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The recovery of train braking energy: the case of Catania (Italy) metro line

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Abstract

A method to analyse the operation of a metro railway transit line by increasing the energetic exchange between the trains during braking and traction phases is proposed. Based on the track profile and mechanical and electric characteristics of the trains, a simulation model has been developed to calculate the energy which is absorbed or supplied to the power line, for a fixed operational situation. The model allows the estimation of the fraction of electrodynamics braking energy which cannot be recuperated and is dissipated on board resistors when no train needs get power from the electric line.

The train operation can be optimised by estimating, for a fixed train headway, what the number of simultaneous operating trains is which determines the minimum percentage of the electrodynamics braking energy that cannot be regained, and calculating the relevant energetic savings.

The simulations are related to the metro railway line of Catania (Italy), which is under construction by the Circumetnea Railway Company.

1 Introduction

Most electric rail vehicles use dynamic braking; the motors are used to slow the train, with the energy dissipated in train-borne resistors, generating a large amount of heat.

This saves brake wear, but does not recovery any of the energy used to accelerate the train, which, in metro services with frequent stops, is the largest component of energy usage. Regenerative trains, able to feed braking energy into the line, can recover most of the energy otherwise lost to braking. A train with a mass of 240 t running at the speed of 80 km/h owns a kinetic energy of almost 60 KJ (16.67 kWh), which is theoretically recoverable in each stop of the train.

This paper shows which benefits can be gained by a railway metro line operator, if the trains are equipped with systems able to recover the braking energy. Using a simulation model, the amount of energy saved is calculated as a function of the number of trains which are simultaneously on line. The model is able to incorporate the geometric characteristics of the track line as well as the electromechanical performance of the rolling stock used and the frequency of service.

2 Simulation model for a metro railway line

In order to quantify the amount of the energy saving which can be obtained by the recovery of the train electrodynamics braking energy, a simulation model has been built. It is a train performance simulator that determines speed, time, distance and energy consumption of a transit unit running over a track profile. The model includes the effects of grades, curves, train resistance, speed restrictions, propulsion and brake characteristics. The model is able to reproduce the cinematic and electric behaviour of a single train or of several trains for different operating situations.

The simulation model is based on a computer program written in the C++ language.

The calculus procedure consists of the following steps, which will be described in detail later in this paper:

- simulation of a single train on the metro rail line by the construction of the motion profile;
- calculus of the power consumption when one or more trains are simultaneously running;
- calculus of the braking energy fraction which is recovered and which is available for the traction.

2.1 Geometry of the railway metro line

Circumetnea Railway has operated, since 1895, a narrow gauge line, 110 km long, to link Catania with several small towns around the volcano Etna. In the last decade Circumetnea has started the transformation of the urban and suburban sections of the line, changing the old narrow gauge single track surface line into a standard gauge double track underground line, to operate a metropolitan passenger service from Catania to Misterbianco.

An urban section 3.8 km long began its service in 1999 between the stations of Porto, Galatea and Borgo, while civil works for the prolongation of the line to reach Misterbianco from Catania are in progress.

In this paper we consider the planned metro line from the station of Stesicoro (in the down town of Catania) to the station of Misterbianco (a town placed at the border of Catania with 50,000 population).

The line is 11.5 km long, with 14 stations (see Figure 1).

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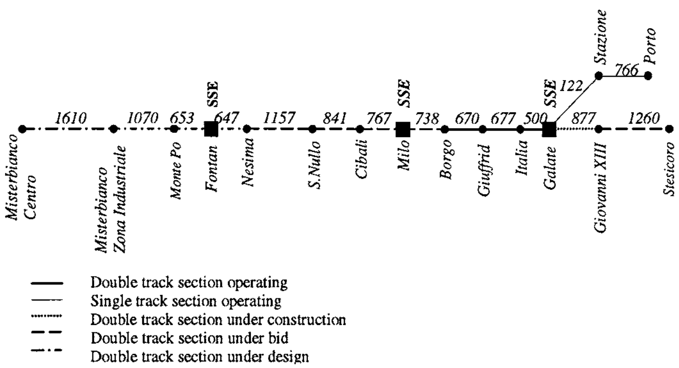

Figure 1: Schematic layout of the metro railway line.

The track plan and profile are built in spreadsheets and then read by the computer program. Data can be rapidly changed and the effects on performance can be quickly investigated. Data include station locations, curve radii, grade, elevation and speed restrictions versus track location. For the examined case the maximum allowable speed is the minimum between 120 km/h (according with the performance of the rolling stock used) and the value calculated to respect the curve equilibrium, by the following expressions:

$$V_{\max} = \sqrt{\frac{(h + 152.91 \cdot a_{nc})}{11.8} R} \quad \text{(km/h)} \tag{1}$$

R (m) being the curve radius, h (mm) the superelevation and a_{nc} (m/s^2) the centrifugal not compensated acceleration (<0.90 m/s^2 for metro line). However it should be considered that the train speed has to be limited form the maximum allowed value to meet the need of a regular train ride with a constant speed drive.

2.2 Transit unit

The transit units (see **Figure 2**), supplied by the Firema Consortium, are composed of two coupled bogies, each equipped with four three-phase asynchronous 300 kW electric engines. The engines are driven by a two-stage system: the first is a chopper converter used to lower and stabilise the line voltage, the second is a three-phase inverter which feeds the permanent bridging connected motors.

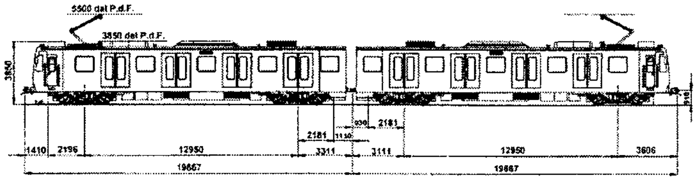

Figure 2: FCE metro railway transit unit.

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2.3 Integration of the motion equation

The model achieves its accuracy by employing numerical integration using a fixed time step. This enables an accurate description of the propulsion and braking systems (see Figure 3) which can include nonlinear relationships between speed and tractive effort.

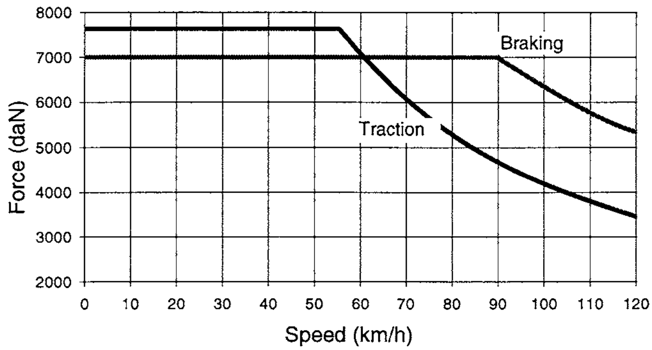

Figure 3: Traction and braking characteristics of half transit unit.

If we consider a railway vehicle in a generic instant of its motion with speed *v* and acceleration *dv/dt,* the dynamic motion can be described simply with Newton's second law of dynamics. The equation of motion is

$$T - R_{tot} = \frac{P\alpha}{g}\frac{dv}{dt} \tag{2}$$

T being the tractive effort applied to the vehicle, R_{tot} the resultant of all external forces opposing the motion, *P/g* the vehicle mass, *dv/dt* the vehicle acceleration and α a coefficient grater than one which consider the presence of rolling masses.

The integration of equation (2) allows, instant by instant, all the motion characteristics, such as space covered, time spent, speed, acceleration and, as result, the vehicle performance, to be known.

The curves of speed, space and acceleration versus time are the so-called motion curves and constitute the base for the design of the entire process of supplying a transport railway service.

If we know the speed value at a fixed time, we can calculate *T*(*v*) and *R*(*v*), and therefore the acceleration from the following expression

$$a = \frac{dv}{dt} = [T(v) - R(v)]\frac{g}{P\alpha} \tag{3}$$

while the speed variation is obtained from

$$\Delta v = a\Delta t \tag{4}$$

The integration of the motion equation is conducted by the method of finite differences, with an iterative algorithm: in each step, time is increased by Δt. In

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our case a value of 0.25 seconds has been chosen. It corresponds to a few meters of distance covered by the train, so that the variations in the track geometry are properly considered. To increase the precision of the numeric integration method, the space run during Δt is calculated with an average speed value between the initial v and the final $v + \Delta v$.

For every step of integration, $T(v)$ is calculated as a function of speed, according to the characteristic traction curve of Figure 3. The traction is upper bound by the frictional grip limit faPa, being fa the grip coefficient and Pa the adhesive weight, coinciding, in our case, to the vehicle weight (each wheel is connected to a driven axle).

The algorithm built up for the construction of the motion curve, calculates the traction force as follows:

1. if the vehicle is stationary or in braking phase, T is set equal to zero;
2. if the speed exceeds the maximum value allowed by the track geometry or by any imposed speed restrictions, T is set equal to the global motion resistance, in order to obtain a uniform motion (constant speed equal to the maximum allowed); if the resistance is negative (i.e. in a steep descent), T is set equal to zero;
3. in the other cases, T is set equal to the lowest value between the limit frictional grip and the ratio between the available wheel power W and the speed: $T = \min(f_a P_a; W/v)$

The global motion resistance is calculated as the sum of the ordinary resistance (rolling resistance, friction in the bearings of the cars, aerodynamic drag), and the accidental resistance (grade resistance and curvature resistance). For the ordinary resistance, the formula of Borisowsky has been used (equation~(5)).

$$R_{ord} = \frac{3.2 + 0.034V + 0.00047V^2}{1000} P \ [\text{N}] \tag{5}$$

V being the speed in km/h and P the weight in kN.

The gradient resistance is calculated from the known equation (6)

$$R_i = i\, P \ [\text{N}] \tag{6}$$

i being the specific grade resistance expressed in ‰.

Finally for the curve resistance, the formula of Desdonits is used:

$$R_c = \frac{0.5 \cdot s}{R} P \ [\text{N}] \tag{7}$$

R being the curve radius and s the track gauge, both in meters.

The algorithm calculates the global motion resistance as follows:

1. if the vehicle is stationary, resistance is set equal to zero;
2. if the speed is not zero, the program reads the actual progressive distance and the relative gradient and curvature, then the global resistance is obtained as the sum of equations (5), (6) and (7), as a function of the current speed;
3. if the vehicle is braking, the braking force is added to the motion resistance.

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In each step of integration, the program calculates the distance to stop as a function of the current speed and the track geometry; if the distance to arrest the motion is lower than the next station distance, the braking force is calculated according to the supplier specifications (see Figure 3) and is added to the resistance forces. When the speed is 5% over the maximum allowed due to a descent slope, a braking force opposite to the gradient is added, in order to maintain a uniform motion.

At each step of integration, with the traction and resistance forces related to the current speed being known, the program calculates the acceleration using equation (3) and the speed for the next step as $v = v + a\Delta t$. As already said, the space increase is obtained as a function of the last two step speeds, as $\Delta s = v_m \Delta t$. When the track location corresponds to a station, the speed is set zero.

The duration of the train stop at the station is conditioned by the number of passengers that embark or exit the vehicle. The program is able to treat this time as a random variable based on a chi-square distribution. The train headway is considered as a constant, while the inevitable differences of the running time are compensated by increasing or diminishing the terminus stop.

To simplify the simulation, the hypothesis that the block sections are coincident with the sections between the stations has been accepted.

3 Simulation results

Launching the simulation program, the motion equation has been integrated for a single transit unit with 30 minutes of running time.

Figure 4 shows the graph of simulation results in terms of speed and space as functions of time for a transit unit running on the line *Stesicoro–Misterbianco–Stesicoro*, while Figure 5 shows the power profile: positive areas represent the energy absorbed for traction and on board auxiliary services, negative areas are the braking energy which, in the case of a single train, is completely lost.

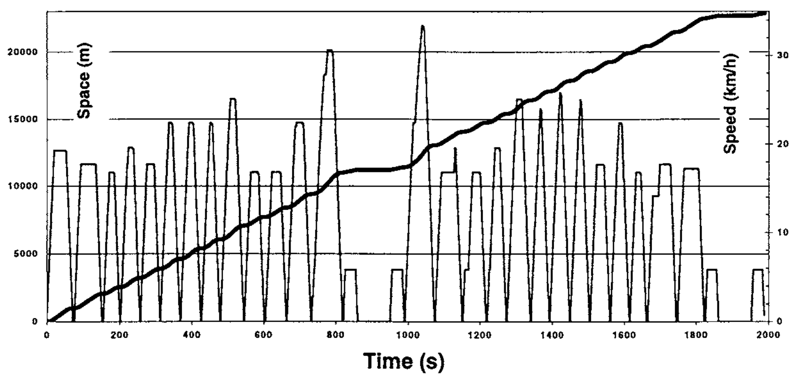

Figure 4: Simulated motion profile of a transit unit.

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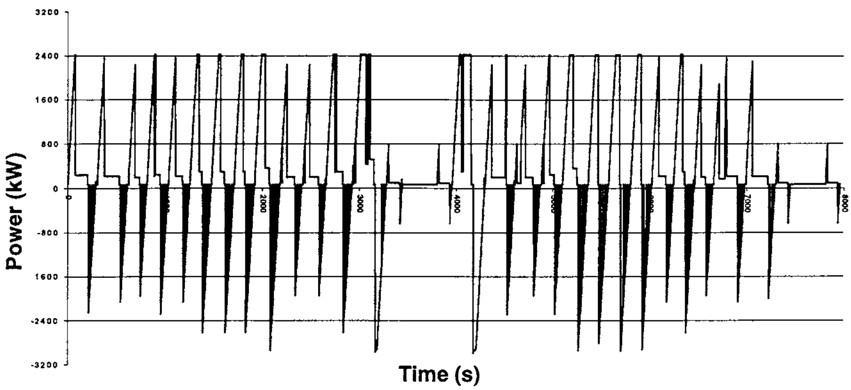

Figure 5: Power absorbed as a function of time for a single transit unit.

Known for each instant the traction force and the speed, the power for the i^{th} train is calculated by the expression:

$$W_i(t) = T_i \cdot v_i \ \text{[kW]} \tag{8}$$

From equation (8), introducing adequate considerations on the efficiency of the engines, drive system and feed line, the traction and braking energy for a single train can be obtained.

The braking energy is transmitted through the line filter to the feeding wire; when the line is not receptive (there is no train needing energy), the braking choppers are used to dissipate the energy on the board resistors.

The simulation model considers that the trains brake using the electrodynamic braking system, which works until the speed is over 10 km/h. Under this speed, the pneumatic braking is automatically used.

If the stop time in the terminus stations is fixed, together with the desired headway, the vehicle performances being known, the number of trains required to operate simultaneously can be easily calculated.

Figure 6 shows the simulation results of power as function of time for different operating conditions. The global line power W(t) is obtained as the algebraic sum of the Wi(t) power absorbed by the i^{th} train (i=1, 2,..., n); each train has a time distance from the previous and from the next equal to the headway value.

The integration of the function W(t) is the global energy: the negative areas in Figure 6 are the braking energies which cannot be recuperated.

The simulations refer to ten different operating hypotheses, from the operation of a single train with 30 minutes headway to 10 trains with 3 minutes headway; the simulation is conditioned by the random time train displacement due to the random time stops at the stations. Each operating condition has been simulated 50 times, to obtain a reliable statistic description of the system.

As we can see in Table 1, the energy required in our study case is 220 kWh for a single train circulating in the line. All recoverable energy is dissipated on the rheostats. When a second train is added, 10% of energy required is recovered.

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We mean to say that 44 kWh of the 440 required are given back to the line, due to the presence of trains ready to capture the excess of energy in the line, so that only 396 kWh of the energy is used. The percentage of recoverable energy varies from 0% (one train) to 40% (ten trains).

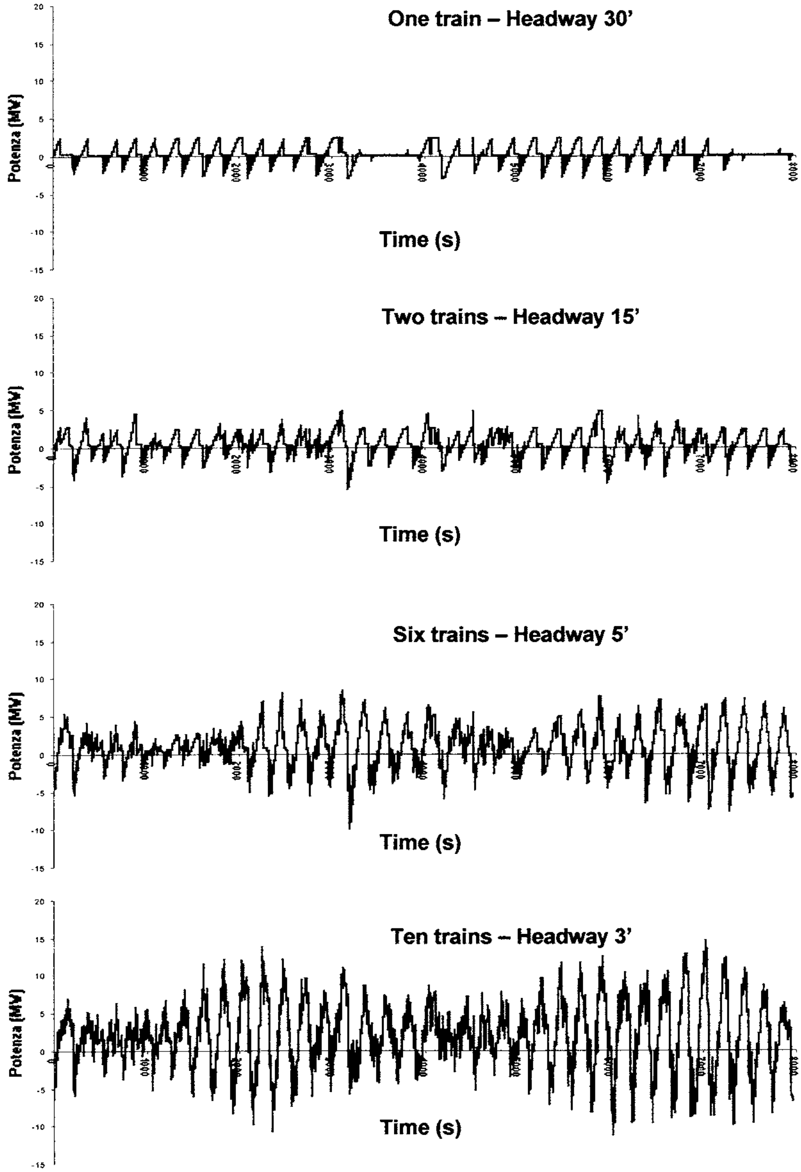

Figure 6: Simulations results for the power variable as a function of time in different operating conditions.

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Table 1: Simulation results.

No. of trains	Required energy without braking recovery **A**	Actual energy with braking recovery **B**	Recovered braking energy **C=A-B**	Not recovered energy **D**	Recovered energy over required energy **(C/A)**	Percentage of not recovered energy **(D/A)%**	Not recovered energy over global braking energy **[D/(nD1)]%**
1	220.00	220.00	0.00	-83.20	0.000	37.82	100.00
2	440.00	396.00	44.00	-126.91	0.100	28.84	76.27
3	660.00	537.90	122.10	-139.64	0.185	21.16	55.95
4	880.00	677.60	202.40	-152.37	0.230	17.31	45.78
5	1100.00	825.00	275.00	-158.94	0.250	14.45	38.21
6	1320.00	957.00	363.00	-153.50	0.275	11.63	30.75
7	1540.00	1047.20	492.80	-145.51	0.320	9.45	24.98
8	1760.00	1117.60	642.40	-143.54	0.365	8.16	21.57
9	1980.00	1207.80	772.20	-138.14	0.390	6.98	18.45
10	2200.00	1320.00	880.00	-125.20	0.400	5.69	15.05

In detail, (see Figure 7), when the number of trains is less than three, the percentage of recoverable energy increases in a linear way; then a reduction in the slope of the curve is observed, and when the trains are more than 9, the percentage becomes almost constant.

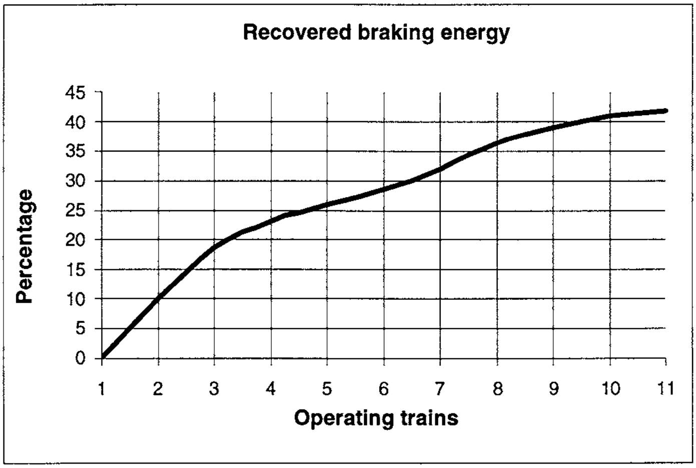

Figure 7: Percentage of the recovered braking energy over the required energy.

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4 Conclusions

The simulation model presented has been used to explore the effects of the regenerative braking on energetic savings. While the recovery of braking energy, normally occurs in a casual manner only between different trains in the process of braking and in accelerating, the model is able to know how the cost savings coming from the braking energy vary with the number of trains in the line and how it can significantly condition the timetable planning decisions. The simulation model is also able to predict how the amount of recoverable energy is affected by track geometry, by rolling stock performance and by the operating conditions of the planned service.

Increasing the number of trains and then recovering the braking energy induces some not secondary benefits:

- decrease in the power peaks with consequent savings in running costs;
- improvement of the voltage profile on the d.c. line which produces a decrease in the losses; moreover the increase in the available traction torque due to a more uniform voltage can improve the running time and the service provided;
- reduction of environmental impacts and the tunnel temperature.

The model is also able to incorporate different stopping patterns at the stations or the variation in weight caused by a time passenger profile for each station.

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