An analysis of the required energy consumption to tow a classical passenger train with an electric locomotive

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Abstract. Ensuring a transport system to increase the mobility of goods and people is one of the great challenges of the modern world. This mobility directly affects the environment. At international level, the regulations adopted in recent years are increasingly stricter with regard to reducing the level of carbon dioxide (CO2). In this context, in many countries, the rail transport system has drawn attention to its performance. This paper seeks to carry out an estimation of electricity consumption in a railway sector in Romania. Taking into account the constructive characteristics of the towing section, the motor vehicle (locomotive) and the at vehicles towed (wagons) that are part of the train, an estimate of the electric power consumption required for the train movement can be made.

1. Introduction

The economic development of the last decades has forced the rail transport system to adapt more and more to the requirements of its customers. Also, a widest use of this displacement system must be related to the degree of safety it confers on goods and passengers compared to other systems such as road, air. [1] Taking these issues into account and the global regulations in the field of transport, the rail system must simultaneously meet two key elements: to be economically efficient and to provide high reliability in order to remain competitive.

At present, one third of global energy consumption and greenhouse gas (CO2) is driven by the transport system, according to data and measurements over the past few years. [2-5]

Table 1 shows the degree of use the European Union (EU 28) transport systems for 2015.

|            | Passenger on Km (%) | Freight on Km (%) | Total (%) |
|------------|----------------------|-------------------|-----------|
| Road       | 82,2                 | 50,8              | 71,5      |
| Aviation   | 9,9                  | 0,1               | 6,6       |
| On the water | 0,3                 | 37,2              | 12,9      |
| Railway    | 7,6                  | 11,9              | 9,0       |

In this context, companies carrying out rail transport services are starting to look for opportunities to reduce energy consumption. Suggestions in literature [6] on reducing energy consumption are: - use of new, more energy-efficient vehicles; - continuous adaptation of transport capacities to demand; - Apply an energy efficient train control (EETC) or economic leadership (the least energy consumption taking into account the timetable).
Currently, many researchers in the field [6-12] seek to find an optimal train driving strategy to minimize energy or fuel consumption (depending on the resource used). In this regard, it is being pursued the optimization of operating times of the train, which is strictly related the signalling and safety systems used on rail.

The following operating modes are identified in the train driving: maximum acceleration - corresponding to the maximum acceleration power, cruise - displacement with the maximum permissible speed, inertia (coasting) - without activated traction or braking systems, braking - with maximum deceleration allowed stop the train at a fixed point (see figures 1 and 2).

Figure 1. Charts of optimal operating modes based on distance.

In Figures 1 and 2 we have: d₁, d₂, d₃ and d₄ respectively t₁, t₂, t₃ and t₄ the distance / time coordinates of the crossing points from one regime to another; d₅₁ and d₅₂ respectively t₅₁ and t₅₂ the distance / time coordinates to stop, from the start of braking; v₅₁, v₅₂ the speed coordinates from where braking starts; v₅₃ speed until acceleration is reached; v₅₄ permitted limit speed.

The challenge of optimal energy management is nothing more than a sequence of operating regimes in which switching from one regime to another is determined and optimized at switching points.

2. Theoretical aspects
For the movement of a train from one station to another (from station A to station B), it is necessary to take into account the principle of force or the second law of Newton’s dynamics (1) and the balance of forces acting on the train to a certain value of the displacement speed (2) [7-10]:

\[ \ddot{F} = m \cdot \ddot{a} \]  
\[ m \cdot \frac{dv(t)}{dt} = F_{(v(t))} - R_{(v(t)),p} \]  

where \( \ddot{F} \) [kN] – train force, m [tonne] – train mass, \( \ddot{a} \) [m/s²] – train acceleration, \( v(t) \) [km/h] – the train speed at a certain point in time, \( \frac{dv(t)}{dt} \) [m/s²] – the acceleration at the same time, \( F_{(v(t))} \) [kN] – the force acting from the outside on the train at the time considered, \( R_{(v(t)),p} \) [kN] – the resistance of the train at the same time.

If the force acting from the outside is positive (\( F_{(v(t))} = F_{0(v(t))} > 0 \)), then it is the traction force developed by the motor vehicle (the locomotive), the train is in traction mode. If this force is negative (\( F_{(v(t))} = F_{f(v(t))} < 0 \)) then it is braking - the train is in braking mode.
The resistance to moving of train \( R_{(v_{(t)}, p)} \) [kN], sums up two components [10] (3): a base resistance \( R_{b(v_{(t)})} \) [kN] (determined by train inertia, wheel and rail friction, respectively air) and additional resistance to moving \( R_{t(p)} \) [kN], due to track characteristics at the positioning point the train on the tracks (the gradient of the track - the rail gradient and the radius of curvature of the line - the radius of the curves)

\[
R_{(v_{(t)}, p)} = R_{b(v_{(t)})} + R_{t(p)} \tag{3}
\]

Determination of base resistance to moving can be achieved with the Davis empirical relationship (4). With respect to the additional resistance (5), this can be obtained by summarizing the relationships (6) and (7) regarding the resistances determined by the railway gradient and the resistances determined by the curvature rays of the line:

\[
R_{b(v_{(t)})} = A + B \cdot v_{(t)} + C \cdot v_{(t)}^2 \tag{4}
\]

\[
R_{t(p)} = R_{g(p)} + R_{c(p)} \tag{5}
\]

\[
R_{g(p)} = m \cdot g \cdot \sin(\alpha) \approx m \cdot g \cdot tg(\alpha) = m \cdot g \cdot \frac{h}{1000} = m \cdot g \cdot i_{p(k)} \tag{6}
\]

\[
R_{c(p)} = m \cdot g \cdot \frac{d}{\rho_{p(j)}} - e \tag{7}
\]

where \( A, B, C \) – are the Davis constants for each type of vehicle; \( g \) - gravitational acceleration; \( \alpha \) – the angle of the vertical deviations of the profile; \( h \) [mm] – height of vertical deviations when travelling 1000 m; \( i_{p(k)} \) [\%] – declivity of the profile element; \( \rho_{p(j)} \) [m] – the radius of curvature of the path; \( d, e \) – gauge dependent constants and radius of curvature.

By referring to the specific weight of the train \( (m \cdot g) \) of these forces, are obtained the corresponding specific forces. With these specific forces it is possible to write the relations for the three operating modes, thus (8) - the traction mode, (9) - the non-traction mode, (10) - the braking mode:

\[
dv_{(t)} / dt = f_{0(v_{(t)})} - r_{b(v_{(t)})} - r_{t(p)} \tag{8}
\]

\[
dv_{(t)} / dt = -r_{b(v_{(t)})} - r_{t(p)} \tag{9}
\]

\[
dv_{(t)} / dt = -f_{t(v_{(t)})} - r_{b(v_{(t)})} - r_{t(p)} \tag{10}
\]

If we note with \( F_{w(v_{(t)}, p)} = m \cdot g \cdot (f_{0(v_{(t)})} - r_{b(v_{(t)})} - r_{t(p)}) \) and taking into account the mechanical power actually used in displacement is: \( P_{mech(t)} = F_{w(v_{(t)}, p)} \cdot v_{(t)} \), we can determine the energy consumed \( E_{c, t} \) [kWh] in the traction mode as follows:

\[
E_{c, t} = \int_0^t P_{mech(t)} dt = \int_0^t F_{w(v_{(t)})} \cdot v_{(t)} dt - \int_0^t F_{d(v_{(t)})} v_{(t)} dt \tag{11}
\]

where \( t \) [s]– the time the train is in traction mode, \( t_i \) – the time during which energy recovery braking is performed, \( F_{d(v_{(t)})} \) [kN]– the dynamic braking force which allows the recovery of energy, if the power system and the vehicle have this option.
3. Case study

In order to carry out this study, 166 km long railway sector was considered in the analysis, within the national railway network in Romania, between Bucharest Nord - Brașov stations (see Figure 3). Characteristic of this section is that the line is built with a significant altitude, over 800 m in climb, recorded between Ploiești and Predeal stations. From the Predeal station to Brasov, the path has a vertical deviation of only 400 m, the area being in the descent.

![Figure 3. Bucharest - Brașov railway sector line [13].](image)

In the area of Predeal station are recorded some of the highest values of the railway gradient recorded on Romanian railways (26.40mm / m for ramps - climbing, respectively 28.31mm / m for slopes - descent)

It should be noted that this track between Ploiești and Brasov is built in a mountainous area. As such, besides the vertical deviations mentioned above, there is a significant number of horizontal deviations (curves). Throughout the longitudinal profile of the towing section from Bucharest to Brasov there are 464 profile elements with vertical deviations (rail gradients) and 207 curves (horizontal deviations).

In order to reduce the volume of calculation, a method of simplifying the number of profile elements having vertical deviations is used. For this, it is taken into account that the resistive mechanical work of the resulting equivalent element is equal to the sum of the mechanically resistant work of the actual elements that make up it. Grouping the profile elements consists of joining successive elements of the same type and transforming them into an equivalent element having the length given by the sum of the lengths that make up it. The equivalent gradient \( i_{ech} \) is calculated by the relationship (12). The condition for checking the resistance mechanical work in the passenger traffic is given in the relation (13). Taking into account the curve resistances determined by the curves (relation 7) and the equivalent gradients resulting from their straightening \( i_{e,c} \) (14), the total equivalent declivity \( i_{e,tot} \) (15) can be written.

\[
i_{ech} = \sum_{j=1}^{n} s_j \cdot i_j \left/ \sum_{j=1}^{n} s_j \right. \tag{12}
\]

\[
s_j \leq 4000 \left/ \left| i_{ech} - i_j \right| \right. \tag{13}
\]
\[ i_{c_e} = \sum_{j=1}^{k} r_{(p),j} \cdot s_{(p),j} / s_j \]  
\[ i_{c_{tot}} = i_{c_e} \pm i_{ech} \]

where \( i_j [^\circ/\text{m}] \) - the declivity of the real element; \( s_j [\text{m}] \) - the length of the real element; \( r_{(p),j} [^\circ/\text{m}] \) - the specific resistance given by the curve; \( s_{(p),j} [\text{m}] \) - length of the curve.

As a result of the simplification, 89 profile elements are obtained as in figure 4.

The calculation of energy consumption for this track sector is made for classic trains consisting of a locomotive and a number of towed wagons. The number of towed vehicles is differentiated according to the train composition. For this, account was taken of the type of towed vehicles used in passenger traffic (single-deck wagons and double-decks wagons). Of the possible situations, the cases where the train is composed only of identical wagons have been analysed. In this way, two types of land with single-deck wagons and double-decks wagons.

The Davis coefficients from the resistance to moving for the towed vehicles considered and the mass of a loaded wagon are shown in Table 2.

**Table 2.** Davis coefficients and mass for vehicles what are forming the train.

| Type                | m [t] | A [N]   | B [N/(km/h)] | C [N/(km/h)^2] |
|---------------------|-------|---------|--------------|----------------|
| 060 LEMA 6000kW     | 120   | 2968.4  | -51.347      | 0.649          |
| Single-decks wagons | 48    | 82.4    | 0            | 0.0125         |
| Double-decks wagon  | 67.8  | 86.5    | 0            | 0.014045       |

For the traction of the two types of trains, the TransMontana locomotive of type 060 LEMA, with a rated output of 6000 kW, was considered. Its mass and the Davis coefficients of resistance to moving are set out in Table 2, and the traction effort characteristic \((F_0)\) of the locomotive is shown in Figure 5.

Taking into account the characteristics of the locomotive, the characteristics of the longitudinal profile of the towing section and taking into account the international regulations in force (the maximum number of axles in the composition of the passenger trains is 80) determine the number of wagons (20 of single-deck wagons and 18 of double-decks wagons). These wagons will correspond to a mass of the towed convoy of 960 tonnes for the single-deck train and 1220.4 tonnes respectively for the double-decks train. The resistance characteristics to motion for the two train types \((R_{sd} - \text{resistance of single-deck train}, R_{dd} - \text{resistance of double-decks train})\) are shown in Figure 5.

**Figure 5.** Traction characteristics and trains resistances.

**Figure 6.** Energy consumption for the two trains.
The energy consumption for the situation when the trains travel directly from Bucharest to Brasov is shown in figure 6 and the time required for scrutiny in the two cases is approximately 83,65 min for the double-decks train and 80,28 min respectively for the single-deck train.

4. Conclusions
The constructive characteristics of the towing sections, aggregated with those of the vehicles involved in the composition of the train and taking into account its operating mode, directly affect the energy consumption during the journey.

Using the method of simplifying the number of profile elements on the towing section allows a decrease in the amount of energy consumption calculation. In the track sector chosen for analysis (Bucharest - Brașov line) this method allowed a decrease by more than 80% of the number of elements reals, which considerably reduced the calculation volume.

Trains with high tones, as can be seen in Figure 6, have higher energy consumption. In fact, the tonnage difference of 21.34% caused a delay of about 3.38 min. and an increase in energy consumption of 3.88% for the two trains analyzed.

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