Experimental Investigation into the Effect of Mechanical Design of an Escalator and Passenger Loading on its Energy Consumption

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***Abstract*—.An experimental investigation has been carried out into the factors that affect the energy consumption of an escalator. The type of energy consumed by the escalator is classified into fixed losses and variable losses.**

The two main factors that affect the energy consumption have been identified as the mechanical design of the escalator (that affects the fixed losses) and the number of passengers using the escalator (that affects the variable losses).

Experimental and survey work have been carried out on a large number of heavy duty escalators to find the relationship between the mechanical design aspects, the number of passengers using the escalator and the energy it consumes. The generic mechanical and electrical design features of the escalators were extracted to allow a grouping of the escalator in order to find general rules. Surveys were also carried out on the total daily number of passengers using an escalator and the corresponding daily total energy consumed.

The relation between the various parameters has been analysed with good correlation.

***Index Terms*—Escalator, energy consumption, power, mechanical design, passenger, walking.**

I. Introduction

The approach towards understanding the energy consumption of escalators is based on three principles: Outlining the general characteristics of the consumption; the factors affecting it; and the calculation of the total energy. This paper will attempt to highlight some of these points, and point the direction in terms of others.

In some cases the terms power and energy although distinct have been used interchangeably for convenience. However, the reader has to be aware that power is the rate of transfer of energy.

When escalators are running unloaded they need some power to overcome friction in the step-band and the handrail, and inefficiencies in the motor and the gearbox. This power is referred to as fixed losses (or overheads, in analogy to overheads in a business or a factory which are not used to produce any tangible product or service; only to keep the business or the factory going and to support other functions).

As passengers start boarding the escalator, the power consumed starts to rise if it is an up going escalator, or to drop if it is a down going escalator. The power needed to move passengers is termed as variable losses or variable power (in analogy to the variable costs of producing products in a factory, which will be sold and will create revenue).

So, in addition to the fixed losses in an up moving escalator, it is imparting energy to the passengers (variable losses) and thus is consuming power. Thus, the total power consumed is equal to the summation of the power needed to move the passengers between levels and the power needed to overcome the friction within the escalator.

On the other hand, a down moving escalator is recovering the potential energy stored in the passengers. The total energy consumed by a down moving escalator is the difference between the fixed losses and the energy recovered from the passengers. As passenger loading progressively increases on a down moving escalator, the escalator gets to a point where it is consuming no power at all, because it is driven by enough passengers to generate power equal to the losses needed to drive it at no load. As passenger loading further increases, the escalator starts to feed power back into the supply (i.e., regenerate). This crossover point depends on the level of fixed losses, and the reverse efficiency of the gearbox.

The main factors which affect the daily energy consumed by an escalator are:

- Rise.
- Machine type.
- Number of passengers boarding the escalator.
- Direction of travel (up or down).

In the following sections, these factors are discussed in detail. More detailed analysis can be found in [1].

II. Fixed Losses

We can think of the fixed losses of an escalator as the base mark from which it start. The fixed losses are equal to the power consumed when no passengers are travelling on the escalators.

A. Methods of deriving fixed losses

Two methods are described here for calculating the fixed losses for an escalator. The first method discussed only needs a power consumption survey over one day, while the

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second method requires both the power consumption survey as well as the passenger survey for one day (has to be the same day). Each method gives a different level of accuracy.

1) Method A for deriving fixed losses

The easiest and most straightforward method to calculate the fixed losses is to assume that the escalator for the last 30 minutes of its operation in the day is very lightly loaded with few passengers using it. If the average of the power consumed over these 30 minutes is taken, this will be a good representation of the fixed losses of that escalator, with a very small error. The error will arise from the small number of passengers who might use the escalator in these 30 minutes. A diagram of the power consumption for a public service escalator is shown in Figure 1 (17.2 m rise and 18 000 passengers per day). It can be seen that due to the high loading on the escalator, it is still being used in the last 30 minutes, and this will lead to errors in the estimation of the fixed losses. It is not advisable to use the first 30 minutes, when the escalator is started, as the machine in the first half hour will be warming up, and thus the reading in that period might not be representative of the whole day. This can also be seen in Figure 1, where the power drops during the first half hour.

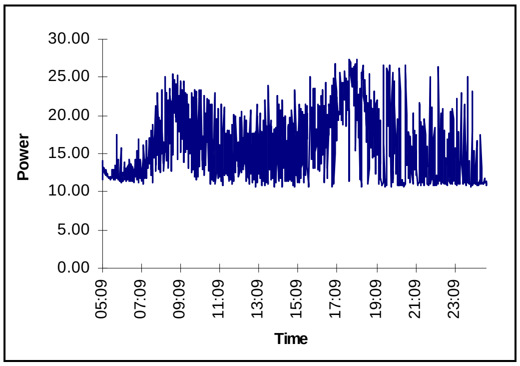

Figure 1: Power trace over one working day (power in kW).

The same principle applies to a down escalator, where the fixed losses can be found by taking the average value of power during the first 30 minutes, or the last 30 minutes, or both. As the escalator is a down escalator, the fixed losses represent the maximum (rather than the minimum value of power consumption, as the case is with up moving escalators).

Despite the error mentioned above, this method is very attractive because it is easy to use, and only needs the measurement of the power consumption in the first half hour and the last half hour. However, it suffers from some inaccuracy because of the reasons explained above. This method has been referred to as method A for deriving the fixed losses.

Applying method A to seven escalators, the fixed losses have been plotted against the rise on a scatter diagram, shown in Figure 2, which shows the fixed losses as a function of rise, and gives the resultant equation.

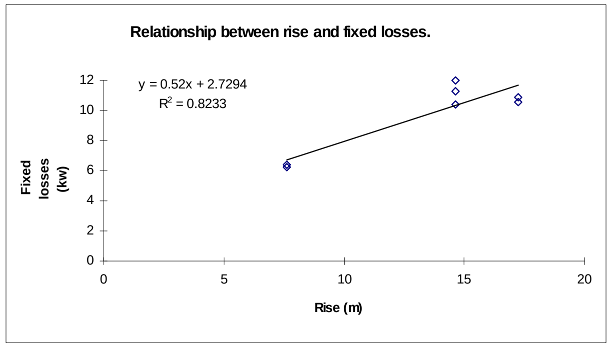

Figure 2: Scatter diagram of fixed losses against rise using method A for deriving the fixed losses.

On the diagram is shown the resultant equation, which represents the relationship between the passenger numbers and the power consumed. It also gives the coefficient of correlation, which is a measure of how well the variation in one variable (the power consumed) is explained by the variation in the independent variable (the number of passengers). When this value is near 1, it indicates a good positive correlation between the two variables (the increase in one value produces an increase in the other), while a value of -1 indicates a good negative correlation between the two variables (the increase in one variable produces a decrease in the other). A value near zero shows that no or little correlation exists between the two variables.

Thus, as shown in Figure 2, the relationship between fixed losses and rise can be approximated by a straight line, with a non-zero intercept. The resulting equation is:

$$\text{Fixed losses}\,(\text{kW}) = 0.52 \cdot \text{rise}\,(\text{m}) + 2.79 \tag{1}$$

In other words, the fixed losses of an escalator (in kW) are dependent on rise and are nearly equal to half the rise in metres plus a fixed amount equal to nearly 3 kW. This 3 kW would be needed by a fictitious zero rise escalator. We could think of this 3 kW quantity as being the power needed to run the gearbox and the motor.

From the scatter diagram, r^2 is equal to 0.8233, which indicates that the rise is a strong factor in explaining variation in fixed losses (rise accounts for 82% of the variation in fixed losses; there may be other factors which explain the other 18% variation).

2) Method B for deriving fixed losses

The other more accurate method is to use the passenger data as well as the power consumption data. An example of these two surveys has been plotted in Figure 3. It is very important that these two surveys are synchronised. This means that if the power survey is taken as an average power consumption value for one minute intervals, then the passenger survey should show the number of passenger boarding the escalator in the *same* minute intervals. This has been carried out in the example shown in Figure 3, where passenger surveys were manually carried out by observers at the escalator landings, using clocks synchronised to the nearest second to the clock of the automatic power survey unit. Both the manual surveys and the automatic power unit calculated values based on one minute intervals.

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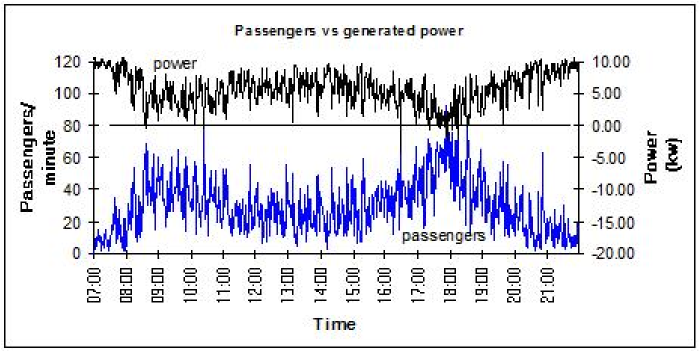

Figure 3: Power trace and passenger trace.

Each pair of readings (i.e., passenger numbers in one minute and average power consumption over one minute) can be plotted on a scatter diagram, as shown in Figure 4. From the scatter diagram, the resultant equation can be derived, which is assumed to be linear. Note that the slope is negative, because this is a down escalator (a positive slope would be expected for an up escalator).

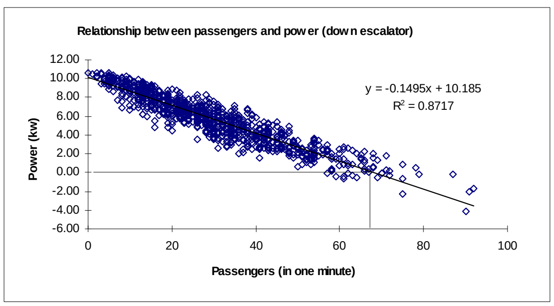

Figure 4: Scatter diagram for the down escalator, between power and passengers.

The best fit line can be drawn through the data points, the equation of which is also shown on the diagram. When the number of passengers is equal to zero (i.e., when $x = 0$) then the value of the power consumed at that point is the value of the fixed losses. The equation gives the value of y (power in kW) when x is zero (passengers) as 10.185 kW. Thus this intercept is the value of the fixed losses. This method is obviously more accurate, but involves more data collection and processing. This method will be referred to as method B for deriving the fixed losses.

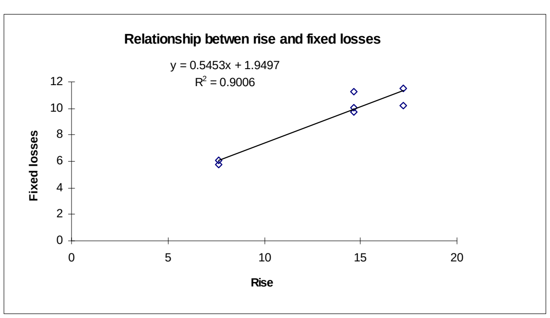

Figure 5: Relationship between rise and fixed losses, based on method B (Fixed losses in kW; rise is in m).

This method has been applied to the same seven escalators. The scatter diagram along with the equation and correlation coefficient are shown in Figure 5. It can be seen that the correlation coefficient is higher than that obtained by method A, pointing to the higher accuracy of this method. Using method B, the resulting equation is as shown in Figure 5:

$$\text{Fixed losses}(\text{kW}) = 0.55 \cdot \text{rise}(\text{m}) + 1.95 \tag{2}$$

As discussed above, methods A and B gives an estimate of the fixed losses of an escalator based only on rise. Method B gives better accuracy, but requires passenger usage data as well as daily power consumption. Moreover, the data for this method has to be synchronised between the passenger data and the power consumption data.

Both methods however ignore the mechanical design differences between escalator types. The next subsection addresses this issue, In order to arrive at a more accurate estimate of the fixed losses for an escalator based, not just on the rise, but also the mechanical design.

B. Dependence of fixed losses on mechanical design

Methods A and B assume that the mechanical features of a machine do not affect the fixed losses. This sub-section attempts to explore the effect the mechanical design on the fixed losses of an escalator in addition to the rise.

A group of machines, with specific design features have been used for this exercise. The various design features for each type of machine are shown in Table I.

Table I: Summary of machine categories in relation to mechanical features.

Design	Bearings	Guiding system	Gearbox
A	Ball bearings	Chain guidance	Involute
B	Ball Bearings	Chain guidance	Cavex
C	Plain bearings	Wheel guidance	Involute
D	Ball bearings	Wheel guidance	Involute

The four design-feature groups have been designated as A, B, C and D. Each group could represent more than one machine design. The main three criteria for mechanical design are:

- The type of bearing used in the step chain and for the wheels.
- The type of guiding system for the step chain and the step band.
- The type of gearbox.

The fixed losses for each machine group have been derived against rise and plotted in Figure 6. Although rise is still the dominant factor, there are differences between the different types of mechanical design.

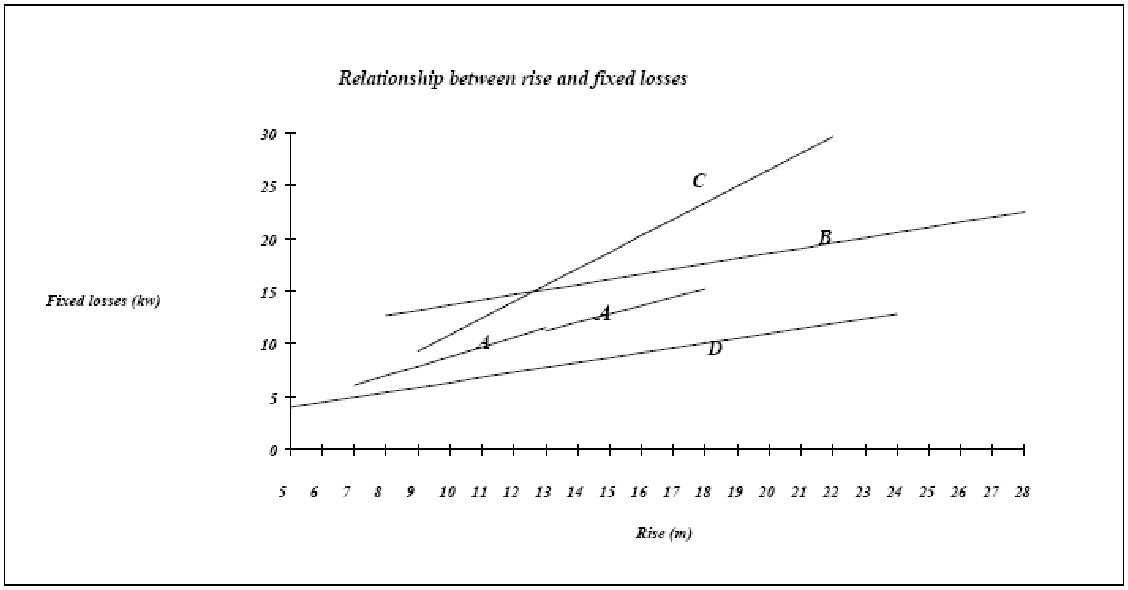

Figure 6: Relationship between rise and fixed losses for various mechanical designs.

It can be seen from the equations that the highest slope is the line representing the C type machine. This slope, is dependent on rise, and thus is related to the step band. The main difference between C type machines and all other machines which would contribute to higher friction is the fact that they have plain wheel bearings as opposed to ball bearings which exhibit less friction.

The other important factor is the type of guidance: chain guidance against wheel guidance. The group of machines D represents several machines which have very similar curves and thus have been grouped together. They all have wheel guidance systems and are fitted with ball bearings. On the other hand, the group of machines A have similar lines, but display a higher slope than the group D. This is because A type machines use chain guidance systems. B type machines have a similar slope but a larger intercept, which indicates a larger loss with the gearbox or the motor. The only explanation for that is the fact that it uses a unique type of gearbox, the so-called Cavex types as opposed to the Involute type used on all other machines. This is also confirmed by the fact that the gearboxes on these group of machines run much hotter than other gearboxes.

Most modern machine designs will be within group A, although some might use a Cavex type of gearbox or even a helical gearbox.

The equations for the fixed losses depending on rise and depending on mechanical design features are shown in Table II. All equations give the fixed losses in kW as a function of rise in metres.

Table II: Equations relating the fixed losses to the rise of different types of escalators.

Machine Type	Equation for fixed losses
A (low rise)	$y=0.9 \cdot x-0.19$
A (high rise)	$y=0.79 \cdot x+1.02$
C	$y=1.56 \cdot x-4.7$
D	$y=0.47 \cdot x+1.74$
B	$y=0.49 \cdot x+8.76$
y is the fixed losses in kW, and x is the rise in m	

It can thus be seen that if more accuracy is required in calculating the fixed losses of a machine, the mechanical features can be compared to the features in Table I. Once the type of machine which best fits the machine under question if found, then the equation for fixed losses can be found in Table II, and the fixed losses calculated based on the rise in metres. Note that the results in this sub-section have all been derived based on method A, for simplicity. It is assumed that the accuracy of this method is sufficient for most cases.

All the analysis carried out so far has only addressed the fixed losses. It has been shown how fixed losses can be calculated based on mechanical design and rise of machine. When passengers start boarding an escalator, variable losses start to be incurred (or recovered for a down machine). The next section addresses this topic.

III. VARIABLE LOSSES

The two factors which affect the fixed losses are:

- The machine rise.
- The mechanical design.

The other two factors which have not been discussed yet, but do affect the energy consumption are:

- The passenger numbers boarding the escalator in one day.
- The direction of movement of an escalator.

These two factors affect the variable losses, and are discussed in this section.

However, before discussing the effect of passenger numbers on variable losses, the effect of walking passengers is analysed.

A. *Energy consumed by walking passengers*

An issue which has been the subject of much debate is whether passengers consume more or less energy when they walk up escalators. Nine passengers were used to carry out the following test on a public service escalator, while it was running in the up direction. The first test was carried out with the passengers standing and the second test with the passengers walking up. The power consumed was monitored during the test, by measuring the DC current drawn, and the result is shown in Figure 7, which clearly shows that passengers have spent less time walking, while not consuming any more instantaneous current in the process. This is a DC fed motor, so the current consumed is directly proportional to the power drawn as the dc voltage is constant.

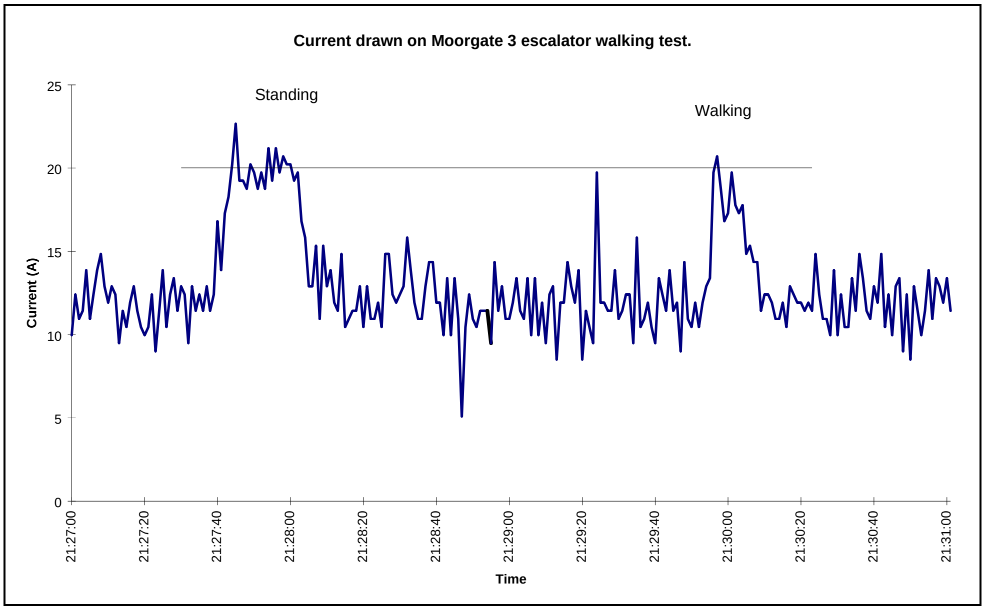

Figure 7: Current consumed during the walking test.

The fact that the passenger spent less time when walking shows that passengers use less energy when walking up an up moving escalator.

The explanation for this effect can be outlined as follows. Passengers approaching an up moving escalator will accelerate themselves up to the running speed of the escalator in the direction of the angle of the escalator. Once they have accelerated themselves, the only power required from the escalator is that necessary to keep them moving at 0.75 m/s (i.e., the linear rated speed of the escalator) in the direction of inclination of the escalator. This power is the same whether the passengers are walking or standing. The only difference in the two cases is that walking passengers will spend less time on the escalator, because they are moving at a speed which is equal to the summation of the speed of the escalator and their own walking speed. The fact that they spend less time on the escalator is clearly shown in Figure 7. The difference in energy between the walking case and the standing case is equal to the energy supplied by the passenger's muscles.

Thus, passengers walking up escalators do not affect the instantaneous power consumed, but use less energy overall.

As for passengers walking down an escalator, they do not return as much energy back to the power system as stationary passengers would have done, because they spend less time on the escalator than their standing colleagues.

B. *Calculating the variable losses*

The variable losses for any machine (or gains) depend on the number of daily passengers, the average mass of a passenger and the rise of the machine. Thus, the variable losses daily losses for an up machine can be calculated by multiplying the number of passengers per day, 75 kg (average mass per passenger), by 9.81 m/s^2(acceleration due to gravity) and by the rise of the machine in metres. However, when measured values where compared with this calculation, a discrepancy was found.

The variable losses on a large group of escalators were measured, by measuring the total loss, and subtracting from it the fixed losses. This resulted in a measured variable

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loss for each escalator. These values where plotted on a scatter diagram against the theoretical calculated variable loss based on the number of passengers and the rise of the machine. (Notice, that the variable losses are in fact variable gains for a down moving escalator, and thus have been given a negative sign). When attempting to relate the calculated energy to the measured variable energy by using this method, there was consistently a factor of 0.7, as shown in Figure 8. The equation shows the approximate factor of 0.7 between measured and calculated. This indicates that the measured energy is 70% of what it should be in theory. This applies equally to the down direction as well as the up direction (i.e., the energy expended to lift passengers is 70% of its calculated theoretical value *and* the energy recovered from down moving passengers is only 70% of what it should be in theory).

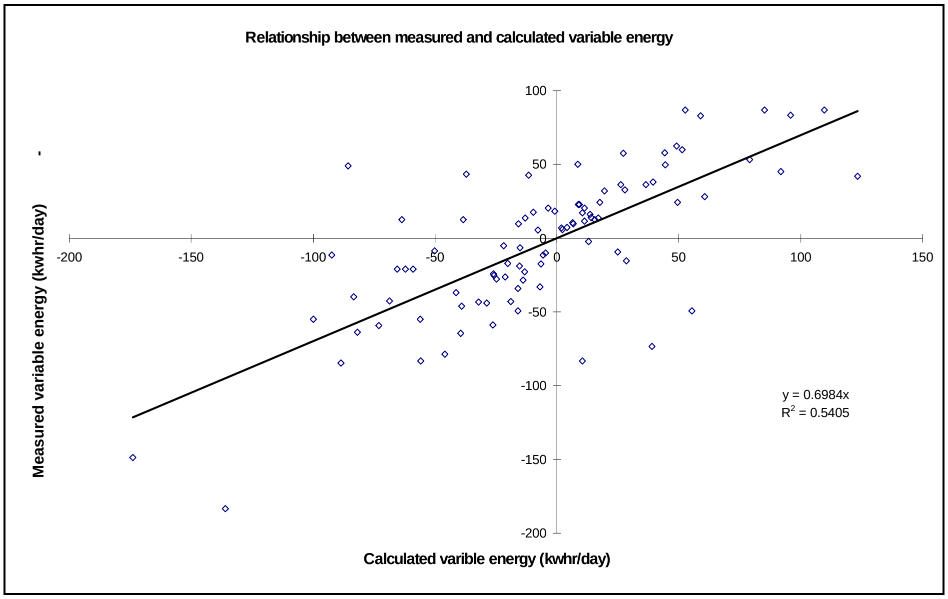

Figure 8: Relationship between measured variable energy and calculated energy.

One explanation for this 0.7 factor is the fact that a percentage of passengers walk up and down the escalator (which relates to the walking effect explained in the previous sub-section). Thus, they spend less time on the escalator, and thus consume less power if walking up, and return back less energy if walking down.

Thus, when calculating variable losses, the so-called walking factor has to be taken into consideration, to account for the fact that the variable losses are reduced due to the walking of passengers up and down the escalator.

Although a value of 0.7 can be used generally, a more detailed analysis shows that different values have to be used for up and down situations, and for peak and off-peak times [3].

This relationship between power drawn and passenger numbers can also be used to automate passenger surveys [2].

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