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Measuring traction power and rolling resistance of model railroad

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Anotace:
Tento článek se zabývá možností využití metod běžně používaných pro návrh a dimenzování hnacích vozidel, popř. pro určení jejich výkonnosti, a jejich aplikaci pro modelové železnice v měřítku 1:8. Práce obsahuje návrh měřícího vozu, zpracování získaných dat a jejich srovnání s reálnou železnicí.

Annotation:
This paper deals with the possibility to utilize methods used for locomotive design, or to determine locomotive performance, and their application in 1:8 scale model railroads. It includes design of a measuring carriage to obtain necessary data, which are analyzed and compared to real railroads.

INTRODUCTION

Traction mechanic is used as a basis for locomotive design and development, train load on given track and timetables. Because of its importance and also the long history of railroad transportation, this field is thoroughly described and well understood [1].
However this applies mostly for the normal gauge and similar gauges. In recent years interest in large scale railway models is expanding. While the visual and mechanic layout of these models is derived from the full scale railroad, the powertrain of these models are usually only improvised. Parameters of the drive depend on readily available components.
Independently from the chosen power source and transmission of the model, the modeler needs to determine how much power his model should have and how heavy it should be. Less powerful and lighter model is preferred for convenience, but the model needs to be able to do the work it was designed for. Some model locomotives are designed to run only with model carriages, while others can easily haul over a ton of load, usually passengers [2].
The aim of this work is to measure and analyze one of the model railroad systems and provide modelers with basic data to enable them to use standard locomotive design methods in order to improve their designs.

THEORY

The main goal of the method discussed in this article is to determine the power that needs to be installed in the model vehicle. The power calculation is shown in the following equation:

$$P = F * v \tag{1}$$

where P is power in watts, F is force in newtons and v is speed in m/s.
The force the locomotive needs to develop composes of three main parts as seen in the following equation:

$$F = F_a + F_o + F_{sred} \tag{2}$$

where F_a is acceleration force, F_o is vehicle resistance and F_{sred} are forces created by track resistance.
The acceleration force can be calculated using the following equation:

$$F_a = m * \xi * a \tag{3}$$

where m is the mass of the train, ξ is a coefficient of rolling mass and a is acceleration.
Vehicle resistance is calculated as a sum of three components (Davis formula [3]):

$$F_o = A + B * v + C * v^2 \tag{4}$$

where large letters A, B and C correspond to dry friction (resistance in bearings), hydraulic friction (rolling resistance) and aerodynamic resistance respectively. Dividing each of these coefficients by weight of the train (or the specific vehicle) results in specific coefficients for the given vehicle type, which are usually marked by small letter a, b and c [4], [5].
The track resistance composes from the track elevation, railway curve and tunnels. Measurements described further in this paper were conducted only on a straight and leveled track and therefore the track resistance will not be discussed further in this article and will be part of a future study.
The above mentioned formulas can be used to determine the locomotive power through speed and traction effort. In order to determine if the traction effort can be reliably transferred from the wheels to the rail, we need to know if adhesion of the vehicle is sufficiently large.
Adhesion is the ability to transfer tangential forces in the wheel-rail contact. In the simplest form it is characterized by adhesion coefficient μ:

$$\mu = \frac{F_{tmax}}{m * g} \tag{5}$$

where F_{tmax} is the maximum traction effort that can be developed, m is adhesion mass and g is the gravitational acceleration. The most commonly used equation to determine this coefficient is the Curtius-Kniffler formula [4]:

$$\mu = \frac{7500}{V + 44} + 161 \qquad (6)$$

where V is the speed in km/h and the result is in N/kN.

The Curtius-Kniffler formula was determined by regression from measured values [4] and therefore it cannot be used in this work. It is listed to show that with increasing speed the adhesion coefficients is getting smaller. Many formulas like the Curtius-Kniffler exist, sometimes with very different results. This is because adhesion heavily depends not only on speed, but also weather and vehicle type.

A part of this work was aimed to measure the adhesion coefficient values. Based on previous theory regarding traction force and this coefficient, the needed normal wheel load and thus needed mass of the model itself can be determined [4].

MEASUREMENTS

To determine values of force needed to pull a certain load and also traction power of a model locomotive a measuring carriage designated MV-1 has been designed and build.

Fig 1. Measuring carriage MV-1 during measurements at University of Žilina.

The MV-1 is a two axle carriage build to comply with 1:8 scale model railroad [6]. The vehicle itself is not a model of any real life vehicle and was designed as a measuring device. Therefore many construction features have been simplified in order to speed up development and construction. The frame of the carriage is "H" shaped with doubled crossbar and two axles. On the front side the coupling mechanism includes a strain gauge to measure pulling force applied on the hook. Also bumpers on this side are shortened to prevent interference in measurement, while still functioning when the vehicle is being pushed. The front axle is also equipped with a magnetic encoder.

The outputs of these measuring devices are connected to a 56F8322 controller board and transferred to a computer using the Freemaster application and JTAG interface.

Fig 2. Detail of MV-1 under construction. The strain gauge and encoder can be seen on the left side.

Fig 3. One of many measuring runs. A steam locomotive model 310.017 is pulling the MV-1 and three Pa-4 platform carriages with passengers.

DATA PROCESSING

Filtering

The measured data, as shown in Fig 4, contains considerable amount of ripple. Some part of this ripple is just measurement noise, but a substantial part is caused by the sinusoidal torque produced in the steam engine.

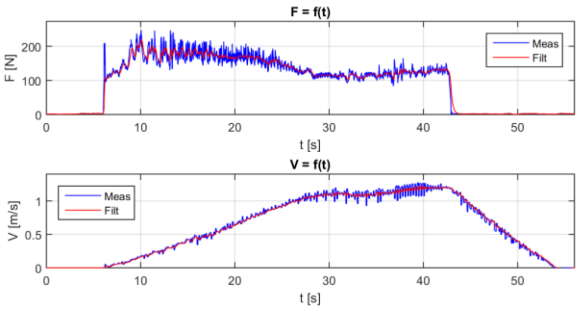

Fig 4. Example of measured and filtered values of traction force and speed.

To achieve the desire filtering result a first order Infinite Impulse Response (IIR) filter has been used based on the following discrete transfer function:

$$G(z) = \frac{B_0 + B_1 * z^{-1}}{1 - A_1 * z^{-1}} \qquad (7)$$

where A_1, $B_0$and $B_1$are filter coefficients and z is the discrete operator.

This filter was implemented with the following equation:

$$Y(n) = A_1 * Y(n-1) + B_0 * X(n) + B_1 * X(n-1) \qquad (8)$$

where n is the current step, X is input and Y is output.

Data obtained by the Freemaster application were sampled roughly at 65 Hz and a bandwidth was experimentally determined as 1 Hz. These parameters were used to calculate filter coefficients for a low pass filter. Every filtering done in this work used the same filter settings to prevent data distortion caused by different phase lag from different filter settings.

Tractive force characteristic

Filtered data from previous section was used to calculate traction power. Both force and power were plotted against speed and approximated by a quadratic function, see Fig 5.

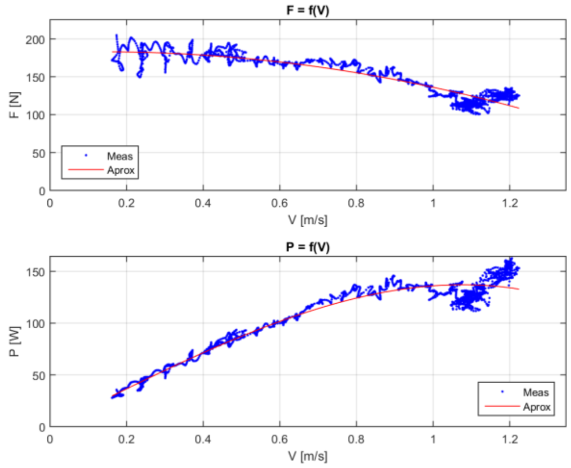

Fig 5. Force and power as functions of speed.

These graphs were created for every test. Different types of loads were applied during measuring:

- Regular operation test – these consisted up to 4 carriages (including MV-1) with a random number of passengers and were simulating regular service.
- High speed test – Only MV-1 and one Pa 3 carriage. Aim was to reach the highest speed possible on the limited track length.
- Heavy train test – With as much load as possible, the aim was to run the model train on the adhesion limit. During one test the total load reached about 1.3 tons.

Data from all of these tests were processed as described above. Traction characteristics from each test were merged into one characteristic. The merge was done by selecting the highest measured value of tractive effort for the given speed. The result is shown in Fig 6.

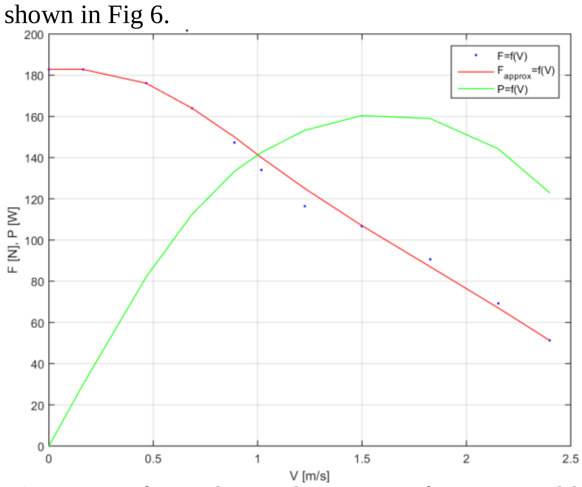

Fig 6. Tractive force and power characteristics of a 310.017 model steam locomotive.

Fig 6 shows that about 180 N of tractive effort on the locomotive coupling is enough to pull over a ton of load including the carriages. Also in regular service tractive power of 160 W is sufficient.

An important fact to note is that these values are measured at the coupling of the locomotive, meaning the power necessary to overcome the locomotive resistance is not contained in these values.

Because the locomotive model 310.017 has all three axles powered, using the maximum tractive effort and its mass (with added water in the tanks), we can calculate the maximum adhesion coefficient.

$$\mu_{max} = \frac{F_{t\,max}}{m * g} = \frac{182.3}{79.4 * 9.81} = 0.234 \qquad (9)$$

For comparison, using the Curtius-Kniffler formula **(6)** for zero speed and after conversion from N/kN we obtain the adhesion coefficient 0.33.

Vehicle resistance

Vehicle resistance was measured and processed in a similar way as described above. For this measurement, the MV-1 was turned backwards towards the locomotive and additional Pa 3 platform carriage was placed between the locomotive and the MV-1. Thus only the force required to pull load located behind the MV-1 was measured.

Rolling resistance of two Pa 3 platform carriages was measured without load and with load.

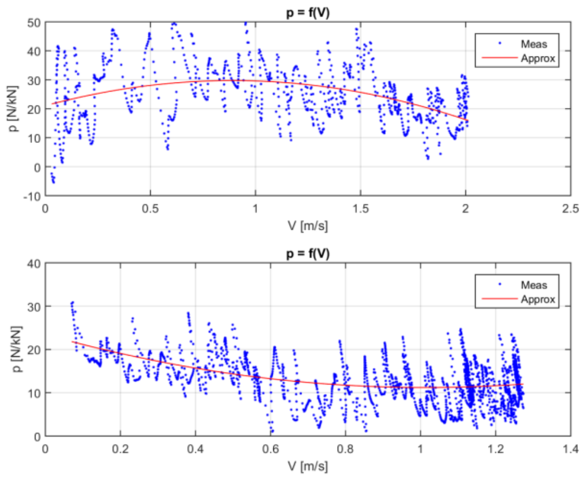

Fig 7. Specific rolling resistance of empty Pa 3 platform carriages (upper figure) and loaded Pa 3 carriages.

The measured values shown in Fig 7 were approximated by a quadratic equation according to **(4)**. It can clearly be seen, that the approximations look very differently to established theory, because the parabolas should be rising only. A possible explanation is that due to the low speeds, the shape and mutual position between the wheels and the rails has a much larger effect. Therefore only the span of the approximated values will be considered from now on.

An example equation of passenger carriages with all coefficients taken from [3] is:

$$p_o = 1.35 + 0.008 * V + 0.00033 * V^2 \qquad (10)$$

where V is speed in km/h.

Depending on the load of the carriages, their specific rolling resistance varies from 10 to 30 N/kN. If we convert the speed at which the measurements took place we get 0 to 7.2 km/h. For these speeds the formula (10) gives a span of values from 1.35 to 1.42 N/kN.

COMPARSION TO FULL SCALE RAILROAD

Comparison between the obtained results and a full scale model was made. Tab. 1 compares basic parameters of the model 310.017 locomotive with a full scale locomotive. As already implied in the introduction, while the outer mechanical arrangement is very precise to achieve model accuracy, the inner workings of the steam engines are completely different. They are modified for simplicity, easy production and maintenance. Because of this, no performance parameter after scaling matches that of the real locomotive.

Tab. 1 Comparison between the measured model and a full scale locomotive [5].

Steam locomotive model 310.017			
	Model	Full scale	Ratio
Gauge	184 mm	1 435 mm	1 : 7.8
Length over bumpers	956 mm	7 927 mm	1 : 8.3
Wheel arrangement	C	C	-
Wheel diameter	116 mm	930 mm	1 : 8
Empty weight	65 kg	30,6 t	1 : 470.8
Number of steam cylinders	2	2	1
Diameter of steam cylinders	38 mm	345 mm	1 : 9.1
Number of pipes in the boiler	20	99	1 : 5
Boiler pressure	5	11	1 : 2.2
Approximate maximum power	160 W	230 kW	1 : 1437.5
Traction force at comparable speed •	117 N	20,7 kN	1:177
Maximum speed	10 km/h	40 km/h	1:4

- Speed 40km/h for the full scale locomotive and 5 km/h for the 1:8 scaled model.

The adhesion coefficient value of 0.234 is about one third lower than the 0.33 value gained from the Curtius-Kniffler formula. However it must be noted, that the adhesion value varies significantly depending on many factors. The weather on the measurement day was rainy, but this was partly compensated with sanding the tracks.

Measured specific rolling resistances are much higher on the model railroad than in the full scale and also the curves don't show the appropriate trend. This can be explained by the low speed at which the measurements were conducted.

CONCLUSIONS

The main goal of this work was to provide necessary data to enable usage of traction mechanics theory in the 1:8 scale model railroads. For this purpose, the MV-1 carriage has been designed and build to measure traction force and train speed. Also weight of the locomotive, carriages and load has to be known. These values are sufficient to determine locomotive power, adhesion and train rolling resistance.

The results were analyzed and compared to full scale railroad. It was confirmed that while visually accurate, the performance parameters doesn't change according to scale. Also while performance parameters of the model locomotive were lower, the specific resistance is much higher. Despite this, the achieved model speed after scaling was twice larger.

While this work provides necessary theory, creation of corresponding measuring device and data analysis methodology, it only works with data from few measurements. Additional measurements need to be performed, particularly focused on different vehicles on similar track layouts, in order to provide a comprehensive database of the performance parameters for different vehicle types.

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