The pull bar load 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 75mm wheel with a Tufnell calliper break working round the diameter of the wheel pulling on a calibrated spring balance. 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	A	V	W
		Kg	Nm	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
455 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 or less for these drawbar pull's depending on speed and drive train efficiency.

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 75 mm Wheel	Draw Bar Pull	Output		Battery Input Power		
		Torque	Power	A	V	W
	Kg	Nm	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 does 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. It's 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 30kg loco weight on two driving axles to pull 8 to 10kg 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 best to have motors connected directly to the controller output and not connected in series across 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 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 or 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.

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.

Circuit Breaker	Current to trip in time				
	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

Standard cartage fuses would give very similar results.

Powered driving wagon and motor

