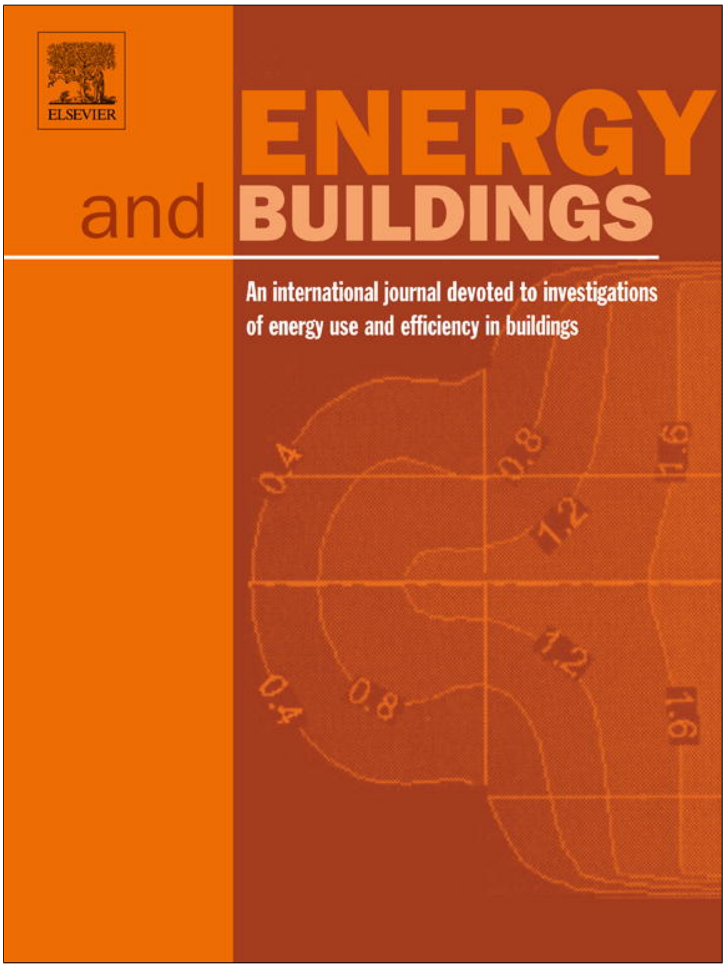
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A methodology for energy analysis of escalators

C. Carrillo*, E. Díaz-Dorado, J. Cidrás, M. Silva-Ucha

Department of Electrical Engineering, University of Vigo, Campus Universitario de Vigo, CP 36310, Spain

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ABSTRACT

Escalators are a common method of transportation for people in commercial and residential buildings, for this reason its energy efficiency is usually a matter of concern. Typically, the design of energy saving systems to be used in them involves the control of their speed. In this situation, in order to estimate the achievable energy savings it is necessary to evaluate the escalator's behaviour in terms of traffic (e.g. people per hour, loaded and unloaded periods of time, etc.). In this paper, a method to analyze this behaviour using only electrical measurements is proposed. As a result from the proposed approach, the energy saving obtained using the common two-speed control is also analyzed using data from real escalators.

1. Introduction

In addition to lifts, escalators have become the main method of transport for people inside buildings, commercial facilities or even outdoor areas. In fact, there were more than 500 thousand escalators and moving walks around the world at the end of 2008 [1]. Their market can be divided in: transit escalators (45%), commercial escalators (40%) and moving walks (15%) [1]. The structure of the industry is characterized by the dominance of four big companies (Kone, Otis, Schindler and ThyssenKrupp) whose joint share was 70% during 2006 [2]. According to the E4 project, the annual energy consumed by escalators is 904 GWh, as shown in Table 1, and the potential energy savings are around 30% [3–5].

In order to achieve the above mentioned savings, it is necessary to use high efficiency motors, drives, transmissions, bearing, etc. Maintenance and lubrication must also be taken into account to keep the efficiency at its maximum level. Apart from design aspects, the control strategies of the electric motor being used as the prime mover have a significant impact on the energy consumption. Usually, the energy wasted when the escalator is unloaded can be partially avoided by stopping the escalator (zero speed standby mode) or by using a reduced speed (low speed standby mode). In any case, the running speed variations of escalators must be carefully designed and maintained in order to reduce potentially hazardous situations [6]. For the sake of passenger safety, low speed standby mode is commonly preferred instead of zero speed standby mode.

The evaluation of energy savings in a particular installation should be based on the characterization of the actual energy consumption of the escalator, which strongly depends on the traffic pattern. For example, in escalators with steady or heavy traffic there is little room for energy savings by adjusting the running speed.

The energy consumption of escalators is usually analyzed by collecting the characteristics of the escalators (rise, speed, etc.) and their energy consumption. With this information, the average behaviour of escalators can be obtained, and the average energy saving potential can be estimated [3,4,7]. Nevertheless, the evaluation of energy savings in a particular installation should be based on a detailed characterization of the actual energy consumption of the escalator. Usually the characterization of an escalator involves electric power measurements combined with traffic measurements. These last measurements are usually done by means manual counting, video counting, installation of infrared detectors or indirect surveys of its usage [6–11]. These methods are quite difficult to maintain over long periods of time and their accuracy could be quite low in certain circumstances. To overcome these obstacles, this paper presents an approach that provides a detailed analysis of the escalator using only power measurements. With this approach, a detailed breakdown of the escalator's behaviour during loaded and unloaded periods can be obtained.

The paper is structured as follows. Section 2 includes a model of the escalator where the main equations related to energy consumption are presented. The data of the escalators used in this paper to apply the proposed approach is depicted in this section. The measurement campaign characteristics and the initial results are presented in Section 3. The method used to obtain the traffic behaviour is presented in Section 4, and the results derived from it are shown in Section 5. Finally, the application of the results to estimate the energy savings related to the implementation of a two-speed system is presented in Section 6.

* Corresponding author. Tel.: +34 986 813 912; fax: +34 986 812 173.
E-mail address: carrillo@uvigo.es (C. Carrillo).

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Table 1
Estimated escalator electricity consumption in EU-27.

		Commercial Buildings	Public Transportation
With inverter	Running (GWh)	65	59
	Standby (GWh)	38	36
Without inverter	Running (GWh)	354	344
	Standby (GWh)	7	1
Total (GWh)	904	464	440

2. Escalator parameters

For European countries, the foremost standard that faces escalator specifications is the European Standard EN 115:1995 [12]. The main parameters used to define an escalator are (see Fig. 1) [12–14]:

- Rise between landings (H in m), typ. between 3 and 6 m although different rises are easily found.
- Angle of inclination (α in degrees), its maximum value allowed is 30° which can be increased up to 35° when the rise is not higher than 6 m and the rated speed is not higher than 0.5 m/s.
- Step depth (x in m), whose minimum value is 0.38 m.
- Rise between threads (y in m) that shall be higher than 240 mm.
- Step width (z in m), whose standard values are 0.6, 0.8 and 1.00 m and must be higher than 0.58 m and lower than 1.10 mm.
- Rated speed (v in m/s), whose maximum value is 0.75 m/s for angles of inclination up to 30° and 0.5 m/s for angles of inclination between 30° and 35°.
- Incline travel distance (L in m), that can be obtained from:

$$L = \frac{h}{\sin\alpha} \tag{1}$$

The theoretical transport capacity C_t of an escalator measured in passengers per hour (pass/h) for a step tread depth (y) of 0.4 m can be derived by using the equation:

$$C_t = \frac{3600\,vw}{y} \tag{2}$$

where w represents the number of passenger per step (w = 1.0 for z = 0.6 m; w = 1.5 for z = 0.8 m and w = 2.0 for z = 1.0 m). Nevertheless, the actual effective transport capacity is at the most 80% of the theoretical value, one reason for this is the fact that most users tend to be hesitant at higher escalator speeds [11,15].

The power requirement to transport, simultaneously, a number N of passengers can be expressed by means of [8,13,14,16]:

$$P = P_0 + \frac{NMgv\,\sin\alpha}{\eta} \tag{3}$$

where P is the power consumption in W, M is the passenger mass (usually 80 kg), g is the acceleration due to gravity (9.81 m/s^2), η is the transport efficiency and P_0 are the fixed losses that represent the power consumption when the escalator is unloaded.

Fixed losses P_0 depends on mechanical design (chain guidance, step chain bearings and gearbox), speed and rise between landings [8,16]. The relationship between fixed losses and rise is linear when similar escalator technologies are compared [8,16]. Besides fixed losses can vary during the running hours mainly due to thermal processes.

The second term of (3) represents the variable power required for transportation, so the ideal power to transport one passenger can be obtained from:

$$P_{\text{ideal}} = Mgv\ \sin\alpha \tag{4}$$

The energy related to variable power depends on the time spent by the passenger on the escalator. Passengers walking up escalators reduce the energy demand compared to those that are standing stationary during the journey, whose travel time is close to the rated one [8,16]. The relationship between the time spent by walking passengers and the rated travel time is called walking factor K:

$$K = \frac{T_w}{T_r} \tag{5}$$

where T_w is the mean travel time of passengers (walking and standing ones) and T_r is the rated travel time. So the energy E consumed by the escalator in a determined period of time can be defined by:

$$E = E_0 + \frac{KNMgv\,\sin\alpha}{\eta} \tag{6}$$

where E_0 is the energy related to the fixed losses. Furthermore, walking factor affects to the real transport capacity by increasing its value.

An aspect that is essential for energy saving strategies is the fact that fixed losses P_0 depend on speed when the escalator is unloaded (low speed standby mode). This relationship is quasi-proportional which means that a 30% speed reduction implies approximately a 30% reduction on power demand [17,18]. This is due to the fact that escalators require a nearly constant torque throughout their speed range, for a specific load.

In order to apply the methodology presented in this paper, real data from escalators in a clothing store have been used as reference. This store has four levels and three escalators (called 1–3) between the different floors, see Table 2. The escalators are only in the upwards direction, so access to the downstairs floors is done by means of stairs and an elevator. The main difference between the escalators is the rise between landings which mainly affects the rated power of the electrical motor used as drive and the rated travel time.

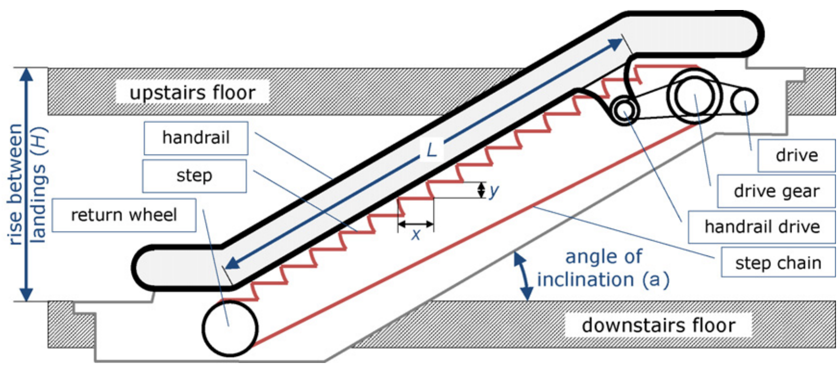

Fig. 1. Escalator scheme.

Table 2
Escalator characteristics.

Escalator	1	2 and 3
Travel direction	Up	
Daily running hours	10 (10:00 to 20:00)	
Rise between landings (m)	5.12	3.80
Inclination (°)	35	
Theoretical transport capacity (pers./hour)	6.750	
EN 115-1 transport capacity (pers./hour)	4.800	
Step width (m)	0.8	
Rated speed (m/s)	0.5	
Rated travel time (s)	19.3	17.0
Rated power of motor (kW)	5.50	4.00
Incline travel distance (m)	9.0	6.6
Steps	26	20.5

Table 3
Parameters of the measurement campaign.

Escalator	1	2	3
Sampling period (ms)		20	
Length of records (min)		3 or 4	
Samples per record		9000 or 12,000	
Periodicity of records (min)		10	
Duration of measurement campaign (days)	12	9	4

3. Power measurements in escalators

The measurement of the power consumption of escalators is the basis for the methodology presented in this paper. Using solely this information besides de escalator parameters, all the information relative to traffic in an escalator can be derived. In this section, the measurement procedure and tests to obtain the transport efficiency are depicted.

3.1. Measurement campaign

A measurement campaign on the escalators depicted in section II has been carried out, where a portable network analyser LEM TOPAS 1000 has been used.

The measurement campaign has been designed according to the systematic sampling technique, in that way data obtained represents the escalator behaviour properties [19]. Measurements are formed by groups of records of 3 or 4 min lengths with a periodicity of 10 min, where electrical parameters have been registered with sampling period of 20 ms (see Table 3 and Fig. 2). This kind of measurements is common when low frequency components in electric power (e.g. those related to flicker) have to be measured [20–22].

The above mentioned data will be mainly used to characterize traffic patterns. For example, in the records, it can be observed several steep changes that appear when passengers enter (power increases) the escalator and when they leave it (power decreases). However, the data is quite noise, which makes necessary the process depicted in the following section in order to obtain information about the traffic in the escalator.

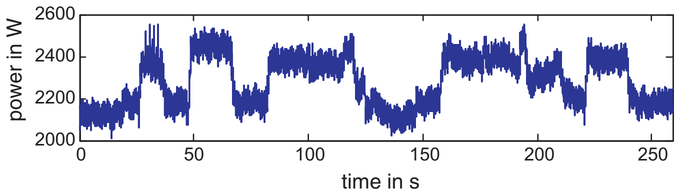

Fig. 2. Record example: power in escalator 1.

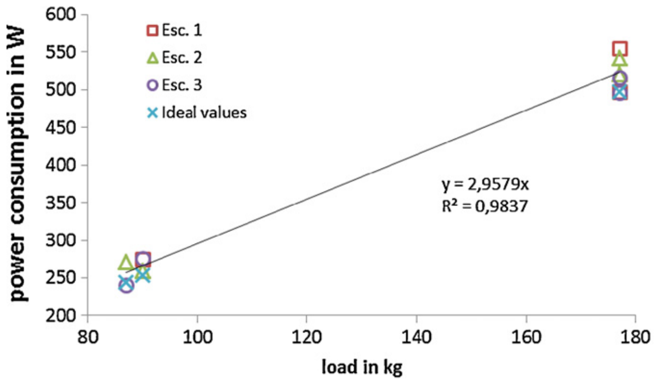

Fig. 3. Power consumption due to traffic in different escalators.

3.2. Tests to obtain the transport efficiency

An experiment with different loads was conducted in order to estimate the transport efficiency, see η in (3). Escalators have been loaded with known weights, and the power consumption due to traffic has been obtained as shown in Fig. 3. Using linear regression the value of transport efficiency is estimated at having a value of 95% (η = 0.95), see Table 4. As can be seen, the efficiency values obtained for the three escalators are very similar.

4. Traffic estimation method

The main difficulty that arises when trying to analyze the power pattern of escalators under different situations is to obtain the traffic pattern. In this paper, the traffic has been obtained from long records as those depicted in section III.A. The steps followed for this purpose are: power normalization, data filtering and traffic detection.

4.1. Power normalization

In a first step, measured power values have been normalized to compensate the effect of voltage variations, as shown in Fig. 4. In asynchronous machines, power consumed depends on squared voltage when speed is constant [23]. Assuming that voltage variations are lower than 5% and that speed variation related to voltage is negligible, the following relationship can be used for each record:

$$p_{nj}(t) = p_{mj}(t)\left[\frac{U_n}{u_{mj}(t)}\right]^2 \qquad (7)$$

where sub-index j represents the record j, $p_{nj}(t)$ is the normalized power, $p_{mj}(t)$ and $u_{mj}(t)$ are the measured power and voltage, and U_n is the nominal voltage of power network.

4.2. Data filtering

As shown in Fig. 2, the power measured in the escalator is quite noisy, hindering the identification of power steps related to traffic. To overcome this problem the use of an edge detection filter called Nonlinear Diffusion Filter, which is typically used to enhance edges in noisy data, is proposed. A one-dimensional version of the filter has been implemented and applied to the normalized power. So, the

Table 4
Escalators efficiency.

Ideal transport consumption (W/kg)	2.81
Measured transport consumption (W/kg)	2.96
Transport efficiency	95%

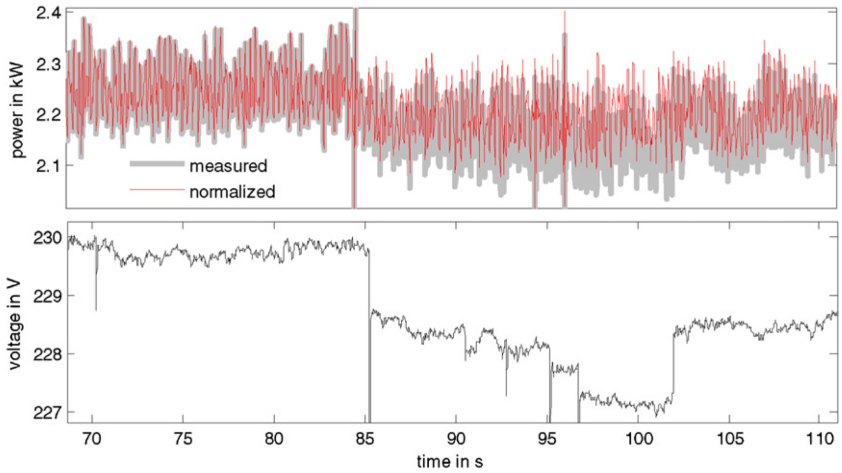

Fig. 4. Measured and normalized power and measured voltage.

filtered $p_{fj}(t)$ data can be obtained by solving the equation [24–26]:

$$\frac{\partial p_{fj}(t,T)}{\partial T} = \nabla\cdot(g(|\nabla p_\sigma|^2)\nabla p_{fj}(t,T)) = \frac{\partial}{\partial t}\left(g\left(\left|\frac{\partial p_\sigma}{\partial t}\right|^2\right)\frac{\partial p_{fj}(t,T)}{\partial t}\right) \quad (8)$$

where $p_{fj}(t,T)$ represents the filtered data being t the time instant of measured data and T the time scale used to iterate with the filter. So, for a given record j, the following relationship can be established: $p_{fj}(t,0) = p_{nj}(t)$. And, for a given simulation step ΔT and a number of iterations n, the solution can be written as: $p_{fj}(t) = p_{fj}(t, n\Delta T)$. ∇p_σ is the gradient of a smoothed version of p_{fj} which is obtained by convolving *it* with a Gaussian:

$$\nabla p_\sigma = \nabla(K_\sigma * p_{fj}(t,T))$$
$$K_\sigma = K_\sigma(t) = \frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{t^2}{2\sigma^2}\right) \quad (9)$$

The value of standard deviation σ makes the filter insensitive to noise at scales smaller than σ.$g(\,)$ is the non-linear equation for diffusivity function:

$$g(|\nabla p_\sigma|^2) = \begin{cases} 1 & |\nabla p_\sigma|^2 = 0 \\ 1-\exp(-C_m/(|\nabla p_\sigma|^2\lambda)^m) & |\nabla p_\sigma|^2 > 0 \end{cases} \quad (10)$$

where C_m can be derived from:

$$1 = \exp(-C_m)(1+2C_m m) \quad (11)$$

This value of the diffusivity function is designed to preserve edges whose effect is enhanced for larger values of m. Theparameter λ plays the role of a contrast parameter; data with $\nabla p_\sigma > \lambda$ are regarded as edges, where the diffusivity tends to 0, while data with $\nabla p_\sigma < \lambda$ are considered to belong to the interior of a region limited by edges, so the diffusivity tends to 1.

Table 5
Parameters of the diffusion equation.

Contrast parameter λ	1.5
Number of steps	200
Step size	Variable from 0.5 to 1000
Standard deviation σ	Variable from 50 to 1
Exponent m	10

In order to solve the filter equation, it has been discretized and calculated by using the additive operator splitting (AOS) method [25] implemented in MATLAB [27]. The parameters used in this paper are shown in Table 5.

Finally, an example of the results of data filtering is shown in Fig. 5 where the effectiveness of the filter in preserving edges and in reducing signal noise can be seen.

4.3. Traffic detection

The main objective of analysing power and voltage measured in the escalator input is to detect when a person enters and leaves the escalator. The signal resulting of filtering (see Fig. 5) roughly represents this traffic. In order to estimate the traffic, the filtered signal is approximated by means of a sum of square functions that represent a single travel of a person or a group of them in theescalators,

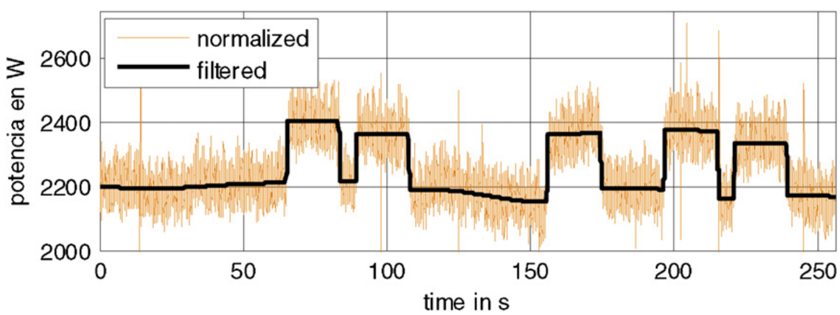

Fig. 5. Measured and filtered power consumption.

and a constant value that represents the fixed losses. So, for each record the following expression has been used:

$$p_j(t) = P_{0j} + \sum_{i=1}^{N_j} P_{ij} u\left(\frac{t-\tau_{ij}}{T_{ij}}\right) \tag{12}$$

where $p_j(t)$ is the estimated power consumption during the record j. $P_{0,j}$ represents the fixed losses during record j which are supposed to be constant during each record (the time dependence of these losses is analyzed in section V.B.). N_j is the number of single travels during record j. $P_{i,j}$ is the power consumption related to single travel i in record j. $\tau_{i,j}$ ans T_{ij} are the instant of starting and duration of the single travel i in record j. $u(t)$ is a step function defined by:

$$u(t) = H(t) + H(t-1) \tag{13}$$

where $H(t)$ is the Heaviside step function.

The parameters N_j and τ_{ij} can be easily calculated from filtered power because they can be derived from the steep changes in the power. The remaining parameters $P_{0,j}$, $P_{i,j}$ and T_{ij} have been obtained by minimizing for each record "j" the index O_j:

$$O_j = \sum_{k=1}^{M_j} [p_j(k\Delta t) - p_{fj}(k\Delta t)]^2 \tag{14}$$

where p_{fj} is the filtered power during the record j, M_j is the number of samples of each record and Δt is the sampling period (see values in Table 3). The method chosen to minimize O_j is the Nelder–Mead simplex method [28].

An example of traffic power decomposition is shown in Fig. 6, where in the top image the normalized power and the estimated power are represented. In the middle plot, numbered from 1 to 5, the power related to each single travel is shown. Finally, the fixed losses P_0 are represented in the bottom image.

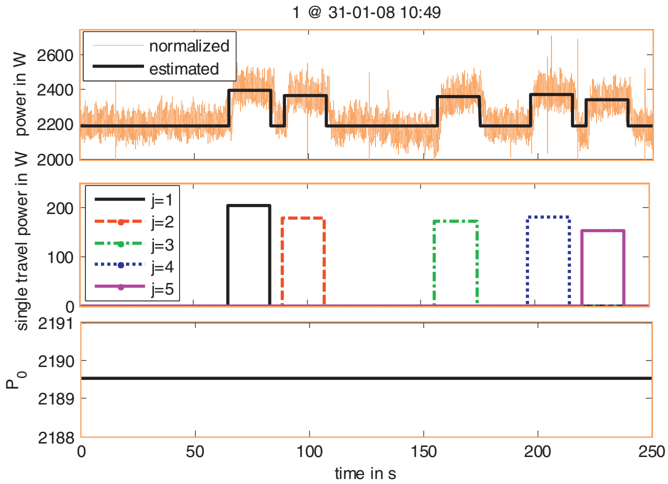

Fig. 6. Traffic power calculation by using the power consumed in single travels (top image: normalized and estimated power; bottom image: fixed losses; middle image: power consumed by the different single travels).

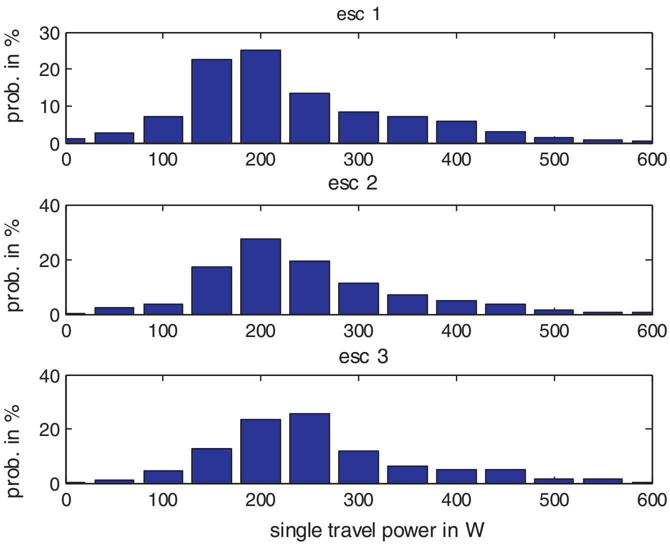

Fig. 7. Single travel power consumption histogram.

5. Traffic estimation results

In the previous paragraphs, the methodology to obtain the traffic power as a sum of single travels has been depicted. Using the resulting traffic power, the following information can be derived: the traffic in passengers per hour, the walking factor and the mean time between travels. For this calculation, a typical passenger mass is used, see (3), and also the transport efficiency η obtained in Section 3.2. By means of these traffic parameters, the impact of control strategies for energy efficiency improvement can be analyzed.

5.1. Traffic pattern

Once single travels have been obtained as depicted in Section 4.3, the number of single travels, the mean power of them and the number of passengers per day (or number of single travels per day) can be obtained, as shown in Table 6.

The consumption associated to single travels is shown in Fig. 7. Considering the values of traffic consumption in Table 4 the daily pattern of traffic can be obtained, as shown in Fig. 8. In these results, it can be seen that there is a lower level of traffic over the lunch period, and traffic is at its busiest in the afternoons.

Table 6
Traffic characterization results.

Escalator	1	2	3
Number of single travels	4159	958	508
Mean power of single travels (W)	234.5	245.6	256.0
Mean mass of passenger travelling (kg)	76.6	80.26	83.66
Number of passengers per day (pass./day)	347	106	127
Walking factor K	0.91	0.81	0.79
Mean unloaded power or fixed losses (W)	1984.2	1483.9	1476.0
Number of loaded and unloaded periods	2383	741	393
Mean unloaded time in s	42.5	142.6	140.79
Mean loaded time in s	22.6	15.0	15.0
Daily energy during unloaded periods (kWh/day)	4.67	4.83	5.65
Daily energy during loaded periods (kWh/day)	2.86	0.61	0.72
Daily energy related to traffic (kWh/day)	0.396	0.099	0.122

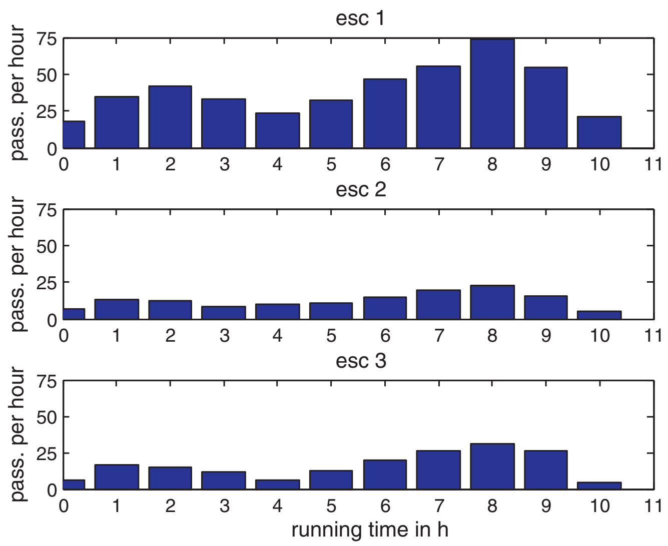

Fig. 8. Daily traffic pattern in passengers per hour.

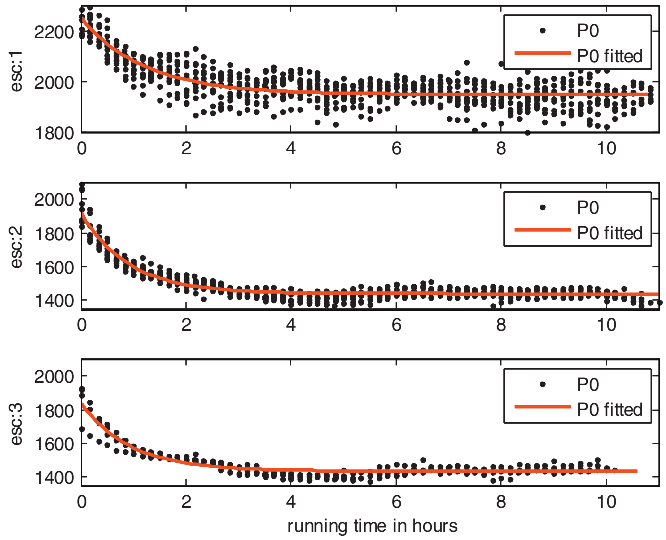

Fig. 10. Unloaded power consumption evolution against running time.

Mean mass of passenger travelling in the escalator can be obtained from the mean power consumed during single travels, shown in Table 6, which is close to the value (80 kg) usually chosen as reference [8,12,13].

Another parameter that can be useful is the walking factor, K in (6), which can be used to estimate the energy consumption. Its value can be obtained from (see results in Table 6):

$$K = \frac{1}{T_r}\frac{1}{\sum_{j=1}^{N_r} N_j}\sum_{j=1}^{N_r}\sum_{i=1}^{N_j} T_{ij} \tag{15}$$

where N_r is the number of records of the measurement campaign. Finally, the probability of individual travel time relative to the rated travel time (see Table 2) is shown in Fig. 9.

5.2. Fixed losses P_0

The unloaded consumption or fixed losses, whose mean values are shown in Table 6, seem to be fairly constant as shown in Fig. 2. However, when it is analyzed in detail, it presents an exponential pattern during the day, as shown in Fig. 10. During the initialrunning hours of the day its value is higher, and after 3 or 4 h from the start it reaches its minimum value. This behaviour could be related to a thermal process in the handrail, gearbox, etc. The time dependence of unloaded consumption $p_0(t)$ can be approximately modelled using the following expression:

$$p_0(t) = P_{0,SS} + \Delta P_0 e^{-t/T_0} \tag{16}$$

where T_0 is the time constant, $P_{0,SS}$ are the fixed losses in steady state and ΔP_0 represent the extra fixed losses during the first running hours. These values are obtained by fitting the curve as shown in Fig. 10 and Table 7. This means that the steady estate is reached between 4 and 6 h (3–4 times T_0) from the escalator running start.

Using (16), the impact on energy consumption of fixed losses behaviour can be evaluated. The relative reduction of energy consumption, that would be obtained if the escalator was running with constant fixed losses equal to $P_{0,ss}$, would be 1.7%, 2.8% and 2.5% for escalator 1, 2 and 3, respectively.

Due to the low impact of fixed losses variation in energy consumption, its mean value has been used in energy calculation expressions, as those shown in Section 2.

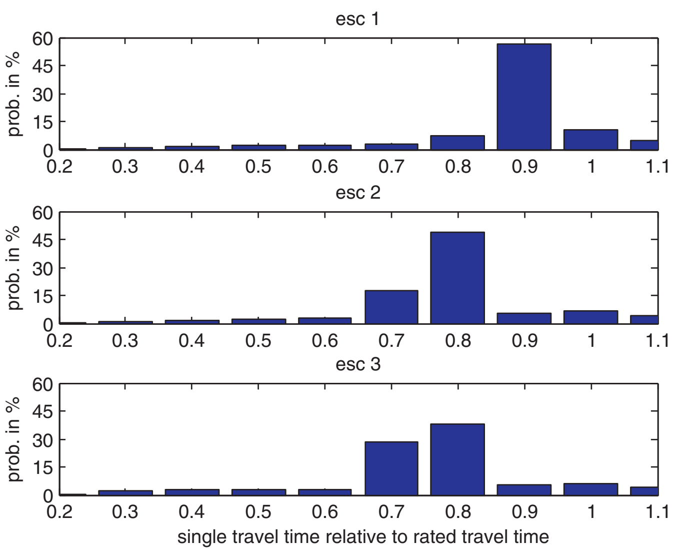

Fig. 9. Single travel time relative to rated travel time.

5.3. Loaded and unloaded periods of time

In order to evaluate strategies of speed reduction in escalators, the analysis of the periods of time when an escalator is unloaded can be useful. The probability of occurrence of a determined unloaded time is shown in Fig. 11 and their mean values are in Table 6. The resulting histogram can be fitted by the exponential density distribution [10]:

$$F(T_{NL}) = \begin{cases} 1 - e^{-T_{NL}/\bar{T}_{NL}} & T_{NL} \geq 0 \\ 0 & T_{NL} < 0 \end{cases} \tag{17}$$

where T_{NL} is a period of time with the escalator unloaded and $\bar{T}_{NL}$ is its mean value (shown in Table 6). As a result of fitting, the values

Table 7
Fixed losses parameters.

	$P_{0,SS}$ in W	ΔP_0 in W	T in hours
Esc 1	194,775	30,309	1.20
Esc 2	143,840	47,858	0.91
Esc 3	143,506	40,393	0.93

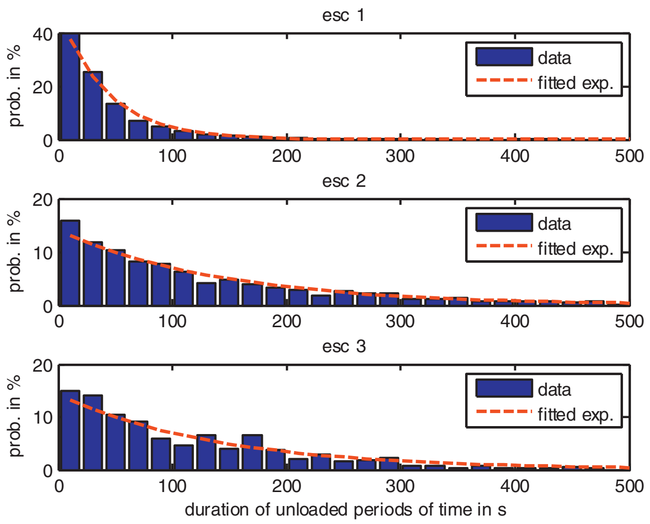

Fig. 11. Histogram of periods of time with unloaded escalator.

of the coefficient of determination R^2 obtained are 0.993, 0.969 and 0.937 for escalators 1, 2 and 3, respectively.

Finally, the histogram of periods of time with loaded escalator is shown in Fig. 12 and their mean values are in Table 6, where can be observed that the maximum probability is near to the rated travel time in Table 2.

5.4. Evaluation of systematic sampling technique

As a final step, the ability of the proposed measurement campaign, based on the systematic sampling technique, to obtain the statistical behaviour of escalators has been tested by means of a Monte Carlo simulation [29]. As an example, the statistical properties of the duration of loaded and unloaded periods have been tested.

According to the above mentioned technique, the results of the measurement campaign are records of 3–4 min lengths taken every 10 min over several days, as shown in Fig. 13. In order to obtain the duration of loaded and unloaded periods, the collected records have been consecutively joined together and the results have been treated as a complete record period, see Fig. 13.

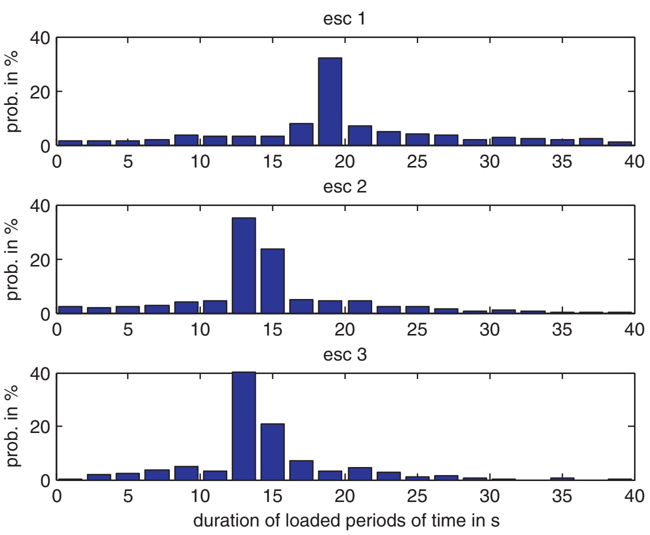

Fig. 12. Histogram of periods of time with loaded escalator.

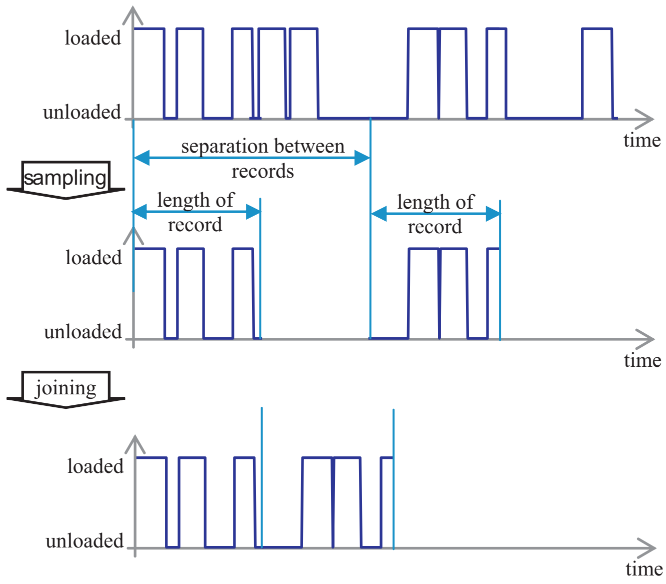

Fig. 13. Records during measurement campaign.

For simulation purposes, the length of unloaded periods has been supposed to have an exponential distribution (see Section 5.3). On the other hand, for the length of loaded periods a normal distribution has been considered (see parameters in Table 9). For reference, the values of mean and standard deviation of the duration of loaded and unloaded periods have been chosen to be similar to those shown in Section 5.3.

From the supposed distributions and using a Monter Carlo technique, a population of lengths of loaded and unloaded periods has been generated, according to the parameters shown in Tables 9 and 10. With these values, a set of data called complete data representing the behaviour of the escalator has been formed. Finally, several records have been taken from this data as depicted above, and a set of data called sampled data has been obtained.

As a result, the mean values and the histogram from complete data and sampled data have been calculated and they can be seen in Table 8 and Fig. 14. The relative error of the mean value obtained from the sampled data is approximately 5% for loaded periods and 3% for unloaded periods. Furthermore, the resulting histograms are quite similar to those obtained from theoretical distributions. This means that the statistical properties of sampled data are similar to those from complete data, which validates the systematic sampling technique to characterize the traffic of the escalators.

Table 8
Monte Carlo and sampling results.

	Mean duration of loaded periods	Mean duration of unloaded periods
Complete data	21.94	42.72
Sampled data	20.62	40.81
Error of complete data	0.2%	1.8%
Error of sampled data	−6.3%	−2.8%

Table 9
Parameters of the probability distributions used in Monte Carlo.

	Length of loaded periods	Length of unloaded periods
Distribution	Exponential	Normal
Mean	22	42
Standard dev.	3	42

Table 10
Monte Carlo data.

Sampling rate	20 ms
Length of record	4 min
Separation between records	10 min
Number of loaded and unloaded periods	10,000
Number of days simulated	7.45

6. Estimation of energy savings

6.1. Strategies to increase the energy efficiency

As can be derived from Table 6, the energy directly related to traffic is less than 6% (esc. 1: 5.26%; esc. 2: 1.82% and esc. 3: 1.92%). This means that fixed losses are responsible for more than 90% of the consumption in an escalator. As a consequence, most of the strategies of energy efficiency involve a reduction in those fixed losses [17,18].

The most common way to improve the energy efficiency of escalator is to implement a speed control system that reduces the escalator speed when it is unloaded [7,30,31]. This is usually done by implementing a two-speed control by means of a two-speed motor or a variable-voltage variable-frequency (VVVF) converter. A reduced speed or standby speed is applied when the escalator is without passengers, and the rated speed is used when a passenger is detected (loaded escalator). After the passenger leaves the escalator, there is a time delay before the slow down from the rated speed to the reduced speed. It is usually recommended using a higher value than 10 s for that time delay [32]. The reduced speed or standby speed is usually set to 0.1–0.2 m/s while the rated speed is 0.5–0.75 m/s [32–34].

The reduction of speed has a proportional relation to fixed losses. That relation has been tested using measurements (see Fig. 15) done in an escalator in a shopping centre, where a two-speed control system by means of a VVVF drive is implemented. In this escalator, the ratio between the reduced speed and the rated speed is 0.29 and, the ratio between the power consumed at the two speeds obtained from measurements is equal to 0.31, very close to the speed ratio.

6.2. Estimation of energy savings with the two-speed strategy

The impact on escalator energy demand, when using the two-speed strategy, can be estimated for the escalators analyzed in this

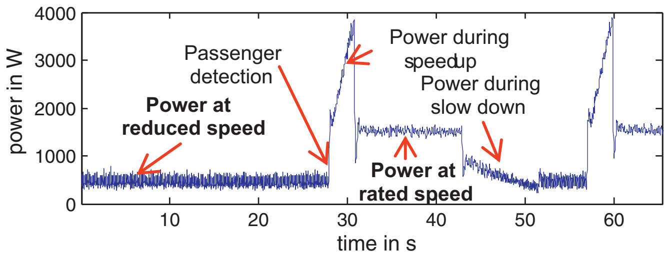

Fig. 15. Power measurements in an escalator with VVVF running at two different speeds.

study. For the sake of simplicity, the energy consumed during the speed up or slow down has not been taken into account; thus the results represent the maximum achievable savings with this strategy. In this case, the energy to be demanded during the unloaded periods is:

$$E_{NL,2S} = E_{NL}Pr(T_d < T_{NL}) + K_{2S}E_{NL}(1 - Pr(T_d < T_{NL})) \quad (18)$$

where E_{NL} is the energy consumed during the unloaded periods in Wh/day (see Table 6). $E_{NL,2S}$ is the energy consumed, in Wh/day, during the unloaded periods with the two-speed strategy (see Table 6). K_{2S} is the ratio between reduced and rated speed in pu, usually lower than 0.5. T_{NL} is the duration of unloaded periods in s (see Fig. 11). T_d is the time delay in s. $Pr(x < T_{NL})$ represents the probability of the duration of unloaded periods to being lower than that of a given time x (see Fig. 11).

Taking into account that the histogram of T_{NL} values can be approximated by the exponential distribution (17), the previous equation can be rewritten:

$$\frac{E_{NL,2S}}{E_{NL}} = 1 - (1 - K_{2S})e^{-T_d/T_{NL}} \quad (19)$$

The impact of the time delay on the escalator energy demand is analyzed considering that the reduced speed is a 20% of the rated speed. If the time delay was not taken into account ($T_d = 0$), the reduction of energy during the unloaded periods of time would be more or less equal to 80%. However, according to (18), the time delay T_d affects the energy reduction. The effect of different T_d values is shown in Fig. 16. The energy savings obtained with the introduction of two-speed controls are shown in Fig. 17, where it can be seen that high values in the time delay can significantly

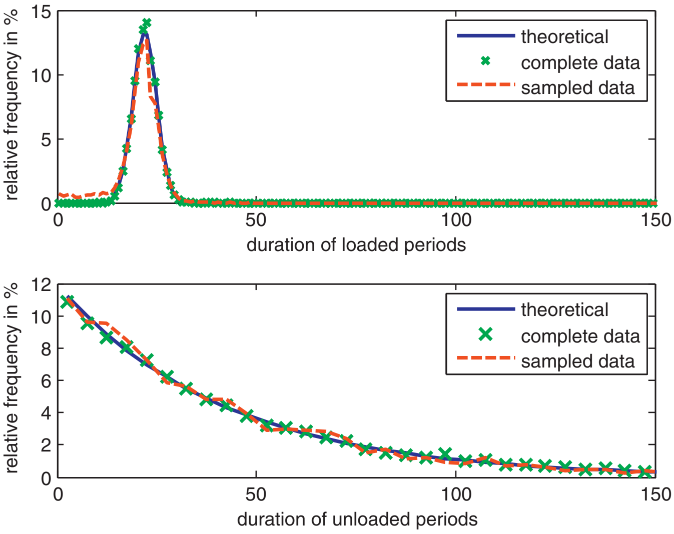

Fig. 14. Histograms of length of loaded and unloaded periods obtained from: theoretical distribution, complete data and sampled data.

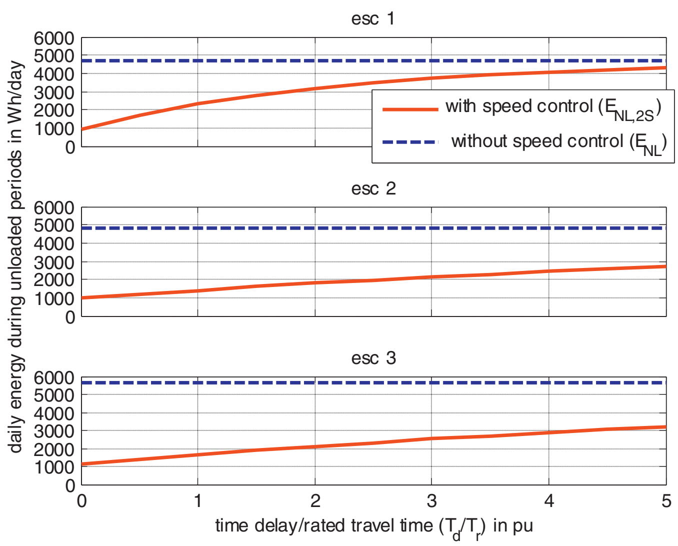

Fig. 16. Daily energy during unloaded periods with and without the two-speed control.

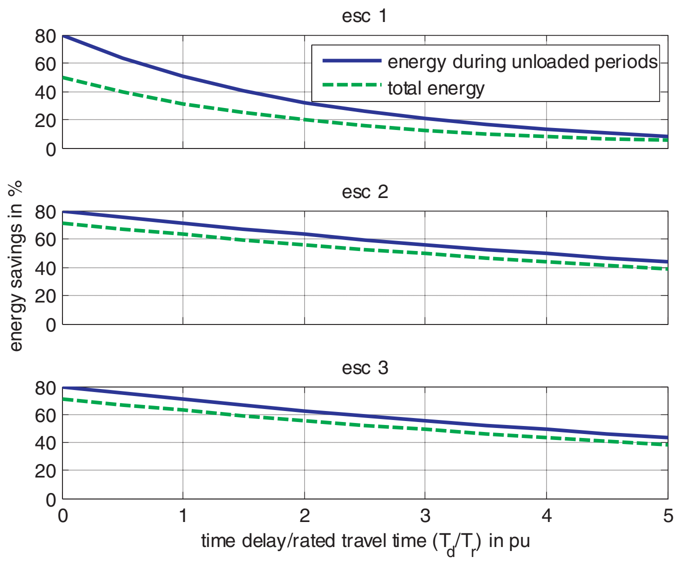

Fig. 17. Daily energy savings, total and during unloaded periods, with the two-speed control.

reduce the achievable savings. This effect is more important in the escalator with the highest traffic (see escalator 1 results).

7. Conclusions

In this paper, a methodology to analyze traffic behaviour in escalators and, consequently, its impact in energy consumption is proposed. The main advantage of the suggested method is that only electrical measurements are necessary. This allows exhaustive analysis during long periods of time without adding additional devices. The proposed approach has the following steps:

- A measurement campaign based on systematic sampling technique.
- Power normalization in order to compensate the effect of voltage variations.
- Data filtering with non-linear diffusion techniques in order to enhance the edges in normalized power related to traffic.
- Traffic detection by means of decomposition of filtered power in single travels defined by using the Heaviside function.

The proposed methodology has a result a detailed characterization of the traffic in an escalator. This allows to derive the following information: walking factor, passengers per hour, distribution of periods of time when escalator is loaded or unloaded, etc. Furthermore, information regarding to the energy consumed by escalators and its relation with traffic can be obtained. For example, the energy consumed during unloaded and loaded periods and the energy associated to traffic can be estimated, which is very useful for estimating the impact of energy saving strategies.

The proposed methodology has been applied to data measured in the three escalators of a clothing store. As a result, the traffic in each instant can be obtained and relevant data of traffic can be calculated, e.g.: the traffic in the busiest escalator was 347 pass/day, the walking factor ranges between 0.79 and 0.91 and the mean unloaded time is 42 s in the busiest escalator and approx. 140 s in the others.

In those escalators, the histogram of unloaded time periods is close to an exponential distribution. This has allowed to obtain an expression to estimate the reduction in energy consumption when using a two-speed strategy. That reduction depends on time delay (time that escalator stands in the normal speed mode when a passenger leaves the escalator). So, when time delay is close to the value usually recommended (10 s) the energy savings are approx. a 30% for the busiest escalator and a 60% for the others.

Another, results of interest is the dependence of fixed losses with respect to the running hours, although its impact in energy consumption is quite low (<3%).

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