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Optimizing Power Consumption of the Electric Vehicle Traction

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Abstract. The study refers to optimizing energy consumption from electric trains, underground trains and electric locomotives. The actual requirements of the dynamic market economy are forcing the railway system to transform into a reliable alternative to the road and air traffic. From this perspective, the railways have to fulfill two key elements: economic efficiency and reliability and to offer what the potential customer needs. One of the main elements is the respect of the timetables or (if possible) the decrease of the running times. The running time is the main referential, especially when it's related to the power consumption. The optimization of the running times and the power consumption is the most important target for railway operators and depends on the correct choice of the drive regimes. The paper deals with energy optimization from the perspective of traction. The analysis can be also applied to diesel railcars and diesel locomotives.

Introduction

The actual requirements of the dynamic market economy are forcing the railway system to transform into a reliable alternative to the road and air traffic. From this perspective, the railways have to fulfill two key elements: economic efficiency and reliability; to offer what the potential customer needs.

In particular, the railway system has to fulfill the following specific conditions: freight service must be safe, cheap, fast and accessible (taking into account the complete service pack to be offered to customers situated far from the railway line); long distance passenger service must be fast, highly comfortable (representing a true alternative to the airways) and to allow conditions for leisure, rest and entertainment; short distance passenger service (including the metropolitan railways) must ensure fast links from the centers of the cities to the suburbs at low prices, compared to the bus services.

These are the main requirements demanded by the potential customers desiring prompt, safe and affordable services. It is important to know that their perception of the quality level of the transport service changes continuously. Railway operators have many analysis elements which might be influencing their economic efficiency. One of the main elements is the respect of the timetables or (if possible) the decrease of the running times. The running time is the main referential, especially when it's related to the fuel or power consumption. The optimization of the running times and the fuel / power consumption is strictly related to the safety and modern signaling systems [1, 2].

This paper deals with the optimization of the railway transport system from the traction point of view. Optimizing the traction segment in a railway company means especially respecting the timetable and of course, the lowest fuel / power consumption [3, 4].

Due to the fact that Romania has a large network of electrified railways, this paper will refer to this particular branch of the railway traction.

The electric traction has a series of specific particularities, such as: high power consumption during the starting process; low power consumption when running at constant speed; null consumption (or very low) during the braking process or inertial running; possible power recovering during electric braking process [5].

The Issue of Optimizing Energy Consumption

The energy supplied by the power system is transformed in mechanical energy used in the traction process. This energy is absorbed by the mechanical and aerodynamic drag and what's left is stored as kinetic or potential energy.

The motion equation for a train in each running regime is: traction (1); no traction (2); braking (3)

$$\frac{dv(t)}{dt} = \varphi \cdot \left(f(v(t)) - r(v(t)) + r_i \right) \tag{1}$$

$$\frac{dv(t)}{dt} = -\varphi \cdot \left(r(v(t)) + r_i \right) \tag{2}$$

$$\frac{dv(t)}{dt} = -\varphi \cdot \left(f_f(v(t)) - r(v(t)) + r_i \right) \tag{3}$$

where: φ - is the specific acceleration; f(v(t)) – is the specific acceleration force determined by the traction force; r(v(t)) – is the specific deceleration force determined by the main drag; v(t) – is the running speed; $f_f(v(t))$ – is the specific braking force; r_i – is the equivalent specific drag caused by the declivity.

The specific mechanical energy determined by the traction process may be written as:

$$l = \int_0^t f(v(t)) \cdot v(t) dt . \tag{4}$$

where: t – stands for the time in which the motor vehicle is in traction regime.

Studies performed on different line profiles revealed that the most efficient solution (from the power consumption point of view) is the following string of operating regimes: traction (maximum acceleration) – no traction – braking (maximum deceleration) (Figs. 1 and 2) or traction (maximum acceleration) – traction at constant speed – no traction – braking (maximum deceleration) (Figs. 3 and 4).

The first diagrams (Fig. 1 and Fig. 2) might be used in the metropolitan railways (subways) for a distance of max. 5 km between two consecutive stops, and the last ones (Fig. 3 and Fig. 4) might be used in short or long passenger service and freight service as well. Taking into account the previous considerations, an automated system to assist the driver might be developed. This system will be designed to indicate the right operating regime or if the chosen regime is the correct one. Thus, an optimal driving diagram will result.

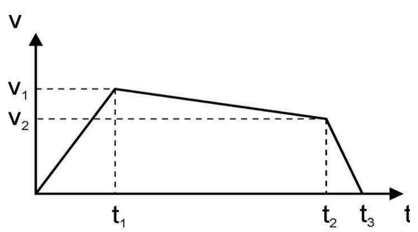

Fig. 1. Speed profile depending on time (metropolitan railways)

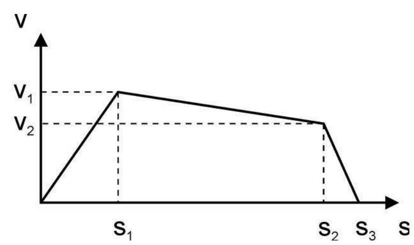

Fig. 2. Speed profile depending on the route already covered (metropolitan railways)

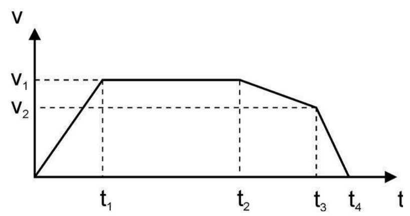

Fig. 3. Speed profile depending on time (long passenger service and freight service)

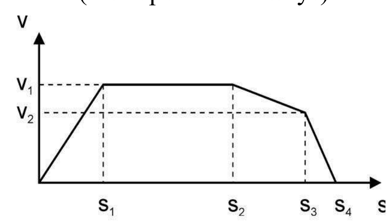

Fig.4. Speed profile depending on the route already covered (long passenger service and freight service)

The strategy assumes a smooth train running, without any accidental stops or speed restrictions. This is unfortunately an ideal situation which considers correctly that the traction is the most power consuming regime. In order to get closer to this ideal, modern traffic organization and proper infrastructure is needed as well.

The constant speed levels are limited by the maximum operating speed and the transport volume. This approach determined the rolling stock manufacturers to increase the installed power on the motor vehicles (e.g. electric locos and trains designed by Siemens AG).

When designing the control strategy, the main issues appearing are linked to the speed limits known as V1 and V2 corresponding to the end of the traction regime and the beginning of the 'no traction' regime and the end of the 'no traction' regime and the beginning of the braking regime, respectively. It is to mention that both values of the V1 and V2 may suffer slight modification according to train mass or load and total drag for each specific vehicle (motor or truck / coach).

For this reason, the following values must be followed and determined: the remaining time until the next stop; determination of the space coordinate of the train (its permanent position) and the remaining distance until the next stop; train speed.

The train driver needs a series of information like: the precise moment for cancelling the 'no traction' regime and to start braking in order for the train to reach the next stop on schedule; any corrections to the operating regime for keeping an accurate schedule and/or to fit in the limited space required for stopping in the next station.

The decision of switching from traction to 'no traction' regime depends on the exact position of the train, its speed, the drag, the line profile and the remaining time until the next stop. The space to be consumed during this regime is:

$$\Delta s_2 = s_2 - s_1 = \left(v_1\right)^2 - \left(v_2\right)^2 \Big/ 2\left(a_{2ft} + a_{i2}\right) \tag{5}$$

where: $a_{2ft} = \varphi \cdot r_t$ – stands for the deceleration in the 'no traction' regime; $a_{i2} = \varphi \cdot r_{i2}$ – is the acceleration component determined by the line profile in the 'no traction' regime.

Depending on the train type and the load, Δs_2 might increase, decrease or to cancel itself.

If at the point where braking starts the train has the (v_2, t_2, s_2) coordinates, the space to be consumed until the next stop is:

$$\Delta s_3 = s_3 - s_2 = \left(v_2\right)^2 \Big/ 2\left(a_{3f} + a_{i3}\right) \tag{6}$$

where: $a_{3f} = \varphi \cdot f_f$ – is the deceleration in the braking process corresponding the specific braking force f_f.; $a_{i3} = \varphi \cdot r_{i3}$ – is the acceleration component determined by the line profile in the braking regime.

The space required for braking may be determined compared to the total space:

$$\Delta s_3 = s - \Delta s_1 - \Delta s_2 \,. \tag{7}$$

where:

$$\Delta s_1 = s_1 - s_0 = \left(v_1\right)^2 \Big/ 2\left(a_{1t} + a_{i1}\right) \tag{8}$$

In order to simplify the equations, the following notes were used:

$$a_1 = a_{1t} + a_{i1};\, a_2 = a_{1ft} + a_{i2};\, a_3 = a_{3f} + a_{i3} \tag{9}$$

The result of the calculus is:

$$\Delta s_3 = 2 \cdot s \cdot a_2 \Big/ a_2 - a_3 - \left(v_1\right)^2 \cdot \left(a_1 + a_2\right) \Big/ a_1 \cdot \left(a_2 + a_3\right); \tag{10}$$

If $\Delta s_3 < 0$, the train may run in the 'no traction' regime and if $\Delta s_3 > 0$ the braking is necessary. The speed at which the braking starts is:

$$V_2 = \sqrt{2 \cdot \Delta s_3 \cdot a_3}\,; \tag{11}$$

The total time elapsed until stop is:

$$t = \frac{V_1}{a_1} + \frac{V_1 - V_2}{a_2} + \frac{V_2}{a_3} \quad (12)$$

If considering the reference time t_{rs} and if $t_{rs}<t$, the train cannot use the 'no traction' regime for reaching the next station in time; if $t_{rs} \geq t$ the train may reach the station earlier, thus in this particular situation, the 'no traction' regime may be used. If $\Delta s_3 < s - \Delta s_1 - \Delta s_2$ the braking is not necessary and if $\Delta s_3 < s - \Delta s_1 - \Delta s_2$ the brakes must be applied.

Switching to the braking regime depends on the train location, the line profile, the current running speed, the braking system's performance and it's a decision the driver has to make without being forced to make any additional regime changes until stopping. The constant speed level (Figs. 3 and 4) is analysed in the same way. The optimization level of the running diagram depends on the maximum running speed and the running times, as the efficiency of the power consumption may be considered only compared to those criteria.

Choosing the right operating regime is crucial in order to follow the timetable (for passenger trains). As for the freight service, a total delay of 1 – 2 minutes per 100 km is acceptable if the power consumption is minimal. Canadian and Australian studies on diesel locos revealed that an automated analysing system reduces the fuel consumption up to 20%. In theory, the calculus reveals that combining the advantages of the electric traction with an efficient driving manner leads to power efficiency up to 30%.

Power Consumption

In order to illustrate the facts presented above, the power consumption of a 5100 kW electric loco is analyzed. The section Bucharest – Galati was chosen for the experiment. The line is 259 km long and is divided in 512 different profile elements. The declivities are 11.565 mm/m for a slope and 9.33 mm/m for the steepest gradient (considering the direction mentioned above).

In order to calculate the power consumption, the number of individual profile elements must be reduced to equivalent profile elements, thus simplifying the calculus. The equation for reducing a number of elements to an equivalent element is:

$$i_e = \sum_{k=1}^{k=n} s_k \cdot i_{rk} \Big/ \sum_{k=1}^{k=n} s_k \quad (13)$$

where: i_e – the equivalent declivity; i_{rk} – the declivity of the element to be reduced; s_k – the length of the element to be reduced; n – the number of simplified profile elements.

The checking of the value for the equivalent declivity is:

$$s_k \leq 4000 \Big/ \left| i_e - i_{rk} \right| \quad (14)$$

The checking is necessary for determining the total number of elements that may be reduced to one single simplified element. Besides the drag given by the line profile, the curves are also generating additional drag. The drag generated by the curves may be considered as a fractional gradient, using the following equation:

$$i_c = \sum_{t=1}^{t=m} r_{ct} \cdot s_{ct} \Big/ s \quad (15)$$

where: i_c – the declivity resulted from the straightening of the curves; r_{ct} – the specific curve drag, depending on the curve radius; s_{ct} – the curve length; s – the length of the profile element in which the curve is located; m – the number of curves in a string of curves on the same element.

The total declivity on the entire line profile is:

$$i_t = i_c \pm i_e . \quad (16)$$

The positive/negative values for the drag are depending on the type of the declivity. Usually, the gradients and the curves are marked as positive and the slopes as negative.

A train mass of 640 tonnes was considered for a passenger train running on this line. This is the limit load that the 5100 kW electric locomotive could haul on this particular line section. The value results from the following:

$$m_{v.c} = \min\begin{pmatrix} m_{v.cl}, m_{v.cl.d}, m_{v.cl.f}, \\ m_{v.cl.cr}, m_{v.cl.s} \end{pmatrix} \tag{16}$$

where: $m_{v.cl}$ – the maximum mass of the coaches to be hauled on the steepest gradient; $m_{v.cl.d}$ – the maximum mass of the coaches admitted when starting; $m_{v.cl.f}$ – the maximum mass of the coaches allowed by the braking system; $m_{v.cl.cr}$ – the maximum mass of the coaches allowed by the coupling system; $m_{v.cl.s}$ – the maximum mass of the coaches allowed by the length of the stations.'

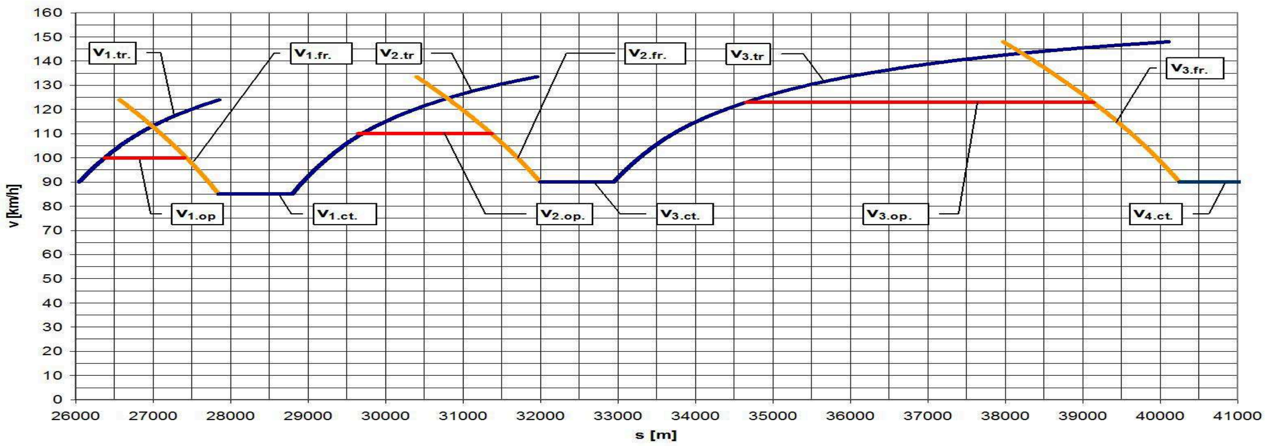

Fig. 5. Speed profile for towing section Bucharest - Galati

For this kind of train, the power consumption on this line is 10900 kWh in limit conditions, using maximum traction force and braking force as well. The total running time is 2 hrs and 45 min.

As a result of the optimization process and keeping tight the timetable, the power consumption was 8980 kWh, thus resulting a 17.5 % less than the original consumption.

On a 15 km sector of the line (between km 26 and 41), the limit characteristics for the running speeds and the optimized speed diagram is presented in Fig. 5, in which: $v_{1.tr.}$, $v_{2.tr.}$, $v_{3.tr.}$, - represent the variation of the running speeds on three different simplified line profiles when using the traction regime; $v_{1.fr.}$, $v_{2.fr.}$, $v_{3.fr.}$ - represent the variation of the running speeds on three different simplified line profiles when using the braking regime; $v_{1.ct.}$, $v_{2.ct.}$, $v_{3.ct.}$ - represent the constant running speeds on

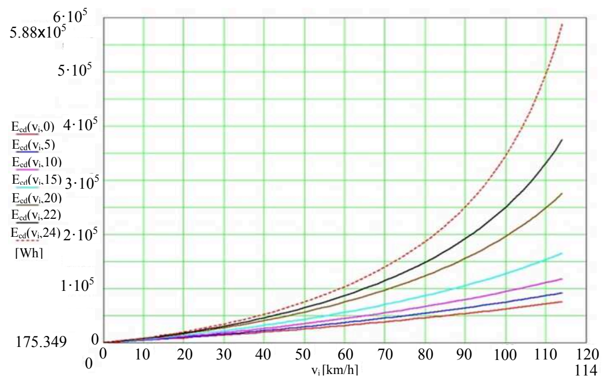

Fig. 6. Energy consumption in passenger traffic

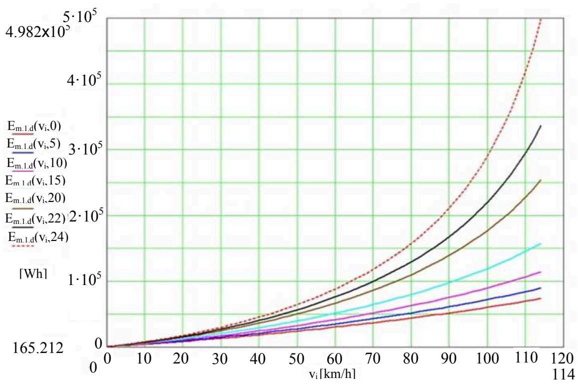

Fig. 7. Energy consumption in freight traffic

three different simplified line profiles when speed restrictions occur; $v_{1.op.}$, $v_{2.op.}$, $v_{3.op.}$ - represent the constant optimized running speeds on three different simplified line profiles.

A second set of determinations was made for the same type of locomotive, towing a tonnage of 450 tons (passenger traffic and freight traffic), on profiles with different gradients (max 28 $^0/_{00}$), in two cases: movement with variable acceleration; movement with constant acceleration.

Energy consumption for variable acceleration (Fig. 6, Fig. 7), and for constant acceleration (Fig. 8 and Fig. 9)

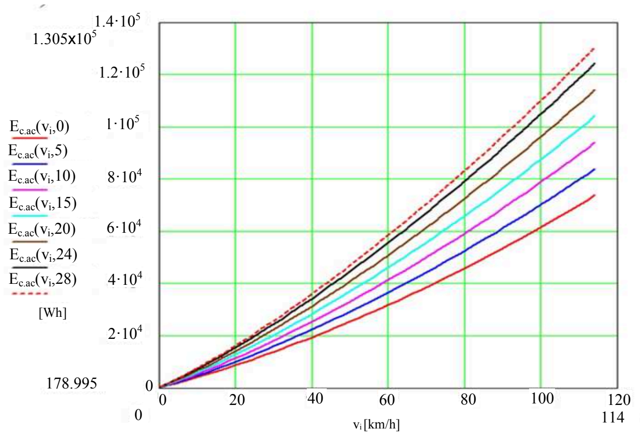

Fig. 8. Energy consumption in passenger traffic

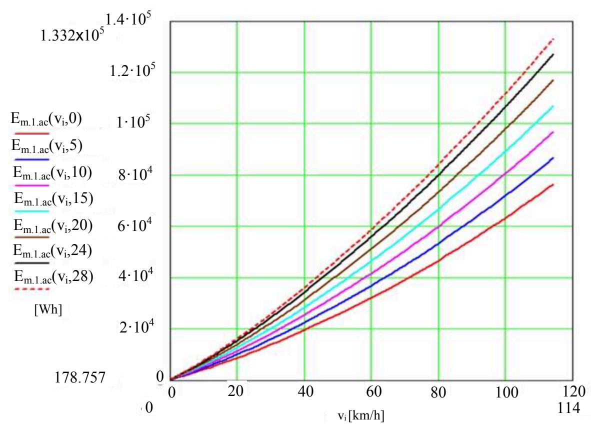

Fig. 9. Energy consumption in freight traffic

Conclusions

Optimizing power consumption enables efficient rail transport, the adoption of control systems that enable the use with lower consumption and even their combination and high traction performance. Optimizing energy consumption optimization strategy requires a mathematical approach that we will present in the next research paper. Also our research aimed at creating a system of automatic driving. By designing and manufacturing adequate automated systems to assist the train drivers, the issue of optimal power fuel consumption might be solved in the future.

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References

[1] G. Popa, B. Ţăruş, Operation of railway vehicles, MatrixRom Publishing, Bucharest, 2005.

[2] G. Popa, Railway traction with three-phase asynchronous motors, MatrixRom Publishing, Bucharest, 2005.

[3] G. Popa, Determining the Optimal Operating Regime of the Traction Motors for Constant Power Operation of the Vehicle, IEEE-TTTC International Conference on Automation, Quality and Testing, Robotics, Cluj-Napoca 2006.

[4] G. Popa, S. Arsene, Determination of the electricity consumption at LE 5600 kW - Siemens (in Romanian), National Symposium of Railway Rolling Stock. MatrixRom, Publishing, Bucharest 2004.

[5] G. Popa, The analysis of the response time at the start of the vehicles equipped with asynchronous tri-phase motors, Proceedings of IEEE-TTTC International Conference on Automation, Quality and Testing, Robotics, Cluj-Napoca, 2006, .