Energy Consumption and Service Performance of Escalators

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In the present paper, an index is proposed about the overall efficiency of single escalators in terms of energy consumption and service performance. The index correlates the energy consumed with the number of passengers being served, the elevation height and the average time needed for the service provided. The index may serve as an assisting tool towards designing more efficient escalators in terms of operation and energy consumption. The data needed for the evaluation of the proposed index are derived by applying specialized circulation studies for the estimation of traffic load and energy consumption analysis considering the mechanical and electrical design of the escalator. A case study exemplifies the proposed approach.

Keywords: *escalators, energy consumption, service performance, index, mechanical design, circulation study*

1. INTRODUCTION

Reduction of energy consumption in building transportation systems has become an issue of extensive scientific research because these systems consume a significant percentage of total energy in multi-storey buildings. Escalators could not be excluded from this research as they contribute to the transportation of large amount of people in various commercial and public facilities (malls, railway stations etc.).

The analysis of energy consumption of escalators is a complex issue as it is affected by their design as well as various operational factors such as maintenance, control and circulation demand. The latter is characterized by high diversity of both intensity and passenger load depending on building type, purpose and population and should always be examined carefully when designing new conveying systems that should obtain low energy consumption. From another point of view, provision of effective transportation service is the main goal that should be achieved by the operation of in-building transportation systems and this goal should not be underestimated for the sake of energy consumption reduction. Thus, in the context of designing overall efficient escalators, there is a necessity to systematically correlate their calculated energy consumption with their expected transportation operation and performance.

A thorough examination of the relevant scientific literature reveals that a lot of work has been done focused on the measurement - via proper equipment - of the energy usage of escalators [1][2][3]. The extracted data are used for the analysis of the traffic load to the escalators' energy consumption and for the formulation of generic guidelines to obtain energy savings, without any in-depth reference to quality of service or to mechanical design details.

Focusing on design models, International Organization of Standardization [1] proposes a simple method to estimate the future energy consumption of escalators that are being designed. However, this is an oversimplified method that uses data based on average values for few generic parameters that cannot depict details of the mechanical design and it does not take into account the operation efficiency in relation to energy consumption. In a work by Al-Sharif [4], an energy estimation model is proposed, which does not pertain service performance and is based on measurements in already installed machines, thus incorporating all their inefficiencies and drawbacks. The connection between operation, performance and energy consumption is examined in a paper by Ma et al. [5]. Their work, however, is restricted in analyzing measurement data obtained in specific escalators in existing buildings, without proposing any advanced generic technique referring to design.

In this paper, an index is proposed that represents the overall efficiency of single escalators by correlating energy consumption and service performance. This index can be used as a generic metrics tool for assisting design of energy efficient escalators with all desirable characteristics and attributes in terms of service performance. The data needed for the evaluation of the proposed index are derived: a. by applying specialized circulation studies [6, 7] in order to estimate the amount of passengers that can be served and the average time period that would be consumed for the transportation of a passenger and b. by calculating the energy being consumed by the escalator in order to obtain the estimated service level. For the estimation of energy consumption, an analytical model is proposed that is based on a detailed analysis of escalator subsystems and assemblies. This model may also lead to reduced con–sideration of empirically determined design parameters.

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The proposed method is exemplified in a case study where the design of a single escalator for a commercial building is examined.

2. CORRELATION OF ESCALATOR SERVICE PERFORMANCE AND ENERGY CONSUMPTION IN A UNIFIED EFFICIENCY INDEX

2.1 Estimation of escalator service performance depending on basic engineering characteristics and traffic load

Escalators are rated according to their *step width* (*stw*), their *nominal speed* (v_n) and secondary, their *inclination angle* (*inc*) (see figure 1 in next page). According to standard EN–115:2008+A1 [8], (*stw*) varies from 0.58 m to 1.1 m, however typical (*stw*) values practically are restricted to 0.6 m, 0.8 m and 1 m. Again according to EN-115, nominal speed (v_n) should not exceed 0.75 m/s when escalator inclination (*inc*) is up to 30^o and 0.50 m/s when (*inc*) is up to 35^o (most used values are 0.5, 0.65 and 0.75 m/s). Inclination (*inc*) varies from 27.3^o to 30^o regardless of *escalator rise* (H_e), with commonest value being that of 30^o [6, 7]; however if (H_e) is lower than 6 m, (*inc*) can reach 35^o.

According to the literature of building transportation systems [6, 7], the parameter that is usually calculated for the evaluation of escalator service performance is the *escalator capacity* (C_e) in terms of persons per time period (t). (C_e) is a function of *escalator speed* (v), the *number of passenger density per step* (*pd*) and the *number of steps per meter* of escalator step row. The latter depends on the length of *step pitch* (*stp*). According to EN-115:2008, (*stp*) must be larger than 0.38 m and typical (*stp*) values are 0.394, 0.4, 0.4064 and 0.4104 m, with that of 0.4 m being by far the commonest value. Finally, the capacity of an escalator in persons per *time period* (t) (s) is:

$$C_e = t \cdot v \cdot pd \cdot (1/stp) \tag{1}$$

In this expression the symbol (v) is used for escalator speed instead of (v_n) because modern escalators feature vvvf drives and are capable to operate at different and lower to (v_n) speeds when the traffic load is lesser for a significant time period.

Passenger density per step (*pd*) depends on step width and on escalator speed as the higher the speed is the more difficult is for passengers to catch up a step and board on escalator. EN-115:2008 provides with maximum escalator capacity values in persons/hr for all combinations between 0.6, 0.8 and 1 m (*stw*) values and 0.5, 0.65 and 0.75 m/s (v_n) values, considering both the aforementioned factors that affect (*pd*). The use of expression (1) with these data gives, for every (*stp*) value, the maximum (*pd*) values that are expected when the escalators with the aforementioned (*stw*) - (v_n) combinations operate in full load. For (*stp*) equal to 0.4 m, maximum (*pd*) is given in table 1 below.

In conventional circulation studies, the *expected amount of transportation demand* in terms of persons per period ($T(i)$) of time ($t_{T(i)}$) is estimated and then, the escalators that obtain relatively higher maximum capacity (C_e) are selected. In other words, the *arrival rate* (λ) in persons/s of passengers who approach the escalator system should be lower than the maximum escalator capacity in persons/s, that is reached when (*pd*) is maximum.

Table 1. Maximum expected passenger density per step for escalators with 0.6, 0.8, or 1 m step width and 0.5, 0.6 or 0.75 m/s nominal speed

stw (m)	v_n (m/s)		
	0.5	0.65	0.75
0.6	0.8 per./step	0.752 per./step	0.726 per./step
0.8	1.067 per./step	1.008 per./step	0.978 per./step
1	1.333 per./step	1.248 per./step	1.215 per./step

In the present study though, where energy consumption is considered, not only the period with the highest traffic load is examined, but also every other time period with different demand. In every period ($T(i)$), the *amount of served persons* ($P_{T(i)}$) is calculated and the actual (*pd*) is estimated. The value of (*pd*), is an indicator of how much the escalator is crowded and also is related to the passenger weight load that is distributed along the escalator, something that is used in energy consumption calculations.

Furthermore, the *travel time* (t_{tr}) is introduced as a parameter for the evaluation of service performance,. This parameter is used for the evaluation of service "quality" [6] rather than "quantity" (i.e. capacity), revealing how fast a passenger is served by the transportation system. Travel time (t_{tr}) is the time needed for a single passenger to cover the height between two levels using an escalator. The lesser (t_{tr}) is, the greater the quality of service and hence the overall service performance of the escalator is. It is calculated by the following expression:

$$t_{tr} = (l_{inc} + 2 \cdot l_{fs}) / v \tag{2}$$

Here, (l_{inc}) is the *length of escalator* and (l_{fs}) is the *length of the row of flat steps that passengers step on in boarding and alighting landings* (see figure 1).

The estimated traffic demand in building transportation systems planning is expressed with arrival rates of passengers to the systems for different time periods [6][7]. The values of arrival rates are given by probability distribution functions (pdf) which in most cases it is the uniform pdf and in fewer cases the Poisson pdf.

2.2 Analytical calculations for the estimation of escalator energy consumption

Escalators belong to the category of apron conveyers, so the general theory for the mechanical design of that type of conveyors is used for the calculation of their energy consumption. For reasons of simplicity, in present paper the acceleration of masses when operative speed changes are not taken into account.

The analysis starts with the calculation of specific dimensions of the escalator layout. First, the escalator rise (H_e) is identical to the height between the levels to be served. Then, inclination (*inc*) (^{o}) is chosen and the length of escalator inclined line (l_{inc}) is defined:

$$l_{inc} = H_e / \sin(inc) \tag{3}$$

Then the horizontal projection of (l_{inc}), denoted as (l_1) is:

$$l_1 = H_e / \tan(inc) \tag{4}$$

Other length to be calculated *is* (l_2) in *boarding and alighting parts of the escalator*, which extends between the points where escalator inclined line intersects the horizontal line and the upper peripheral points of return and drive sprocket wheels respectively (see figure 1 below).

$$l_2 = l_{fs} + l_3 \tag{5}$$

Here, (l_{fs}) (m) depends on the escalator nominal speed (v_n) and rise (H_e) and its minimum values are given in following table.

Table 2. Minimum length of flat step row in escalator landings (*l_{fs}*) [8]

v_n (m/s)	H_e (m)	
	≤ 6	> 6
$\leq 0,5$	0.8 m	1.2 m
$0.5 < v_n \leq 0.65$	1.2 m	1.2 m
$0.65 < v_n \leq 0.75$	1.6 m	1.6 m

Length (l_3) (m) is the *length of the step row that slides horizontally below the boarding or alighting panel*. For example (l_3) is equal to (stp), if escalator is designed so that one step slides horizontally below panel before it is turned by the sprocket wheel.

Other escalator layout features are the *curvatures of step guides* in lower and upper landings. Their *angle* (ca) (rad) is equal to inclination (inc) and their radii depends on (v_n). Their values are given in table 3, where (R_{cl}) and (R_{cu}) are the *radii's notations for the guides' curvatures in lower and upper landings* respectively.

Table 3. Minimum radii values (*R_{cl}*) and (*R_{cu}*) of step guides' curvatures in lower and upper landings respectively

v_n (m/s)	R_{cl} (m)	R_{cu} (m)
$\leq 0,5$	≥ 1.0	≥ 1.0
$0.5 < v_n \leq 0.65$	≥ 1.0	≥ 1.5
> 0.65	≥ 2.0	≥ 2.6

The calculation of these parameters is followed by the definition of step design parameters that affect escalator energy performance. These are the step width (stw), pitch (stp) and its *weight* (stq). The (stw) and (stp) affect the energy consumption not only because they affect (stq) but also because they affect the maximum amount of passenger load on the escalator. Regarding (stq), a general approach is that a typical steel step of 1 m width weighs about 20 kg, 0.8 m width steel steps can be assumed to weight about 16 kg and 0.6 m width steps about 12 kg. Aluminum alloy steps are claimed to weigh up to 40% lesser than the steel ones. The *linear gravity force of step row* (in N/m) is:

$$q_{st} = g \cdot stq \cdot (1/stp) \tag{6}$$

Next, the step roller chain is chosen. Its maximum strength must be at least five times the maximum applied tension on it. Step chain selection should be followed by the definition of the following parameters: its *pitch* (chp) which is a sudivision of (stp), the *diameter of its supporting wheels (rollers)* (D_{cw}), the *diameter of wheel shafts* (d_{cws}), the *diameter of chain pins* (d_{chp}) and finally, the *chain linear gravity force* (q_{ch}) (N/m).

Modern escalators have two assemblies with drive sprockets, step chain and return sprockets that accept and translate evenly the passenger load. So, in order to calculate the total consumed power from the motor, the tractive force applied by each drive sprocket to its step chain should be calculated. For that task, except load, the various resistances in linear and curvilinear sections of the chain guides and in sprockets should be taken into account.

In linear sections, the *coefficient of resistance* (w) [9, 10] to motion of chain wheels on guides can be found by the expression:

$$w = c(\mu_{cws} \cdot d_{cws} + 2k_{wrf}) / D_{cw} \tag{7}$$

Here, (c) is a coefficient to account for *resistance of wheels due to their friction on guides' flanges* and for escalators with plastic chain wheels, or steel with a cast-rubber rim, its value is about 1.1, (μ_{cws}) is the *coefficient of friction in wheel shafts* that are assembled with roller bearings and (k_{wrf}) is the *coefficient of rolling friction expressed in relation to wheel diameter*. Their average values for typical escalator - good operatinng conditions are about 0.01 and 0.06 respectively [9, 10].

Examining now the resistances in a curvilinear section, if (S_{on}) and (S_{off}) are the *tensions of step chain in run-on and run-off points*, then [9][10]:

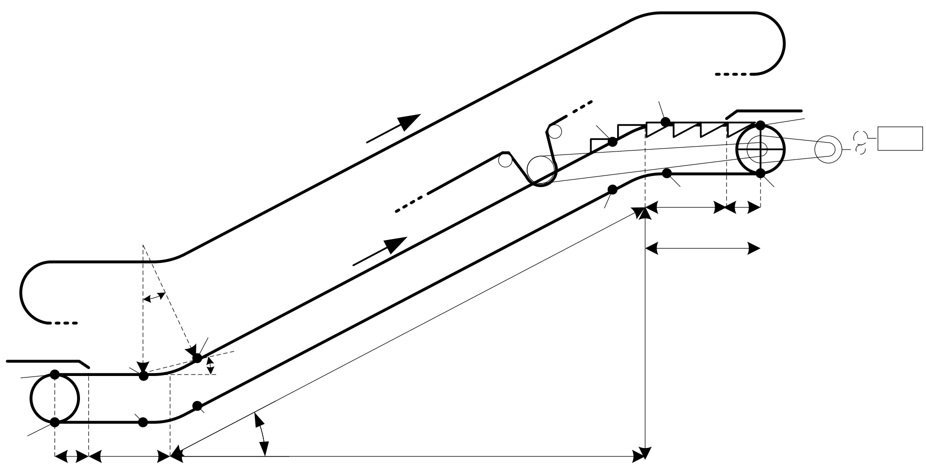

Figure 1. Abstract representation of escalator mechanisms for step and handrail motion

$$S_{off} = S_{on}e^{w\cdot ca} + \left(\frac{q_{st}}{2} + q_{ch} + \frac{q_l}{2}\right)(\pm\sin\beta \pm w\cdot\cos\beta)\cdot R_c \cdot \frac{e^{w\cdot ca}-1}{w} \quad (8)$$

Here, from (±) symbol in $w\cdot\cos(\beta)$ adder, the (+) applies for curves with the convex upwards and the (-) applies for those with the convex downwards. Now, from (±) symbol in $\sin(\beta)$ adder, the (+) applies for upward motion of step chain, while the (-) applies for downward motion. (β) is the slope of the examined curve. This angle is variable, but it can be assumed constant and equal to $ca/2$. (q_l) is the *linear gravity force of the load*:

$$q_l = pw \cdot pd \cdot g \cdot (1/stp) \quad (9)$$

where, (pw) is the *average weight of a passenger* which in Europe is assumed to be equal to 75 kg. In curves of the run-off lower side of escalator (q_l) equals to zero.

The resistance to chain motion in drive and return sprockets (k_{sch}) is given by the expression:

$$k_{sch} = 1 + \frac{2}{D_{sp}} \times \left(\sin\left(\frac{a_{wr}}{2}\right)\cdot d_{sps}\cdot \mu_{sps} + d_{chp}\cdot \mu_{chj}\right) \quad (10)$$

Here, (a_{wr}) is the *wrapping angle of the chain to sprockets* and it can be assumed always equal to 180^o. (D_{sp}) is the *effective diameter of the sprocket wheel* and it is given by the expression [11]:

$$D_{sp} = chp \big/ \sin(180/nt_{sp}) \quad (11)$$

In this expression, (nt_{sp}) is the selected number of sprocket teeth. Next, (d_{sps}) is the diameter of the sprocket wheel shaft and it is defined after the sprocket selection. (μ_{sps}) is the coefficient of friction in the rolling bearing of sprocket wheel shaft, reduced to the shaft diameter, and its average value varies from 0.03 to 0.06 (in cm). (μ_{chj}) is the coefficient of friction in chain joints with average value in case of periodic lubrication from 0.15 to 0.25 [9, 10].

In order to determine tensions S_{12} and S_1 in drive sprocket (see figure 1), the tensions in individual sections of the escalator should be calculated. First, S_5 is the minimum tension of step chain, so it is equal to the applied pre-tension S_{min} that varies in the interval 1-3 kN [9]. Then, for an escalator as that of figure 1, with upwards direction, the tensions from S_6 to S_{12} are calculated clockwise starting from S_5.

$$S_6 = S_5 + \left(\frac{q_{st}}{2} + q_{ch}\right)\cdot l_2 \cdot w \quad (12)$$

$$S_7 = k_{sch}\cdot S_6 \quad (13)$$

$$S_8 = S_7 + \left(\frac{q_{st}}{2} + q_{ch}\right)\cdot l_2 \cdot w + \frac{q_l}{2}\cdot l_{fs}\cdot w \quad (14)$$

$$S_9 = S_8 e^{w\cdot ca} + \left(\frac{q_{st}}{2} + q_{ch} + \frac{q_l}{2}\right)(+\sin\beta - w\cdot\cos\beta)\cdot R_{cl}\cdot \frac{e^{w\cdot ca}-1}{w} \quad (15)$$

$$S_{10} = S_9 + \left(\frac{q_{st}}{2} + q_{ch} + \frac{q_l}{2}\right)\cdot\left(l_1\cdot w + H_e\right) \quad (16)$$

$$S_{11} = S_{10} e^{w\cdot ca} + \left(\frac{q_{st}}{2} + q_{ch} + \frac{q_l}{2}\right)(+\sin\beta + w\cdot\cos\beta)\cdot R_{cu}\cdot \frac{e^{w\cdot ca}-1}{w} \quad (17)$$

$$S_{\max} = S_{12} = S_{11} + \left(\frac{q_{st}}{2} + q_{ch}\right)\cdot l_2 \cdot w + \frac{q_l}{2}\cdot l_{fs}\cdot w \quad (18)$$

Tensions S_1 to S_4 are determined in the inverse order:

$$S_4 = \left(S_5 - \left(\frac{q_{st}}{2} + q_{ch}\right)(-\sin\beta - w\cdot\cos\beta)\cdot R_{cl}\cdot\frac{e^{w\cdot ca}-1}{w}\right)\Big/ e^{w\cdot ca} \quad (19)$$

$$S_3 = S_4 - \left(\frac{q_{st}}{2} + q_{ch}\right)\cdot l_1 \cdot w + \left(\frac{q_{st}}{2} + q_{ch}\right)\cdot H_e \quad (20)$$

$$S_2 = \left(S_3 - \left(\frac{q_{st}}{2} + q_{ch}\right)(-\sin\beta + w\cdot\cos\beta)\cdot R_{cu}\cdot\frac{e^{w\cdot ca}-1}{w}\right)\Big/ e^{w\cdot ca} \quad (21)$$

$$S_1 = S_2 - \left(\frac{q_{st}}{2} + q_{ch}\right)\cdot l_2 \cdot w \quad (22)$$

The *tractive force* (F_{dr}) applied by each one drive sprocket to its step chain is:

$$F_{dr} = S_{12} - S_1 + w_{dr} = S_{12} - S_1 + \left(S_{12} + S_1\right)(k_{sch} - 1) \quad (22)$$

Analogous calculations can be done for downwards escalator motion.

Another escalator's assembly which consumes energy is the mechanism for the motion of handrail. This mechanism can be examined part by part, but in the present paper, for reasons of simplicity, it can be assumed with acceptable accuracy, that the main amount of energy is consumed for the confrontation of resistance in handrail motion. So, if (hdr_{lm}) is the *handrail linear mass* (kg/m) and (μ_{hdr}) is the *coefficient of friction on handrail guide*, *the tractive force applied to a single handrail* by its pulley is:

$$F_{hdr} = 2\cdot\left(l_1 + 2\cdot l_2\right)\cdot hdr_{lm}\cdot g\cdot \mu_{hdr} \quad (23)$$

According to [9], (hdr_{lm}) is 1.85 to 2.5 kg/m, and (μ_{hdr}) 0.27-0.37.

Finally, a significant energy consumer in escalator operation is its electrical subsystem. According to ISO/DIS 25745-1 [1] the consumed power is divided to a. the *ancillary power* (P_{anc}), which is the power of landing lights, indicators and safety circuits and b. the power consumed mainly by control operator and inverter. The latter is consumed during the whole escalator operation, but it can be measured when the escalator is in stand-by mode, so it is called *stand-by power* (P_{sby}).

These consumptions can be assumed constant for the whole escalator operation period and independent of its size. The ISO [1] provides with estimated values for planning purposes that are P_{anc}= 300 W and P_{sby}= 200 W.

The *total required power* of the escalator (W) is:

$$N = 2\cdot v\cdot\left[\left(\frac{F_{dr}}{\eta_{ts}}\right) + \left(\frac{F_{hdr}}{\eta_{th}\cdot\eta_{ts}}\right)\right]\Big/\left(\eta_{gb}\cdot\eta_{mt}\right) + P_{anc} + P_{sby} \quad (24)$$

Here, (η_{ts}), (η_{th}), (η_{gb}) and (η_{mt}) are the efficiency factors respectively for a. the transmission from gearbox to drive sprocket, b. the transmission to handrail assembly, c. the gearbox and d. the motor.

The required power that corresponds to every time period $T(i)$ of different traffic load, multiplied by the time ($t_{T(i)}$) of the period (in s), gives the *escalator energy consumption* for the period ($E_{T(i)}$) (J). The sum of all periods' consumption for a whole day or year provides with the respective daily or annual consumption.

2.3 A unified index for the representation of escalator energy and service efficiency

In the present study, a unified index is introduced for the evaluation of the overall efficiency of an escalator. The index considers both energy and service performance, is denoted as *Energy – Service Efficiency Index* (I_{ES}) (in kJ·s/person·m) and is determined by the following expression:

$$I_{ES,j} = \sum_{i=1}^{n}\left(E_{T(i)}\right)\cdot t_{tr} \Bigg/ \sum_{i=1}^{n}\left(P_{T(i)}\right)\cdot H_e \tag{25}$$

The index *j* refers to a time period (e.g. day or year) which is divided in *n* sub-periods with different traffic load. The sum of the consumed energy in that period is multiplied by travel time (t_{tr}). Then the product is divided by the sum of persons serviced in the same period and the elevation height. In other words, the index *represents the amount of energy consumed by escalator to translate a person for a certain height in a certain time* or, alternatively, the *amount of energy consumed by escalator to elevate a person with a certain average vertical speed*. It is clear that the proposed index contains both the energy consumption and the service “quantity” and “quality”. The service "quantity" refers to the amount of served persons and the elevation height, while the “quality” refers to how fast a passenger is transported to its destination.

It is obvious that the value of (I_{ES}) is sensitive to decisions made during design because it depends upon (E_T) (P_T) and (t_{tr}), parameters that are strongly dependent to electromechanical structural and operational elements. It is also strongly bonded to the traffic profile for every *unique* building. Finally, it should be noted that lower values of (I_{ES}) correspond to higher values of overall escalator efficiency.

It is proposed that (I_{ES}) is calculated in annual basis $I_{ES,y}$, if from month to month there is difference in traffic demand profile. However, if it is assumed that every operation day presents the same traffic pattern, then the calculation of daily ($I_{ES,d}$) is adequate.

3. CASE STUDY

An escalator will be installed in a mall. The elevation height is H_e = 5 m, and the estimated daily traffic load follows uniform pdf and consists by four different periods: T(1) with 70 persons/min for $t_{T(1)}$ = 0.5 h, T(2) with 45 persons/min for $t_{T(2)}$= 1 h, T(3) with 22 persons/min for $t_{T(3)}$ = 2.5 h and T(4) with 10 persons/min for $t_{T(4)}$ = 4 h. The escalator will operate with the same traffic load for 25 days per month throughout the year.

It is assumed that the initially selected escalator has the following technical specifications.

The service performance, the energy consumption and the Energy – Service Efficiency Index of the selected escalator, denoted as 800/0.5 from its (*stw*) (in mm) and (v_n), is represented in table 5. Index (I_{ES}) is calculated on a daily basis, as the traffic load is assumed to be the same over the year. Together with 800/0.5 escalator, other alternative solutions are examined considering their overall efficiency.

Table 4. Technical Specifications of the escalator

Layout	**Step Chain**	**Speed**
$inc = 30°$	Type: ST133F3 [12]	v_n = 0.5 m/s
H_e = 5 m	D_{cw} = 7.5 cm	No variable speed
l_{fs} = 0.8 m	d_{cws} = 1.463cm	Friction coef.
l_3 = 0.4 m	d_{chp} =1.463 cm	c = 1.1
R_{cl} = 1 m	chp = 13.333 cm	μ_{cws} = 0.01
R_{cu} = 1 m	q_{ch} = 52.974 N/m	k_{wrf} = 0.06
Step	S_{min} = 3kN	μ_{sps} = 0.045
stw = 0.8 m	**Sprockets**	μ_{chj} = 0.2
stp = 0.4 m	nt_{sp} = 18	**Efficiency factors**
stq = 16kg (steel)	D_{sp} = 76.8 cm	η_{ts} = 0.9
Handrail	d_{sps} = 10 cm	η_{th} = 0.9
hdr_{lm} = 2.2 kg/m	**Electr. subsystems**	η_{gb} = 0.8
μ_{hdr} = 0.32	P_{anc}= 300 W	η_{mt} = 0.92
	P_{sby}= 200 W	**Max permitted pd** 1.008 per/s

Table 5. Service performance, energy consumption and Energy – Service Efficiency Index for the selected escalator and its alternative solutions

Type: 800/0.5	***pd*** (pas/step)	***N*** (kW)	P_T (pers.)	E_T (kJ)	t_{tr} (s)	$I_{ES,d}$
***T*(1)**	0.933	8.798	2100	15837	23.2	**48.054**
***T*(2)**	0.6	6.189	2700	22281		
***T*(3)**	0.293	3.789	3300	34100		
***T*(4)**	0.133	2.537	2400	36526		
Daily sum:			10500	108744		
Type: 1000/0.5	***pd*** (pas/step)	***N*** (kW)	P_T (pers.)	E_T (kJ)	t_{tr} (s)	$I_{ES,d}$
***T*(1)**	0.933	8.854	2100	15937	23.2	**48.763**
***T*(2)**	0.6	6.245	2700	22482		
***T*(3)**	0.293	3.845	3300	34601		
***T*(4)**	0.133	2.592	2400	37328		
Daily sum:			10500	110348		
Type: 800/0.75	***pd*** (pas/step)	***N*** (kW)	P_T (pers.)	E_T (kJ)	t_{tr} (s)	$I_{ES,d}$
***T*(1)**	0.622	9.925	2100	17864	17.6	**43.880**
***T*(2)**	0.4	7.13	2700	25668		
***T*(3)**	0.196	4.559	3300	41030		
***T*(4)**	0.089	3.216	2400	46332		
Daily sum:			10500	130894		
Type: 800/0.5 (Optimized efficiency)						
	pd (pas/step)	***N*** (kW)	P_T (pers.)	E_T (kJ)	t_{tr} (s)	$I_{ES,d}$
***T*(1)**	0.933	7.539	2100	13571	23.2	**39.286**
***T*(2)**	0.6	5.226	2700	18815		
***T*(3)**	0.293	3.098	3300	27886		
***T*(4)**	0.133	1.988	2400	28630		
Daily sum:			10500	88902		

The first alternative is a 1000/0.5 escalator with its specifications remaining the same except of (*stw*) and (*stq*). Table 5 shows that its energy consumption is a bit increased due to 20 kg (*stq*), while its service performance does not change because capacity is regulated by arrival rate and the larger step surface is not exploited. Both are represented effectively by ($I_{ES,d}$) of 1000/0.5, with its value slightly higher than ($I_{ES,d}$) of 800/0.5.

Next, an 800/0.75 escalator is examined with specifications the same as 800/0.5, except of (l_{fs}), (R_{cl}) and (R_{cu}) (see tables 2 and 3). Here, it is interesting that while 800/0.75 consumes about 20% energy, its ($I_{ES,d}$) shows that if the relation energy - service is examined, it is a more efficient machine, as it achieves about 24% faster transportation. So, especially for prestigious buildings, the 800/0.75 might be an overall better alternative.

In the last alternative, it is examined whether (I_{ES}) is sensitive to changes in mechanical design. For that an eco-designed 800/0.5 escalator is tested, which has aluminum steps with stq = 9.6 kg, lighter handrail belt with hdr_{lm} = 2.0 kg/m, friction coefficients $\mu_{sps} = 0.03$, $\mu_{chj} = 0.15$, $\mu_{hdr} = 0.27$ and efficiency factors $\eta_{ts} = 0.92$, $\eta_{th} = 0.92$, $\eta_{gb} = 0.85$ and $\eta_{mt} = 0.95$. With the service performance remaining the same, the lower energy consumption achieved with the enhanced design is depicted impressively on ($I_{ES,d}$) with significant lower value.

Finally, it should be underlined that various other tests have shown that (I_{ES}) performs efficiently, corresponding to any other changes to escalator design, to elevation height, or to traffic load profile.

4. CONCLUSION

In the present paper, a method is proposed for the design of efficient escalators in buildings considering both service performance and energy consumption. For that, the Energy – Service Efficiency Index (I_{ES}) for an escalator is proposed, which correlates data that refer to its energy consumption, together with data that depict its passenger capacity and operation speed in relation to elevation height.

The data related to service performance are extracted after the implementation of specialized circulation studies where various load profiles can be examined, no matter how complicated they are as long as they conclude to arrival rates for certain time periods.

The data related to energy consumption are derived from a detailed mechanical design model, where various parameters can be examined and various loading conditions can be tested. Electrical subsystems are examined also, without any restriction to their depth of analysis, as the model uses fixed energy consumptions of standard electrical circuits that can be assumed with adequate accuracy to be independent to the rest mechanical design.

Various tests have shown that (I_{ES}) depicts efficiently the escalator service performance in relation to the amount of the energy needed to obtain this performance. The index is sensitive to even slight changes in design and/or estimated traffic load profile.

The proposed index may be contribute towards designing of energy efficient escalators, with simultaneous control of possible compromises in their service performance. Finally, it can be used for the evaluation or improvement of existent escalators, if the actual traffic conditions in which they operate are known.

The implementation of the method in multiple escalator systems and the addition to it of a model for the calculation of energy consumption during escalator acceleration is in progress.

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ПОТРОШЊА ЕНЕРГИЈЕ И ПЕРФОРМАНСЕ ПОКРЕТНИХ СТЕПЕНИЦА

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У раду се предлаже индекс укупне ефикасности покретних степеница појединачно са аспекта потрошње енергије и перформанси опслуживања. Индекс повезује утрошак енергије са бројем путника који се опслужују, висином до које се степенице крећу и просечним временом потребним за опслуживање путника. Индекс може да служи и као помоћни алат за пројектовање ефикаснијих покретних степеница у смислу функционисања и потрошње енергије.

Подаци потребни за евалуацију предложеног индекса добијају се применом одређених студија

протока за израчунавање транспортног оптерећења и анализе потрошње енергије узимајући у обзир пројектовање механичких и електричних компонената покретних степеница. Студија случаја је пример предложеног приступа.