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LOCOMOTIVE POWER

First, I would like to thank all members who wrote to me regarding my series on rack railways. One question was posed repeatedly: How is the power of rack vehicles established? I thought the answer to this question might be of interest to all members.

I would like to stress the point that most railway companies have their own rules. This is partly due to the varying rolling resistance conditions prevailing on different lines. For very heavy train rolling on straight flat lines, the rolling resistance proper is of primordial importance, whilst curves and gradients can be neglected. Switzerland's railways, however, have many curves and inclines which have to be considered. In general we must accept that the formulae used are complicated, but there is a simple method which is precise enough for our needs. It can be safely used for speeds up to 140 km/hr.

Alas, there is still need for mathematics. Should you have missed the lessons in mathematics during your school time, skip reading my contribution.

Basically there is no difference in calculating the power between adhesion and rack driven locomotives. For the latter we must bear in mind that there is an additional resistance caused by the rack barbs and that the effect of the rotating equipment is higher.

I shall show step by step the calculations for the locomotive classes 460 and 465 of the SBB and BLS. Both locomotives work on 26‰ gradients, curve radii of 300 meters and haul 650 ton trains at a nominal speed of 80 km/hr. The weights of the locomotives are slightly different, 84t for the SBB ones and 82t in the case of the BLS. The SBB engine is required to accelerate the train from standstill to 80 km/hr within 600 seconds or about 6670 metres, the BLS within 250 seconds or 2780 metres.

We distinguish between 4 main resistances for adhesion operated locomotives:

- Rolling resistance proper – R1
- Curve resistance – R2
- Resistance overcoming the gradient – R3
- Force required to provide acceleration – R4

The required tractive effort is:

$$R1 + R2 + R3 + R4$$

For the rolling resistance it is common practice to use the formula:

$$R1 = 2.5 + k(V1+V2)^2 \times 0.001:$$

in which R1 is the resistance in kg per ton train weight, k a value depending on the train composition, V1 the ground speed and V2 the addition for the air resistance (usually 10 km/hr). For modern rolling and freight car stock k is 0.25. We find 4.5 kg which is, of course, valid for both locomotives. (Calculation: 90 x 90 x 0.25 x 0.001 + 2.5 = 4.5)

For curve resistance on standard gauge the formula is:

$$R2 = 750/R:$$

where R is the curve radius in metres. We find 2.5 kg per ton train weight, again the same for both locomotives on 300 metres curves. (750/300 = 2.5)

For R3 the formula is given by:

1 kg per 1‰ gradient:

on a 26‰ rising gradient, this gives 26 kg for both locomotives.

For R4, we use the formula:

$$R4 = (a \times rc \times 1000)/9.81$$

where 'a' is the acceleration in metres/second², 'rc' the rotational coefficient to take into account the inertia of such things as traction motors.

We calculate the acceleration by dividing the speed of 80 km/hr by the time within which the speed must be reached x 3.6 which results for the SBB locomotive in 0.0370 m/s². For modern locomotives it is common practice to use 1.05 for the rotational coefficient.

Therefore we find 3.96 kg for the train hauled by class 460 (calculation: 0.1019 x 0.0370 x 1.05 x 1000). For class 465 we find 9.51 kg.

We can now proceed to calculate the resistances in kg:

	SBB kg	BLS kg
R1	3303	3294
R2	1835	1830
R3	19084	19032
R4	2907	6961
Total resistance	27129	31117

To obtain the traction force in kilonewton (kN), we multiply by 9.81 and divide by 1000 which results in 266.153 kN for the SBB and 305.257 kN for the BLS. *[Note 1]*

To obtain the needed power we multiply by 80 and divide by 3.6 and obtain 5914 kW (8043 hp) and 6783 kW (9225 hp). *[Note2]* This is the power delivered at the wheel rims. Therefore we have to compensate for the power loss from the motor shaft down the gears and wheels. Usually we are on the safe side with 3%, i.e. the final power output at the motor shafts has to be (rounded) 6100 kW and 7000 kW as mentioned above.

Now let us have a look at the Gornergrat railway rack motor cars Bhe4/8 of 1994. According to Switzerland's railway statistics these vehicles have a power output of 804 kW at a speed of 17.7 km/hr. The metre gauge line's maximum gradient is 200‰, the curve radii 80 metres. If we assume that the usual acceleration of 0.1 m/s² has been required, then the twin motor cars should reach this speed within 45 seconds or 110 metres. We multiply 804 by 0.96 for the higher power loss in rack gears, multiply by 3.6 and divide by 17.7. We find a traction force of about 157 kN or 16000 kg. Fully loaded, the cars weigh 67.420 tons. Therefore the overall resistance to overcome is about 237.32 kg per ton train weight.

Using the formulas given above

- The rolling resistance is:
  2.69 kg per ton
- The curve resistance:
  6.63 kg per ton
- The gradient resistance:
  200 kg per ton
- Extra rack bar resistance (common practice)
  6.20 kg per ton

This leaves a force of about 22 kg available to accelerate the vehicle. It is important to know that the rotational inertia coefficients (rc) are much higher than adhesion operated ones. For a modern twin car with the latest gear techniques it is about 1.7 – 2.0 depending also on stability requirements when the train has to be braked. I suggest we use the factor 1.9 to be on the safe side. In conclusion we find an acceleration resistance of 21.16 kg which brings a total of 236.68 kg per ton train weight. Multiplied by 67.420 x 9.81 we find 156.537 kN, i.e. a difference of about 48 kg explainable by a possible higher power loss caused by the gears.

If you would like to know how the above formulae are derived then you can write to me or send an e-mail to:

<hauser.alfred.hettlingen@swissonline.ch>

I hope you enjoyed my contribution despite the mathematics. Chartered engineers may forgive me the presentation of the formulae, but I had those members in mind who are usually not confronted with establishing the power of a locomotive.

Technical Notes provided by Paul Russenberger, formerly Traction Performance Engineer, Network SouthEast.

Note 1

This particular point is interesting. The calculation assumes that the force resisting the movement of the train is constant from the start to the specified speed, in this case 80 km/hr. This will not be the case as the rolling resistance, R1, is dependent on the square of the speed. If the locomotive is able to exert the tractive effort specified from the start throughout the speed range, it will more than meet the required specification. British practice would allow for this. However, note that the ability to climb against a tight curve is a significant part of the specification, thus reducing the proportion of power required to overcome rolling resistance.

Note 2

Power delivered is obtained by multiplying the force exerted by the speed with which it moves. Hence multiplying the force in kilonewtons by the speed in metres per second gives the power in kilowatts. The factor of 3.6 is introduced to convert kilometres per hour to meters per second.