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INVESTIGATION OF FUEL CONSUMPTION OF NON-SCHEDULED TRAINS THERMAL TRACTION

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Abstract. This article deals with the calculation of fuel consumption of trains with unpredicted scheduling (non-scheduled trains). The need for such investigation was stimulated by the fact that because of many operational and technical reasons when trains lag behind their original schedule and further train routing becomes unscheduled and unpredicted, quite considerable amount of fuel is lost for unexpected train stopping and speeding to reach the previous original running speed. Theoretical approach is presented in this article with the estimation of train-track interaction and resistance factors. The object of this research has typical characteristics of an ordinary train with a thermal locomotive 2TЭ10M which weights 276 tons and 50 wagons, each of them weighting 40 t. Calculated results are presented for different running scenarios.

Keywords: thermal traction, fuel consumption, non-scheduled train traffic, relative resistance, train-track interaction, wear.

1. Introduction

At present railways tend to loose their market position in passenger and freight transportation in Lithuania because of the following reasons, but not only limited to:

- Hard competition from private and state transportation companies;
- Poor permanent way and signaling infrastructure, moderate throughput;
- Bad traffic organization- considerable deviation from train traffic schedules (late arrivals and departures), long delays at intermediate stations (especially for freight trains), unexpected train stops (derived from spontaneous railways traffic management).

It is a well-known fact that for unexpected stopping and starting of a train additional amount of fuel is consummed (some 50–60 l for an average statistical freight train). Thus some 15 % of fuel is wasted (electricity or liquid fuel) on the average train trip because of unpredicted stops on the route.

Another upsetting fact is that at intermediate stations freight trains are forced to wait for authority permission to enter the line and stay there with the engine running idle, for about some 30 % of the whole journey time. Analysis shows that some 30 % of passenger trains at intermediate stations are late for at least 5 min. Such delays are mostly because of the bad routing control (longer delays as a rule derive from serious technical faults or organizational difficulties that are characteristic of international routes).

The above-mentioned facts (bearing in mind the existing train traffic intensity) show that the existing Lithuanian railways traffic management system is ineffective both from an operational and technological point of view (less than a half of the existing throughput capacity is utilized). The abovementioned problems can be solved either by changing traffic management platform (operational approach) or by rectifying technical problems (technological approach). For the railways operators, of course, consummated fuel is a more important fact than late non-scheduled arrivals. Usually fuel consumption is researched as a function of optimal traction force, which is influenced by the train-track interaction. The latter is modeled and discussed [1–4].

In this article our purpose was to focus on investigating various fuel consumption issues for thermal traction.

We have chosen non-scheduled trains, as an object of our research, because such research object permitted us to combine both train-track interaction (and traction influence) and the influence of unpredicted stops and runs.

We have concentrated on this issue, by utilizing some facts about the efficient fuel consumption for a thermal traction case. Various train fuel consumption issues were researched and are analyzed in this article.

2. Relative fuel consumption: a theoretic approach

Relative fuel consumption for a standard thermal traction norm= 10 000 t*km (brutto) can be calculated as follows:

$$a_T = n_p + n_T + n_{st} + n_x , \qquad (1)$$

where n_p – is relative fuel consumption for keeping a train running [kg]; n_T – relative fuel consumption for regaining the original speed after stop [kg]; n_{st} – relative fuel consumption derived because of stopping; n_x – relative fuel consumption derived from idle run [kg].

Whereas relative fuel consumption for keeping the train running could be obtained from this:

$$n_p = n_0 k_i k_t k_\mu , \qquad (2)$$

where n_0 – is initial norm of consummated fuel for running the train; k_i – coefficient characterizing road profile; k_μ – coefficient characterizing utilization of the possible wagon load; k_t – coefficient characterizing environment (mostly temperature is important in our case):

$$k_t = 1 + \left(0{,}00032t' - 0{,}0046\right)\Delta t_v^0 , \qquad (3)$$

where Δt_v^0 is interval of temperatures from t° to 15°, as a difference from the average environmental temperature.

The initial fuel consumption norm for 10 000 t*km is as follows:

$$n_0 = S + (R + T/Q)\omega_0 , \qquad (4)$$

where S, R, T are coefficients characterizing the engine of a thermal locomotive; they are taken from the locomotive fuel technical passport; ω_0 is relative resistance against train movement [kg/t].

Relative resistance against train movement can be obtained from this:

$$\omega_0 = \left(R_l \omega_0' + Q_{br}\omega_0''\right) / \left(R_l + Q_{br}\right), \qquad (5)$$

where R_l – is mass of a locomotive [t]; Q_{br} – train mass [t].

Relative resistance against train movement in case of standard rails:

$$\omega_0' = a_T'\left(2{,}4 + 0{,}01v_x + 0{,}00035v_x^2\right); \qquad (6)$$

in case of long rails:

$$\omega_0' = a_T'\left(2{,}4 + 0{,}009v_x + 0{,}00035v_x^2\right), \qquad (7)$$

where a_T' – is a correction coefficient (for idle run it is equal to 1,1); v_x – is a train speed, for which we will be calculating fuel consumption later.

Relative resistance against wagon movement is:

1) in case of ordinary road:

$$\omega_o'' = \omega_{0ps}''\alpha_{ps} + \omega_{0pr}''\alpha_{pr} \qquad (8)$$

with sliding-bearing:

$$\omega_{0ps}'' = \left(0{,}7 + \frac{8 + 0{,}1v_x + 0{,}0025v_x^2}{q_0}\right)a_T' ; \qquad (9)$$

with ball-bearing:

$$\omega_{0pr}'' = \left(0{,}7 + \frac{3 + 0{,}1v_x + 0{,}0025v_x^2}{q_0}\right)a_T' ; \qquad (10)$$

2) for long rails:

$$\omega_0'' = \omega_{0ps}''\alpha_{ps} + \omega_{0pr}''\alpha_{pr} ; \qquad (11)$$

with sliding-bearing:

$$\omega_{0ps}'' = \left(0{,}7 + \frac{8 + 0{,}08v_x + 0{,}002v_x^2}{q_0}\right)a_T' ; \qquad (12)$$

with rolling bearing:

$$\omega_{0pr}'' = \left(0{,}7 + \frac{3 + 0{,}09v_x + 0{,}002v_x^2}{q_0}\right)a_T' , \qquad (13)$$

where α_{ps}, α_{pr} – part of freights transported with wagons equipped with sliding-bearing or ball-bearing; q_0 – wagon axle load for the average statistic train is equal to 17,5 t; a_T' – coefficient of correction used for the calculation of the main relative resistance against the "idle" run, which is usually calculated for the overall running time.

Additional fuel consumption for regaining the original train speed after the stopping, is expressed for a single stop as follows:

$$n_T' = 0{,}515 \cdot 10^{-5}\frac{R_l + Q_{br}}{Q_{br}}v_x^2\left[102\left(1 + \gamma'\right) - \frac{\omega_0}{a_T}\right], \qquad (14)$$

where γ' – is a spinning mass inertia coefficient (and is equal to 0,028 for loaded wagon; the average value for a statistical LG train with thermal traction is equal to 0,035); a_T – train stopping acceleration, for the average statistical LG train it is equal to 0,22 m/s^2.

Additional fuel consumption for regaining the original train speed after the stopping, when calculated for the complete railways section, is as follows:

$$n_T = n_T' z' ; \tag{15}$$

where z' is a relative number of stops for calculated railways section, which is achieved dividing a number of train stops by the length of the section and multiplying by 100.

Additional devices and gears in the locomotive also consume some fuel n_x', which is usually added to the initial quota and can be obtained from the following:

$$n_x'' = n_x + n_{st} = n_x' \left(k_x + k_x' \Theta \right), \tag{16}$$

where: n_x' is relative fuel consumption for idle run without stopping; k_x is a coefficient describing idle run durations; k_x' is a coefficient characterizing stops with engine turned on, calculated as a rate to the whole stop time; θ is a coefficient characterizing rate of stops versus run time.

Thus, relative fuel consumption for continuous run without breaks could be obtained from the following:

$$n_x' = 10^4 \sigma_x / Q_{br} v_T , \tag{17}$$

where σ_x – is hourly diesel fuel consumption norm [kg/h].

Then relative fuel consumption for idle run and stops is as follows:

$$n_x'' = \frac{10^4 \sigma_x}{Q_{br} v_T} \left(k_x + k_x' \Theta \right). \tag{18}$$

A coefficient of idle run depends on the speed, road profile and can be found from the following:

$$k_x = 0{,}775 - 0{,}0096 v_T - \frac{v_T - 11{,}5}{234} i_E , \tag{19}$$

where i_E is a coefficient characterizing route curves.

Thus, a coefficient, characterizing time duration with engine turned on, calculated as a rate with the overall stop time, depends not only on the stop duration, but also on environmental conditions. On the average this coefficient is equal to 0,5.

A coefficient, characterizing overall stop duration, calculated as a rate with the overall run time, depends on traffic intensity and the number of stops. On the average it is equal to 0,351 – 0,59 for thermal locomotives.

3. Calculation of consumed fuel for non-scheduled trains

Fuel consumption for the stopping of a train (^{st}W) expresses energy consumed to stop the train, and then to recover its previous original speed. Usually such fuel consumptions are estimated by applying fundamental laws of mechanics. But in this case many factors are ignored, such as resistance of the air and road, inertia of spinning mass, energy consumed for stopping and so on. Therefore we will try to use analytic-empiric way for calculating ^{st}W [5]. In case of thermal traction, the amount of consumed fuel for stopping the train, and then recovering its original speed can be found from:

$$^{st}W = 0{,}515 \times 10^{-5} v_\beta^2 \left[102(1+\gamma') - \frac{\omega_{0\beta}}{a_T} \right] \frac{Q_\beta}{100} . \tag{20}$$

Also, fuel consumption for a continuously running train can be expressed as follows:

$$n_0 = \frac{S + \left(R + T / Q \right) \omega_0}{10000} , \tag{21}$$

where V_β – speed of the β-th train [*m/s*]; Q – train mass (locomotive plus wagons) [*kg*]; γ' is spinning masses inertia coefficient ($\gamma' = 0{,}035$); ω_0 – relative resistance against movement of the train [5]; *S, R, T* – are appropriate coefficients from technical passports of locomotives; a_T – train stopping acceleration; let it be equal to

$$a_T = 0{,}22 \frac{m}{s^2} . \tag{22}$$

For our research we will select a standard LG train, consisting of a thermal locomotive 2TЭ10M which weights 276 t, with the following parameters: G=4,1; M=9,4; N=4700; having 50 wagons, each of them weighs 40 t.

We assume that our train will run via a section of straight road without any curves, on long-rails, under normal temperature and environmental conditions, wagons are fitted with ball bearing.

The result of our calculation is the fuel consumption for stopping a train and then speeding up to regain its previous original speed after stopping. The result is displayed in Table 1.

Column 5 contains relative resistance for wagons, calculated by applying formula (13).

Relative resistance for locomotive (column 6) was calculated from formula (7).

Average relative resistance of a train (column 7) is calculated by applying formula (5).

Fuel consumption (column 8), in order to reach the needed speed (column 4) was found by applying formula (20).

Train fuel consumption for the train, running 100 km distances, when the train runs via a section of railroad without any curves and under normal temperature and environmental conditions with wagons that are equipped with ball bearings, was calculated and results are shown in Table 2.

Table 1. Fuel consumption when a train is stopped and started to regain its previous original speed

Mass of a locomotive [t]	Mass of a wagon [t]	Number of wagons [pcs]	Speed which must be reached [km/h]	Relative resistance of wagons	Relative resistance of locomotive	Average relative resistance	Fuel consumption [kg]
1	2	3	4	5	6	7	8
276	40	50	10	0,17655	0,5555	0,222503515	1,23
			20	0,1848	0,5984	0,23495536	4,90
			30	0,19525	0,6567	0,251207909	11,02
			40	0,2079	0,7304	0,27126116	19,57
			50	0,22275	0,8195	0,295115114	30,54
			60	0,2398	0,924	0,322769772	43,93
			70	0,25905	1,0439	0,354225132	59,71
			80	0,2805	1,1792	0,389481195	77,87
			90	0,30415	1,3299	0,428537961	98,38
			100	0,33	1,496	0,471395431	121,23
			110	0,35805	1,6775	0,518053603	146,39
			120	0,3883	1,8744	0,568512478	173,83

Table 2. Train fuel consumption for continuous distances

Mass of a locomotive [t]	Mass of a wagon [t]	Number of wagons [pcs]	Speed of a train [km/h]	Running distance [km]	Relative resistance of wagons	Relative resistance of locomotive	Average relative resistance	Fuel consumption [kg]
1	2	3	4	5	6	7	8	9
276	40	50	10	100	0,17655	0,5555	0,22250351	78,82
			20		0,1848	0,5984	0,23495536	83,23
			30		0,19525	0,6567	0,25120790	88,99
			40		0,2079	0,7304	0,27126116	96,10
			50		0,22275	0,8195	0,29511511	104,55
			60		0,2398	0,924	0,32276977	114,34
			70		0,25905	1,0439	0,35422513	125,49
			80		0,2805	1,1792	0,38948119	137,98
			90		0,30415	1,3299	0,42853796	151,81
			100		0,33	1,496	0,47139543	166,99
			110		0,35805	1,6775	0,51805360	183,52
			120		0,3883	1,8744	0,56851247	201,40

Column 6 – relative resistance against the movement of wagons- was calculated by applying formula (13).

Relative resistance for locomotive is obtained by applying formula (7);

Overall average relative resistance is calculated by applying formula (5); fuel consumption for a certain speed was calculated by applying formula (21).

If we consider a train with standard mass of 2276 tons (from the above mentioned table), standard speed of 90 km/h and running distance of 100 km, we will find that approximately 150 kg of fuel is needed for running via such a distance. If a similar train, running with 90km/h speed, was forced to stop and then its speed was regained back to its previous original 90 km/h, then approximately 98 kg of fuel would be needed for that.

As a result of statements, assumptions and calculations above, the interdependence between fuel consumption and train speed for different statistical LG train weights is shown in Fig 1, where horizontal axis shows train speed [km/h], and vertical- consummated fuel [kg]. Also the interdependence between fuel consumption and various train speeds for traveling different distances is shown in Fig 2, where horizontal axis shows train speed (km/h), and vertical- consummated fuel (kg).

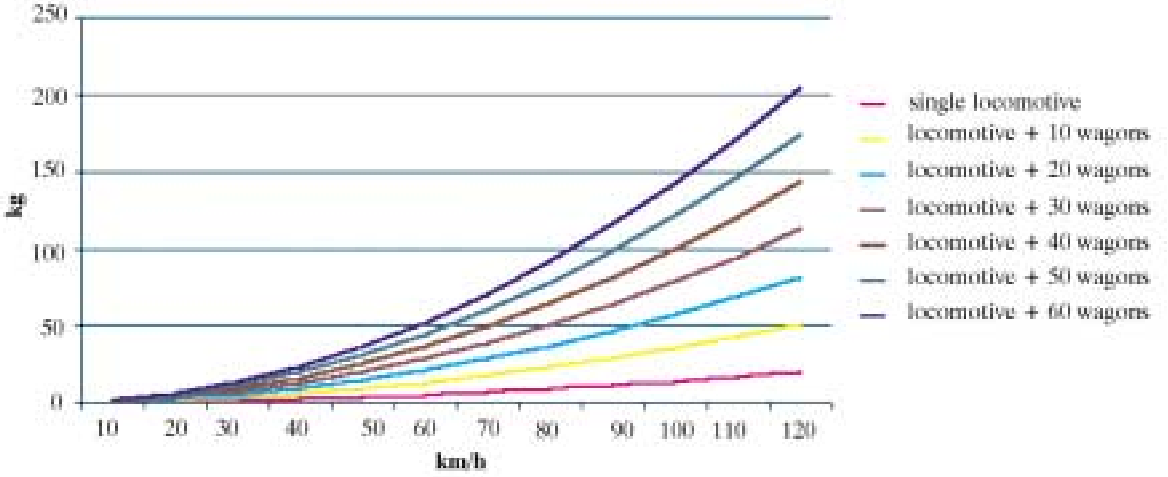

Fig 1. Fuel consumption for different train weights

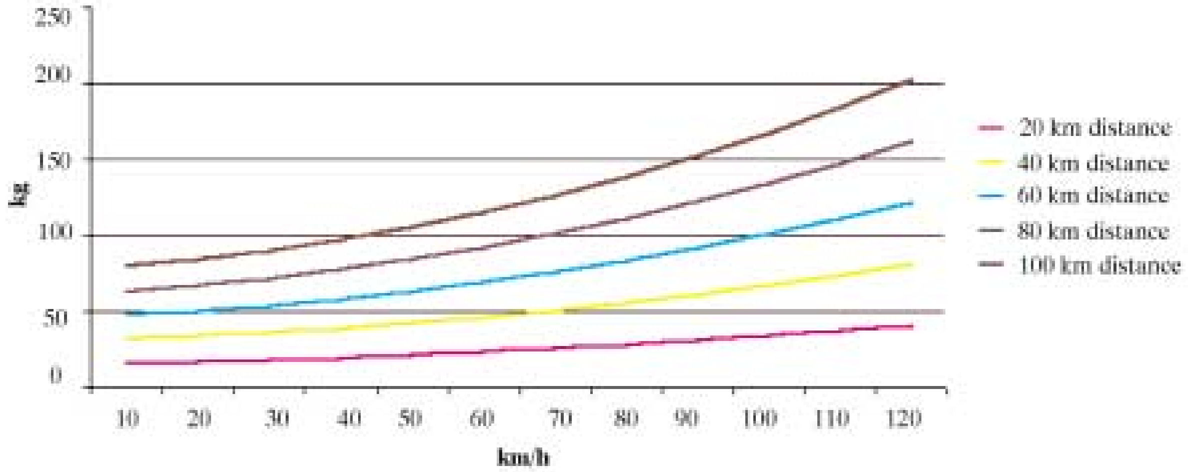

Fig 2. Interdependence between fuel consumption and train speed for different distances

4. Conclusions

1. One of the possible ways to optimize train fuel consumption is by proper route scheduling based on train and road interaction analysis.
2. As it is clearly seen from Table 1 and from Table 2, train fuel consumption could be analyzed as a separate case for:
   - continuously running train;
   - train route with multiple stops (and appropriate efforts towards regaining its previous original speed).
3. Train fuel consumption (see Fig 2) for a certain distance grows proportionally to the train speed. The lowest consumption is characteristic of low speeds because of the type of our analyzed locomotive, namely its efficiency coefficient function from speed.
4. Even a single unexpected or unplanned train stop consumes an extremely large amount of fuel. Although a certain amount of fuel consumption for the running train is inevitable, unexpected stops do make a difference in the overall consumed fuel balance.

5. Fuel consummation could be significantly optimized if a moving blocks automatic train operation system was introduced.

6. More attention should be paid to the investigations of non-scheduled trains, and namely to the possibility to choose the right timing and routing in order to minimize fuel consumption. Under certain circumstances fuel loss because of the non-scheduled train traffic might overshadow losses derived from non-ideal train-track interaction.

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