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DIGITAL TRACTION FORCE METER FOR MODEL TRAINS

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Abstract: Nowadays, model trains have become more and more complex, in order to replicate their real-life counterparts as closely as possible. However, miniaturization may negatively influence the traction power of locomotives because their reduced weight impedes the adhesion of their driven wheels on the tracks. Thus, the miniature trains should match the traction power of their locomotives to avoid wheelslip. There have been some attempts to assess the traction power of model locomotives using strings, pulleys and weights, and also custom-made railway-cars were used for this purpose. Along with these attempts, the authors of this paper designed and made a digital measuring device for traction force using a pressure transducer, an adequately programmed microcontroller and a 16×2 LCD screen. The results of the measurements proved to be consistent, stable and reproducible, and showed the differences between several model locomotives.

Key words: model trains, traction force, adhesion, transducer, microcontroller, measurement.

1. INTRODUCTION

The modern model trains are designed, engineered and built using state-of-the-art technologies, so that they can copy the features of their real-life counterparts, such as shapes, colours, sounds, speed, operation modes etc. In order to do so, they are fitted with one or more high-performance motors and actuators, multiple LED lights, loudspeakers, smoke generators, spark simulators etc., and all these components are driven by a digital decoder. Several abilities and some technical knowledge are required to adequately drive such modern model trains, along with some hardware items, such as the central digital command station, handheld controllers, digital boosters, stabilized power supplies, carefully designed railroad tracks etc. In order to replicate the real trains, it is also necessary to observe their length and their number of cars, which can become a problem because the traction power of the miniature locomotives, already limited by their reduced weight and wheel-to-track adhesion, may sometimes not be enough to haul such realistic trains. In such cases, the driven wheels of the locomotive may slip on the rails or may even not turn at all. There are some multiple aspects to be considered, such as the weight of the train cars, their number, the friction between their moving mechanical elements etc., and the traction power of the locomotive itself must be assessed. There have been some attempts to measure the traction power of miniature locomotives by means of weights, strings and pulleys [1] or by means of custom-built measuring cars [2]. In addition to these measuring methods, the authors of this paper designed and made a digital measuring device for traction force using a pressure transducer, an adequately programmed microcontroller and a 16×2 LCD screen. This device shows the maximum and minimum values of the traction force expressed in grams or Newtons, which allows the user to rank the model locomotives according to this criterion, which is very important among the other quality criteria. Several versions of the microcontroller program and measuring algorithm were tested, along with two different pressure sensors. The results of the measurements proved to be consistent, stable and reproducible, and showed the differences between the model locomotives made by several manufacturers, lighter, heavier, with or without rubber traction tires, with more or less driven wheelsets etc.

2. MATERIALS AND METHODS

This digital measuring device assesses the traction power of the locomotive under test by getting it to push against the pressure transducer as shown in Figure 1. The electronic diagram of the device and the design of its printed circuit board are shown in Figure 2.

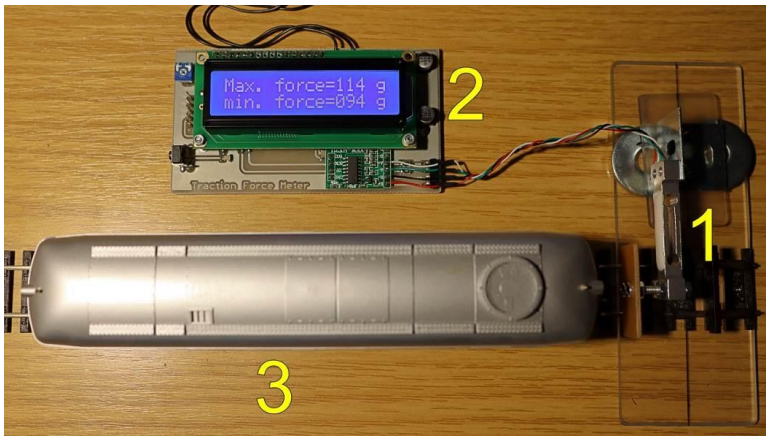

Fig. 1. Digital Traction Force Meter:
1 – pressure transducer, 2 – digital measuring device with display, 3 – locomotive under test.

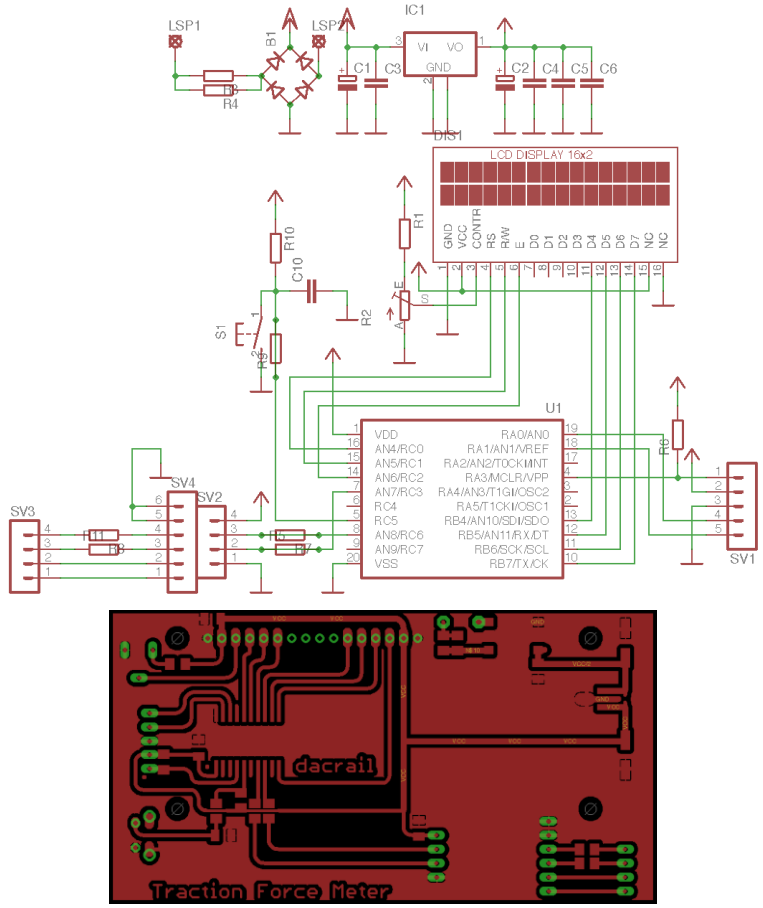

Fig. 2. Traction Force Meter – electronic diagram (left) and PCB design (right).

The main component of the traction force meter is the microcontroller PIC16F677 [3]. The pressure transducer, basically consisting of a Wheatstone bridge [4], yields a very weak electric output signal which gets 128× preamplified and converted analog-to-digital by the dedicated digital load-cell module HX711 [5] in order to be fed to the microcontroller for processing. Due to its custom-made software, the microcontroller is able to process the signal and to show the results on the 16×2 LCD screen.

After power-up, the software calls a self-calibrating routine which includes a two second warm-up time, and then the device enters a standby state, waiting for the transducer to be pressed. The user drives the locomotive under test towards the pressure transducer with the smallest speed possible, such as speedstep 1 of 28. When the palette of the pressure transducer is touched, the device waits for one second for the oscillations to damp down, and then starts to acquire the data. The software performs 10 readings per second, memorizing and displaying the maximum and minimum values. The measurement ends if ten seconds pass without any more changes of the above-

mentioned readings. The displayed measurement units can be changed from grams to Newtons by pressing the microswitch button *S*1.
The pressure transducer (Figure 3) is a 500g load-cell with 12 units per gram sensitivity. Its output signal is proportional to the weight that is senses, expressed in grams, and the software can convert it into force units by multiplication with the gravitational acceleration 9.80665 m/s^2 (Figure 4). An excerpt of the software in assembly language is shown in Figure 5.

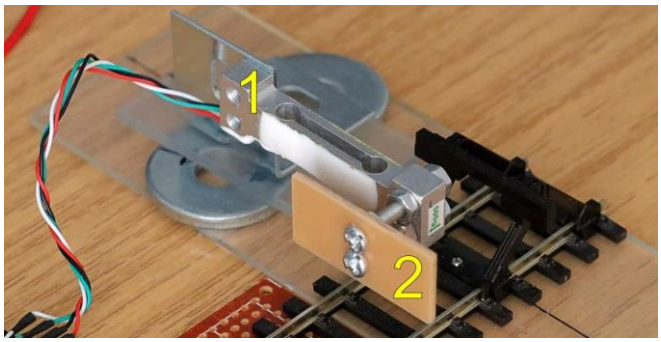

Fig. 3. The pressure transducer; 1 – 500g load-cell, 2 – palette.

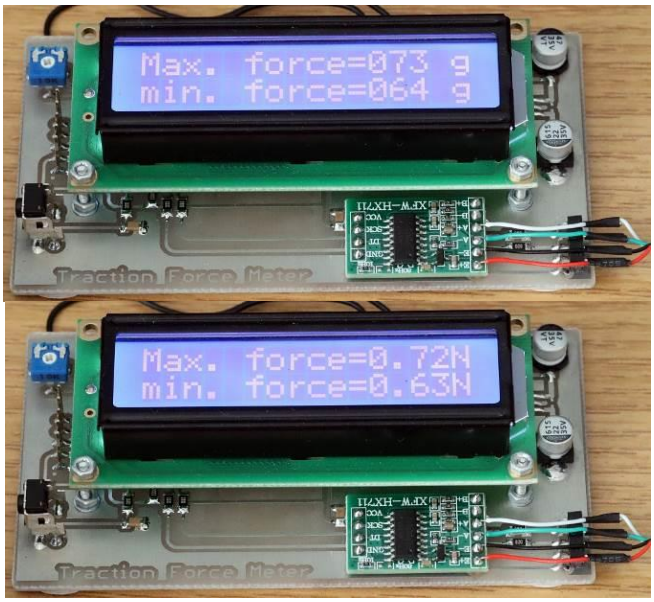

Fig. 4. Measuring units: grams (left) or Newtons (right).

```
;MAIN PROGRAM
        clrf    maxH
        clrf    maxL
        clrf    minH
        decf    minH,f
        clrf    minL
        decf    minL,f
        movlw   .10             ;10 sec counter
        movwf   count3          ;w/o force increasing
main    movlw   .10             ;10 readings/sec
        movwf   count2
read    call    hx711           ;reading in hx10
        movfw   Bx0             ;substract B coef.
        subwf   hx0,f
        btfss   STATUS,0
        decf    hx1,f
        movfw   Bx1
        subwf   hx1,f           ;force (raw) in hx10
        movlw   b'11100000'
        andwf   hx1,w
        btfss   STATUS,2
        goto    ovl             ;overload >= 680g
        call    x1000           ;hx10 -> X3210
        movlw   0x2f
        movwf   hx1
        movlw   0x0b
```
Fig. 5. The software for the microcontroller, written in assembly language (excerpt).

3. RESULTS AND DISCUSSION

This measurement device shows the maximum and minimum values of the traction force exerted by the locomotive under test. The maximum value of the traction force corresponds to the point where the locomotive starts to lose adhesion and wheelslip begins, combined with the abrupt deceleration of the locomotive when it touches the palette of the pressure transducer, and this is the reason to choose the minimum possible speed for the test. The minimum value can be interpreted as a "worst-case scenario" when the adhesion is completely lost and only the coefficient of sliding friction wheels-to-rails is still present. The traction power of a locomotive depends on many factors, such as its weight, its motor torque, its number of axles (driven or not, fitted with rubber traction tires or not, sprung or not), the weight distribution over the driven axles etc., and it is important to assess this parameter in order to safely drive trains over the railway system, either real [6] or model.

Table 1. Locomotives under test – H0 (1:87) collection of Mr.Ursu.

Nr.	Locomotive	Type	Manufacturer	Mass (g)	ηmed (%)	Fmed (g)	Fmed (N)	Fmax (N)	Fmin (N)	Fmax (g)	Fmin (g)	ηmax (%)	ηmin (%)
1	BR01.5	steam	Roco	509	14	71.00	0.70	0.83	0.57	84.33	57.67	16.57	11.33
2	BR012	steam	Roco	539	24	130.00	1.27	1.44	1.11	146.33	113.67	27.15	21.09
3	BR03	steam	Piko	651	16	106.17	1.04	1.24	0.85	126.00	86.33	19.35	13.26
4	BR52	steam	Roco	507	11	54.00	0.53	0.78	0.28	79.33	28.67	15.65	5.65
5	BR64	steam	Gützold	240	21	51.50	0.51	0.65	0.36	66.00	37.00	27.50	15.42
6	BR64	steam	Roco	205	25	50.33	0.49	0.54	0.44	55.33	45.33	26.99	22.11
7	BR78	steam	Piko	389	20	78.67	0.77	0.93	0.61	95.00	62.33	24.42	16.02
8	BR80	steam	Roco	216	18	38.67	0.38	0.42	0.34	43.00	34.33	19.91	15.90
9	BR95	steam	Roco	389	35	134.67	1.32	1.50	1.14	152.67	116.67	39.25	29.99
10	CFR 150	steam	Roco / T.A.	507	21	106.83	1.05	1.31	0.78	134.00	79.67	26.43	15.71
11	CFR 60	diesel	MTB	594	17	98.33	0.96	1.01	0.92	103.33	93.33	17.40	15.71
12	CFR 65	diesel	MTB	591	15	87.67	0.86	0.94	0.77	96.33	79.00	16.30	13.37
13	V60	diesel	Roco	268	23	62.50	0.61	0.72	0.51	73.00	52.00	27.24	19.40
14	BR144	electric	Brawa	410	18	72.17	0.71	0.87	0.55	88.33	56.00	21.54	13.66
15	BR152	electric	Roco	489	21	100.83	0.99	1.07	0.91	108.67	93.00	22.22	19.02
16	BR244	electric	Roco	381	20	76.50	0.75	0.79	0.71	80.67	72.33	21.17	18.99
17	E10	electric	Roco	456	20	90.67	0.89	0.97	0.80	99.33	82.00	21.78	17.98
18	E69	electric	Fleischmann	199	14	28.83	0.28	0.34	0.22	35.00	22.67	17.59	11.39
19	E69	electric	Piko	163	20	32.83	0.32	0.37	0.27	38.00	27.67	23.31	16.97

The authors measured the traction power of some locomotives from their collections (table 1). The traction forces of the locomotives were measured three times each, and the railway tracks were cleaned with an adequate rubber block after each test. The maximum and minimum forces (F_{max} / F_{min}) were measured in grams and converted to Newtons by the measuring device itself, then their average values (F_{med}) were inserted in this table. As there are mentions about the traction power of a well-balanced locomotive being more or less equivalent to 25% percent of its mass [7], we computed also the ratio of the average traction force versus the mass of the locomotive (η_{med}).
Of the locomotives under test, the most powerful locomotive was BR95 by Roco [8] (Figure 6), with the traction force of 1.32 N (134.67 g), which represents 35% percents of its weight (389 g). Surprisingly, this locomotive is

not the heaviest one, but it is very well balanced, with seven axles of which five are driven, and one of the driven axles is fitted with rubber traction tires in order to increase adhesion.

Fig. 6. Steam locomotive BR95 by Roco, scale 1:87 – collection of Mr.Ursu.

The least powerful locomotives under test are E69 by Piko and E69 by Fleischmann [9] (Figure 7), which are also the lightest (Piko 163 g, Fleischmann 199g). They have two driven axles and no rubber traction tires, and they developed 0.32 N (Piko) and 0.28 N (Fleischmann), which represent 20% and 14% percents of their weights. The older Piko version is slightly lighter but slightly stronger than the newer Fleischmann version.

Fig. 7. Electric locomotives E69 by Piko (left) and E69 by Fleischmann (right), scale 1:87 – collection of Mr.Ursu.

The influence of the rubber traction tires was also studied by means of locomotives E10 by Roco for passenger trains and BR152 by Roco for freight trains (Figure 8). They both have four driven axles, of which one is fitted with rubber traction tires. For each locomotive, the authors got one spare wheelset without rubber traction tires and carried out the measurements on two conditions: with and without traction tires (Table 2).

Table 2. Influence of rubber traction tires – H0 locomotives (1:87) – collection of Mr.Ursu.

Locomotive	Traction Tire	Mass (g)	η_{med} (%)	F_{med} (g)	F_{med} (N)	F_{max} (g)	F_{min} (g)	F_{max} (N)	F_{min} (N)
E10	yes	456	20	90.67	0.89	99.33	82.00	0.97	0.80
E10	no	456	16	72.83	0.71	78.00	67.67	0.76	0.66
BR152	yes	489	21	100.83	0.99	108.67	93.00	1.07	0.91
BR152	no	489	15	71.50	0.70	76.33	66.67	0.75	0.65

As expected, the traction power of both locomotives decreased with almost 25% when their wheelsets with rubber traction tires were replaced by normal ones (Figure 9).

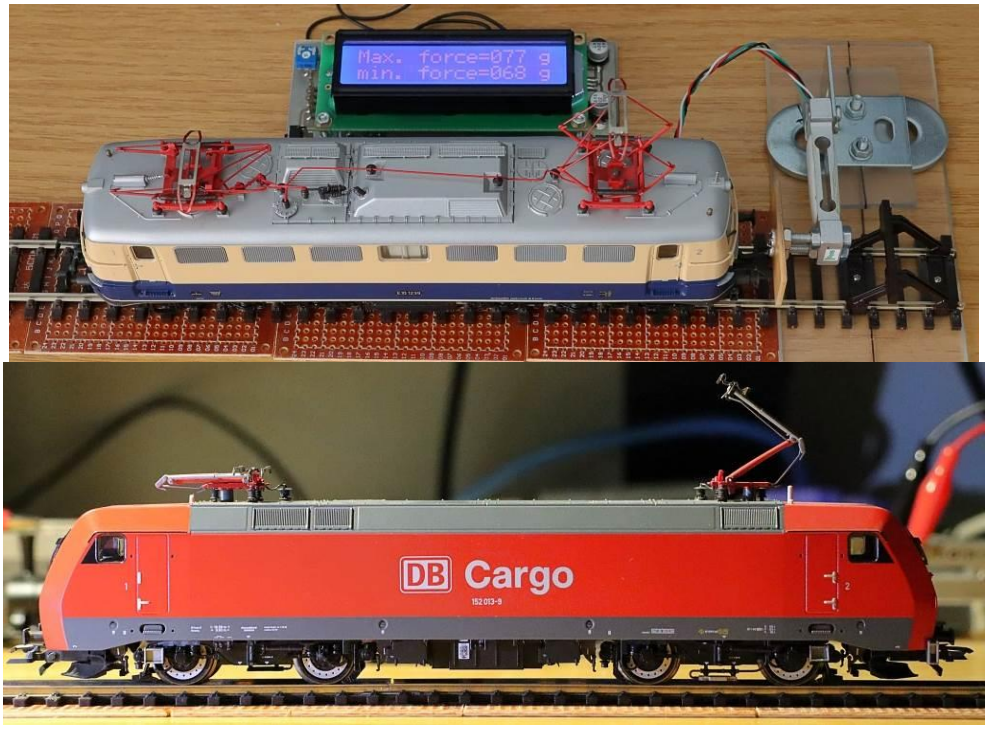

Fig. 8. Electric locomotives E10 (up) and BR152 (down).

Fig. 9. Wheelsets with and without rubber traction tires, for E10 (left) and for BR152 (right).

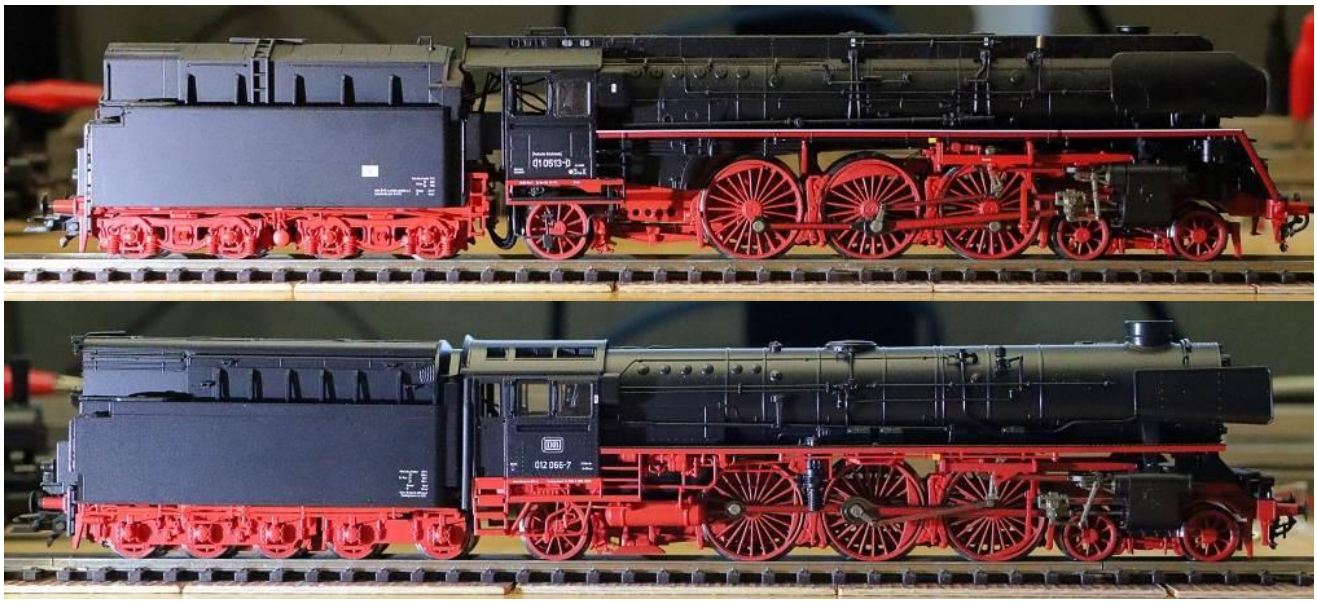

Fig. 10. Express passenger steam locomotives: BR01.5 by Roco (up), BR012 by Roco (middle), BR03 by Piko (down) – scale H0 (1:87) – collection of Mr.Ursu.

Three express passenger steam locomotives were also compared: BR01.5 by Roco, BR012 by Roco and BR03 by Piko (Figure 10). Even if they look similar and their motors are placed into their tenders, they all have their own particularities which make the difference in terms of traction power.

Table 3. Express passenger steam locomotives BR01.5 by Roco, BR012 by Roco and BR03 by Piko – H0 (1:87) collection of Mr.Ursu.

Nr.	Locomotive	Type	Manufacturer	Mass (g)	ηmed (%)	Fmed (g)	Fmed (N)	Fmax (N)	Fmin (N)	Fmax (g)	Fmin (g)
1	BR01.5	steam	Roco	509	14	71.00	0.70	0.83	0.57	84.33	57.67
2	BR012	steam	Roco	539	24	130.00	1.27	1.44	1.11	146.33	113.67
3	BR03	steam	Piko	651	16	106.17	1.04	1.24	0.85	126.00	86.33

Locomotive BR01.5 by Roco is the lightest and the less powerful of all three. Its motor drives the last two tender axles fitted with rubber traction tires and also drives the three main driver wheelsets of the locomotive by means of a cardan shaft, thus this locomotive has five driven axles.

Locomotive BR012 by Roco is heavier than BR01.5 and the most powerful of all three. Its motor drives the last three tender axles fitted with rubber traction tires and also drives the three main driver wheelsets of the locomotive by means of a cardan shaft, thus this locomotive has six driven axles. It is also newer than BR01.5, so its six rubber traction tires grip the rails better.

Locomotive BR03 by Piko is the heaviest and the oldest of all three, and it is more powerful than BR01.5. Its motor drives only the last three tender axles fitted with rubber traction tires, but the main driver wheelsets of the locomotive are not driven at all. Thus, the locomotive itself (cab and boiler) is only pushed/pulled by the tender, so the weight of the entire locomotive is distributed unevenly on its driven wheels, which explains its surprisingly low efficiency.

Also, when the same model locomotive is built by several different manufacturers, each of them has its own features and capabilities, which will have the adequate effects on their traction power.

Fig. 11. Steam locomotives BR64, made by Gützold in 1968 (left) and by Roco in 2008 (right) – scale 1:87, collection of Mr.Ursu.

The older Gützold version of BR64 is heavier and slightly stronger than the newer Roco version, but the Roco version is more efficient because it is better balanced, the last main driver wheelset is fitted with rubber traction tires and the middle main driver wheelset is sprung (Figure 11, Table 4).

Table 4. Steam locomotives BR64 by Gützold and by Roco – H0 (1:87) collection of Mr.Ursu.

Nr.	Locomotive	Type	Manufacturer	Mass (g)	η_{med} (%)	F_{med} (g)	F_{med} (N)	F_{max} (N)	F_{min} (N)	F_{max} (g)	F_{min} (g)	η_{max} (%)	η_{min} (%)
5	BR64	steam	Gützold	240	21	51.50	0.51	0.65	0.36	66.00	37.00	27.50	15.42
6	BR64	steam	Roco	205	25	50.33	0.49	0.54	0.44	55.33	45.33	26.99	22.11

Fig. 12. Electric locomotives BR144 by Brawa (left) and BR244 by Roco (right) – scale 1:87, collection of Mr.Ursu.

The real-life electric locomotives BR144 and 244 are virtually identical, with several functional differences which are not replicated on their 1:87 models. BR144 by Brawa is heavier than BR244 by Roco, but it develops slightly less power and efficiency (Figure 12, Table 5).

Table 5. Electric locomotives BR144 by Brawa and BR244 by Roco – H0 (1:87) collection of Mr.Ursu.

Nr.	Locomotive	Type	Manufacturer	Mass (g)	ηmed (%)	Fmed (g)	Fmed (N)	Fmax (N)	Fmin (N)	Fmax (g)	Fmin (g)	ηmax (%)	ηmin (%)
14	BR144	electric	Brawa	410	18	72.17	0.71	0.87	0.55	88.33	56.00	21.54	13.66
16	BR244	electric	Roco	381	20	76.50	0.75	0.79	0.71	80.67	72.33	21.17	18.99

Two copies of the same model locomotive, made by the same manufacturer, can perform differently because of their different operating time, considering that their rubber traction tires experience wear and tear. Locomotives BR52 and CFR150 are virtually identical, but CFR150 is stronger because it is newer (Figure 13, Table 6).

Fig. 13. Steam locomotives BR52 by Roco (up) and CFR150 Roco & T.A. (down) – scale 1:87, collection of Mr.Ursu.

Table 6. Steam locomotives BR52 and CFR150 – H0 (1:87) collection of Mr.Ursu.

Nr.	Locomotive	Type	Manufacturer	Mass (g)	ηmed (%)	Fmed (g)	Fmed (N)	Fmax (N)	Fmin (N)	Fmax (g)	Fmin (g)	ηmax (%)	ηmin (%)
4	BR52	steam	Roco	507	11	54.00	0.53	0.78	0.28	79.33	28.67	15.65	5.65
10	CFR 150	steam	Roco / T.A.	507	21	106.83	1.05	1.31	0.78	134.00	79.67	26.43	15.71

It is interesting to see that the two similar diesel locomotives CFR60 and CFR65 by MTB have almost the same good traction power (0.96 N / 0.86 N), in spite of the fact that they are not fitted with rubber traction tires. Such good driving characteristics are explained by their six driven axles and the even weight distribution over them (Figure 14, Table 7).

Fig. 14. Diesel locomotives CFR65 (left) and CFR60 (right) by MTB – scale 1:87, collection of Mr.Ursu.

Table 7. Diesel locomotives CFR60 and CFR65 by MTB – H0 (1:87) collection of Mr.Ursu.

Nr.	Locomotive	Type	Manufacturer	Mass (g)	η_{med} (%)	F_{med} (g)	F_{med} (N)	F_{max} (N)	F_{min} (N)	F_{max} (g)	F_{min} (g)	η_{max} (%)	η_{min} (%)
11	CFR 60	diesel	MTB	594	17	98.33	0.96	1.01	0.92	103.33	93.33	17.40	15.71
12	CFR 65	diesel	MTB	591	15	87.67	0.86	0.94	0.77	96.33	79.00	16.30	13.37

4. PC-ASSISTED VERSION

In addition to the standalone version of the digital traction force meter, the authors designed and built a PC-assisted version, which basically consists of the same pressure transducer and HX711-based interface, but connected to PC by means of a USB module (Figure 15). This version uses another custom-made software which allows the PC to perform the same measurements as described above and, in addition, the measurements are all memorized. The raw values are converted by the software into grams and Newtons, and then the authors converted these values into graphs. Figures 16 to 20 show five 1:87 locomotives from the collection of Mr.Condruz and the measurements of their traction forces, expressed in grams, versus the number of measurements. They all have four driven axles and two rubber traction tires placed diagonally on two wheels.

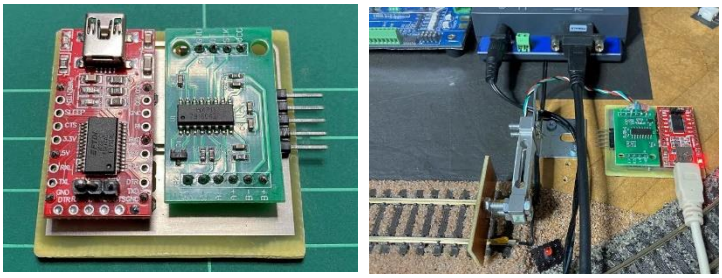

Fig. 15. PC-assisted digital traction force meter.

Fig. 16. Electric locomotive BR101 Expert by Piko – scale 1:87, collection of Mr.Condruz.

The electric locomotive BR101 Expert by Piko weighs 569 grams, and it develops traction forces between 170 ÷ 182 g, so its average efficiency is 30.93%.

Fig. 17. Electric locomotive BR146 Expert by Piko – scale 1:87, collection of Mr.Condruz.

The electric locomotive BR146 Expert by Piko weighs 469 grams, and it develops traction forces between 129 ÷ 159 g, so its average efficiency is 30.38%.
The electric locomotive BR147 Expert by Piko weighs 419 grams, and it develops traction forces between 99 ÷ 128 g, so its average efficiency is 27.09%.

Fig. 18. Electric locomotive BR147 Expert by Piko – scale 1:87, collection of Mr.Condruz.

Fig. 19. Diesel locomotive BR245 Expert by Piko – scale 1:87, collection of Mr.Condruz.

The diesel locomotive BR245 Expert by Piko weighs 431 grams, and it develops traction forces between 179 ÷ 201 g, so its average efficiency is 44.08%.

Fig. 20. Electric locomotive Rh E190 Expert by Piko – scale 1:87, collection of Mr.Condruz.

The electric locomotive Rh E190 Expert by Piko weighs 440 grams, and it develops traction forces between 101 ÷ 111 g, so its average efficiency is 24.09%.
The graphs show different behaviours of these five locomotives, according to their mass and age. All graphs show periodicity, according to the wheel rotation while slipping on the rails. The increasing values show that the adhesion is better due to newer rubber traction tires, and the relative constant maximum and minimum values and/or the lower differences between them show that the adhesion is lower because of the older rubber traction tires. BR245 is the strongest and most efficient, and Rh E190 is the weakest and the least efficient.

Fig. 21. Railway repair equipment PT 07-16 by Bachmann – scale 1:87, collection of Mr.Condruz.

We have also tested the railway service and repair equipment PT 07-16 by Bachmann (Figure 21), which weighs only 99 grams, is not fitted with rubber traction tires and is not meant to haul anything. It develops traction forces between 9 ÷ 10 g, so its average efficiency is 9.60%. The graph shows the raw values yielded by the measuring device, because the values expressed in grams are way too close.

5. CONCLUSIONS

The digital traction force meter, either standalone or PC-assisted, proved itself to be very useful to measure the traction power of the model locomotives, so that they can be classified and ranked according to this important driving characteristic. The pressure transducer, made of a load-cell, got along very fine with the electronic devices that collected its data. The microcontroller, due to its custom-made software, is able to process the data yielded by the pressure transducer, so that the results can be displayed and easily read on the LCD display, either in grams or in Newtons. The readings were consistent, repeatable and reliable, which allowed the authors to perform a great deal of measurements upon their model trains, with results that can be trusted.
Working with microcontrollers, analog-to-digital converters, load-cells and other such devices proved to be challenging, but also interesting and rewarding. Other ideas of improvement are on their way, such as usage of databases, bidirectional sensing (pushing and pulling) etc.

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