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INCREASED EFFICIENCY IN MASSIVE TRANSPORT SYSTEMS BY PROGRAMMING SPEED PROFILES BETWEEN SEGMENTS

Aumento de eficiencia en sistemas masivos de transporte mediante programación de perfiles de velocidad entre tramos

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Abstract

This study aimed to estimate the specific energy consumption in massive metro-type transport systems, with the aim of guiding the identification of projects aimed at increasing energy efficiency. To achieve the above purposes, this research focused on the estimation, through a software application, of the specific consumption of electrical energy. Results of simulations carried out with an application developed in MATLAB, to generate speed profiles in the operation of the train, allow to observe the sensitivity of the specific consumption of electrical energy to changes made in the cruising speed and in the acceleration and deceleration ramps. The results show that the specific consumptions depend to a large extent on the speed profiles and the operation of the metro, which opens an interesting field of application of optimization techniques aimed at the efficient use of energy.

Key words: *acceleration, cruising speed, energy consumption, metro system, specific energy.*

Resumen

Este estudio tuvo como objetivo estimar el consumo específico de energía en sistemas masivos de transporte tipo metro, con el objetivo de orientar la identificación de proyectos tendientes a incrementar la eficiencia energética. Para lograr los propósitos anteriores, esta investigación se centró en la estimación, a través de una aplicación de software, del consumo específico de energía eléctrica. Resultados de simulaciones realizadas con una aplicación desarrollada en Matlab, para generar perfiles de velocidad en la operación del tren, permiten observar la sensibilidad del consumo específico de energía eléctrica ante cambios realizados en la velocidad de crucero y en las rampas de aceleración y desaceleración. Los resultados muestran que los consumos específicos dependen en gran medida de los perfiles de velocidad y del funcionamiento del metro, lo que abre un interesante campo de aplicación de técnicas de optimización orientadas al uso eficiente de la energía.

Palabras clave: *aceleración, consumo de energía, energía específica, sistema metro, velocidad de crucero.*

1. INTRODUCTION

Subway-type mass transportation systems represent a large load on the distribution circuits of cities and are large consumers of electrical energy, thus constituting important systems when identifying potential opportunities for savings and improvements in the efficient use of energy. A key indicator in energy efficiency is the so-called specific energy consumption (energy per unit of production), which can be established as a benchmark in monitoring projects associated with increased efficiency and productivity and finds application in studies and analyses comparing energy consumption per unit of production between different companies, entities, systems, and modes of transport, etc. The specific consumption indicator is well known by energy managers and is very often used in industrial manufacturing and continuous flow companies, but it is little used in other activities such as mass transportation systems that use electrical energy as an input. Difficulties of various kinds such as the lack of knowledge of the “production unit” of these systems and the difficulty in identifying the variables that have the greatest influence on energy consumption hinder its use, thus causing a problem that prevents, among other things, having reliable benchmarks and comparisons for the proper integrated management of energy.

This paper focuses on the computation of the specific electrical energy consumption of Metro-type systems. The central focus of interest is the energy consumed by the traction subsystem (subsystem responsible for the movement of the train), which represents between 40 and 80 percent of the total energy consumed by these mass transit systems. The approach in estimating the specific energy consumption is carried out considering key mechanical variables in the operation, such as acceleration and deceleration speeds and the stationary or cruising speed in each of the sections that constitute a Metro-type system. A crucial aspect that has emerged in recent years, due to pressure from environmental groups, has to do with the introduction of technological innovations that tend to reduce energy using regenerative braking in deceleration. It is worth mentioning that potentials of up to 50 percent of the energy generated in braking could be returned to the electric power distribution system.

In the calculation of the energy required by a metro-type system, the determination of the traction force to produce the movement is key and this is a function of mechanical variables such as the weight of the train, the number of passengers, the average weight of the passengers and the instantaneous speed.

Internationally, and over several decades, sufficient experience and knowledge has been acquired to determine the traction force required in railway systems, so much so that there is a reliable equation (modified Davis equation) for calculating the instantaneous traction force. Once the instantaneous force is available, the next step is the calculation of the instantaneous power and then its integration over time to quantify the total energy for a complete run of a certain length. Knowing the total energy and the length, the specific energy consumption indicator can be determined, which has units of electrical energy per unit length for each train. This indicator is different, depending on the number of users being transported.

A first work that can be mentioned, related to energy efficiency in metro-type mass transit systems [1], addresses the reduction of energy consumption from the point of view of the system as a whole and considers measures aimed at improving the operation and implementation of technologies. The paper concludes that there are several measures that have proven to be successful and that a key aspect in the implementation of these measures is the continuous monitoring of the proxy indicators that are identified. The research work of [2], focuses on an analysis of energy consumption and time spent per route between stations of metro-type systems, considering two modes of operation. The work identifies an interesting potential for energy savings by introducing improvements in route operation; however, it does not focus on monitoring indicators to observe improvements (decreases in energy consumption) in the savings achieved.

The work of [3] examines various cost estimation methodologies and develops functions involving specific energy consumptions for regional rail transportation systems with different fuels (gasoline, gas, electricity). The work presents a specific reference consumption for regional trains, which varies between 3.5 and 5.5 kWh/(km*train) at the European level; unfortunately, the focus of the study is on regional trains and not on metro-type mass transit systems.

In the work of [4], the fundamental interest is the reduction of energy consumption using automatic operation systems that select, on-line, speed profiles within a preset set of optimized profiles. In the paper they propose the design of an automatic operation system with preset profiles considering the energy recovered with regenerative braking to reduce the consumption of energy extracted from the substations that feed the Metro system. The work is based on a case study of line 3 of Metro de Madrid (17 stations, with a total of 13.5 km in each direction), line in which average values of energy consumed in traction and energy recovered with regenerative braking are obtained by numerical simulation. Average values of 12.91 kWh/(km*train) are reached for the specific traction energy and 3.69 kWh/(km*train) for the specific energy returned to the network by regenerative braking. With the above values, and with several scenarios defined, optimized profiles are proposed, and energy savings are estimated.

Three things can be said about the work that has been developed. On the one hand, traction energy can be managed to make efficient use of it. On the other hand, the studies also establish the recommendation to identify key indicators for monitoring and follow-up in energy reduction projects. As key indicators, cost functions and specific consumption indicators are available as tools for planning and public policy decisions.

This paper is organized as follows: In a first part, a characterization of the energy consumption of a system of this nature is made and some reference consumptions of some metros in the world are mentioned. The work continues with the establishment of the theoretical framework related to energy consumption. Then, in the third session, the methodology is presented, including the description of a developed software application and the description of an operation scenario to determine the specific consumption. In the final part, the results obtained are presented and analyzed and the most important conclusions of the work are drawn.

2. CHARACTERIZATION OF CONSUMPTION

Electrical energy consumption in a metro-type system is basically divided into three items corresponding to consumption for auxiliary services, energy for traction itself and energy for regenerative braking, although the latter is returned to the system's power supply network by regenerative braking.

The energy consumption for traction represents between 50 percent and 70 percent of the total energy consumed by the system [5-6], hence the importance of analyzing this energy with the importance of analyzing this energy with the aim of to establish reliable monitoring indicators in the operation and identify potential savings, increase efficiency, and reduce the emission of pollutants into the environment. To be a little more precise in the discrimination of consumption, Table 1 shows some examples of consumption for various metro systems in the world [5, 7-10].

The energy consumption of a subway system depends on many variables, among which are the instantaneous speed, the weight of the cars, the number of axles, the average weight of the passengers, the acceleration, the deceleration during braking, and the slope of the track.

An inquiry of the specific consumptions (energy consumption per unit of travel length) calculated or obtained through simulations, except for the Medellín, Washington and Valencia subways, various subways around the world are shown in Table 2.

Table 1. Typical discrimination of energy consumption in a metro-type system.

Subway	Line	Energy for auxiliaries [%]	Energy for braking [%]	Energy for traction [%]
Madrid [7]	10	14	22	64
n.a. [10]	n.a.	20	33	47
Beijing [8]	Yizhuang	15	30	55
Beijing [5]	Yizhuang	20	33	47

Table 2. Specific energy in some subways around the world.

Subway	Line	Length [km]	Specific energy [kWh/km*tren]
Madrid [7]	10	23	14.22
Madrid [7]	3	16.4	12.91
Medellín [9]	A	25.6	9.18 (measured)
Beijing [8]	Yizhuang	22.73	11.35 (empty)
Beijing [8]	Yizhuang	22.73	31.2 (service)
Portland [10]	MAX Blue	53	10.6
Chicago [10]	Orange	21	31.42
Chicago [10]	Brown	18.3	25.82
Washington [6]	All lines	171	26.5 (measured)
Valencia [11]	7	15.45	31.95 (measured)
Valencia [11]	7	15.45	32.68
Bangkok [12]	BTS Silom	14.67	20.37

3. ENERGY CONSUMPTION MODEL

The model for energy determination includes the electromechanical variables with which both the energy consumed, and the energy returned to the distribution system can be calculated [13]. Equation (1) quantifies the positive (consumed) energy, EC(t), when the train is in traction mode; that is, when energy flows from the distribution system to the train. On the other hand, when the train is in the regenerative braking (deceleration) mode [14], the energy, ECre(t), flows from the train to the distribution system, is quantified by equation (2) and is considered negative.

$$EC(t)=\begin{cases}\alpha_1*\beta_1+\alpha_2*\beta_2+P(t), \forall P(t)>0\\ (\alpha_1*\beta_1+\alpha_2*\beta_2), \forall P(t) \quad <0\end{cases} \tag{1}$$

Where:

EC(t): Instantaneous energy consumed with train in motion, [kWh].

P(t): Instantaneous traction power with train in motion, [kW].

α_1 : Headend power, [kW].

α_2 : Fraction of head-end power (kW) (suggested value: 0.05).

β_1 : Dummy logic variable.

β_2 : Dummy logic variable.

The terms in equation (1): $\alpha_1 * \beta_1$ y $\alpha_2 * \beta_2$ are related to the maximum system load. The constants β_1 y β_2 are logical values that can take the values of 0 and 1. The value of 1 applies in the larger case with β_1=1, and β_2=0, except when the train is stopped waiting for passengers, at which time a fraction of energy must be considered. Equation (2) allows calculating the energy returned to the system and makes sense when the train is braking. For the case of the efficiency with which this energy is returned, a factor must be applied that can be calculated with equation (3) or obtained from Figure 1.

$$ECre(t) = \begin{Bmatrix} P(t) * \eta(t), \forall P(t) < 0 \\ 0, \forall P(t) \geq 0 \end{Bmatrix} \quad (2)$$

Where:

ECre(t): instantaneous energy returned to the grid by regenerative braking, [kWh].

η*(t)*: instantaneous regenerative efficiency coefficient.

$$\eta(t) = \begin{Bmatrix} \dfrac{\dfrac{1}{\alpha}}{e|\alpha(t)|}, \forall \alpha(t) < 0 \\ 0, \forall \alpha(t) > 0 \end{Bmatrix} \quad (3)$$

Where:

α: Model calibration parameter (0.65).

α(t): Instantaneous deceleration during braking, [m/s2].

The specific energy during travel in one direction is the sum of the two energies divided by the distance, as shown in equation (4), where the distance, d, is in km.

$$ECtot_{[KWh/tren*km]} = \sum \left[EC(t) + ECre(t) \right] / d \quad (4)$$

Where:

ECtot: Average specific energy consumed in a trip per unit distance, [kWh/(train*km)].

d: Length traveled by the train in the whole driving cycle, [km].

$$F(t) = \left[\left(0.6 + \frac{20}{W_p} + 0.01V(t) + \frac{K * V^2(t)}{W_p * n_p} + C \right) + D \right] * 4.44 * M \quad (5)$$

Where:

F(t): Instantaneous traction force, [N].

W_p: Train axle load with passengers (75kg/passenger), [ton].

n_p: Number of axles of the train.

K: Drag coefficient (0.65).

V(t): Speed at instant t, [km/h].

M: Total weight of the train including passengers, [ton].

$$C = 20 * \theta \quad (6)$$

Where:

θ: Track slope, [%].

$$D = 70 * \left(\frac{V^2(t) - V^2(t-1)}{8.4 * L} \right) \quad (7)$$

Where:

L: Distance traveled by the train in one second, [m].

$$P(t) = 0.746 * F(t) * V(t) / (375 * 1.61) \quad (8)$$

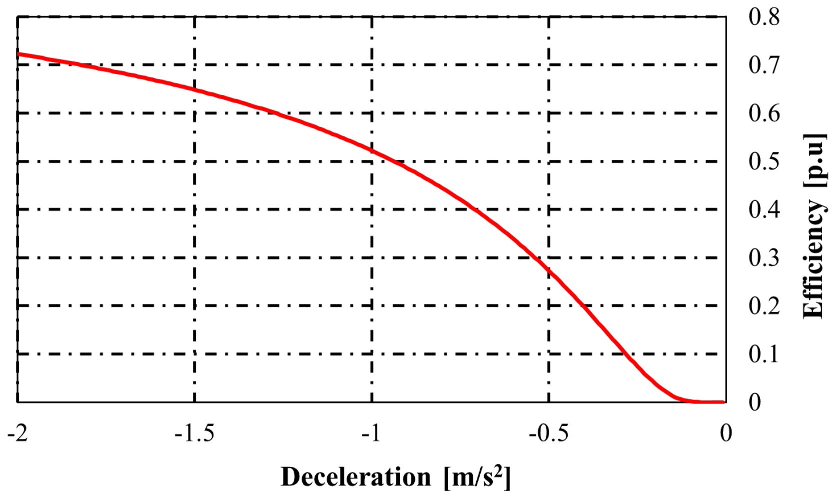

Figure 1. Energy regeneration efficiency depending on deceleration. **Source:** author, 2023.

4. CALCULATION OF SPECIFIC CONSUMPTION

To estimate the electrical energy consumption per unit of distance and per vehicle, a software application was developed in MATLAB to generate speed profiles, as shown in Figure 2.

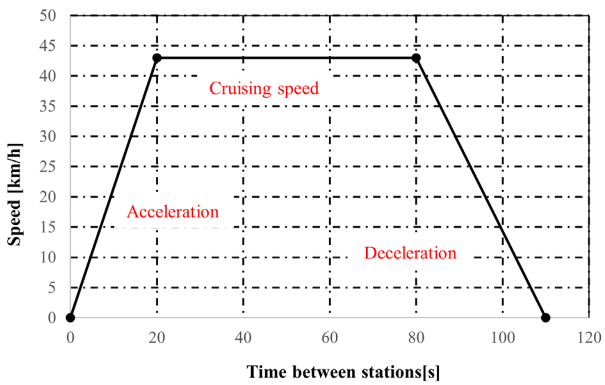

Figure 2. Typical speed profile in a section of a subway type system. **Source:** author, 2023.

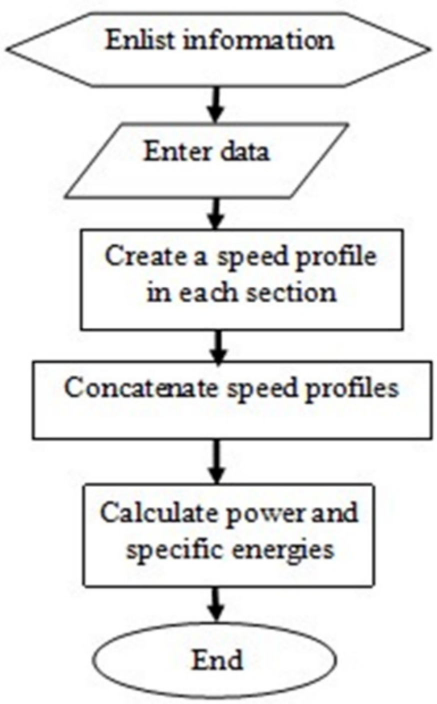

Figure 3. Algorithm flow diagram for calculation of specific energies. **Source:** author, 2023.

The application algorithm or program consists of the following: In the initial part, individual speed profiles are generated for each of the sections, considering an acceleration and an intermediate or cruising constant speed, which last for a certain time in seconds and in the final part there is a deceleration time until reaching the complete stop of the train (see figure 3).

The velocity profiles are generated with a constant initial acceleration of 1 m/s^2 up to a predefined constant or cruising speed. In the final part there is a deceleration period varying around-1 m/s^2.

A second step in the algorithm consists in concatenating the individual profiles of the first step, to obtain the total velocity profile of the total run, as shown in Figure 4, for the particular case of four sections.

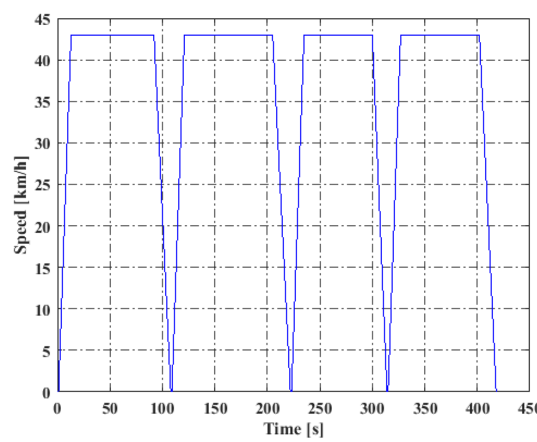

Figure 4. Example of concatenation of speed profiles of a typical route between four stations. **Source:** author, 2023.

5. RESULTS AND DISCUSSION

Representative results were obtained as shown in Figures 5 and 6 for instantaneous power and energy.

The following results were obtained for the specific energy consumed indicator in the 43 km/h cruising speed scenario with 1 m/s^2 acceleration and speed variations above and below the 43 km/h reference speed (see Table 3 and Figure 7).

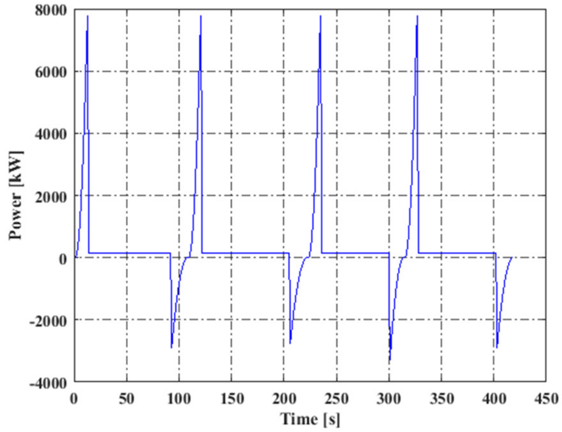

Figure 5. Peaks and valleys of power at acceleration, cruising speed and deceleration instants. **Source:** author, 2023.

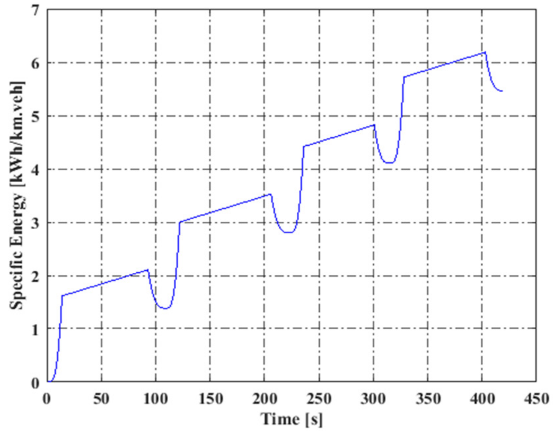

Figure 6. Integration of specific power and energy for a section between four stations. **Source:** author, 2023.

Table 3. Specific energies for different cruise speeds and constant acceleration.

Passengers	38 km/h 1 m/s²	43 km/h 1 m/s²	48 km/h 1 m/s²
450	7.68	10.46	13.82
900	11.57	15.75	20.81
1350	15.46	21.04	27.80
1800	19.34	26.32	34.79

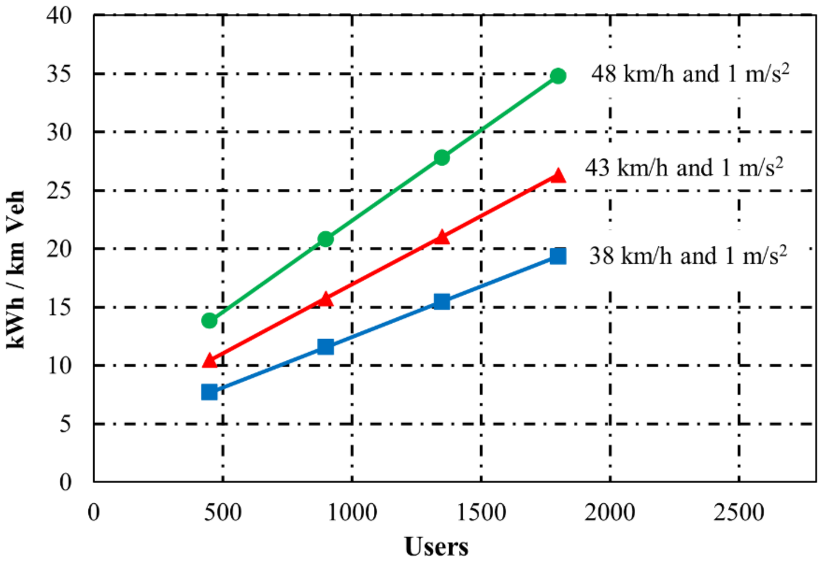

Figure 7. Specific energies for different cruise speeds and constant acceleration. **Source:** author, 2023.

6. CONCLUSIONS

The most important conclusions of this work are the following:

The theoretical formulation for the estimation of the specific electrical energy has been shown to be reliable in producing results that are relatively like the specific consumptions found in various metro-type systems in the world, found either with simulation or with measurements.

Modeling and simulation procedures, to obtain the specific consumptions in subway systems, have a great potential of use to observe the impact of some relevant mechanical variables and to perform sensitivity studies of results to variations of accelerations, decelerations, and cruising speeds.

The management of speed profiles in the operation of a metro-type transport system opens an interesting field of application of optimization techniques in the use of electrical energy.

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