Optimisation of the Running Speed of Escalators on the London Underground

Ben Langham

London Underground AP JNP Escalator Services,
Frank Pick House, Bollo Lane, Acton, London W3 8RP
ben.langham@tubelines.com

Keywords: London Underground, escalator, speed, energy, passenger flow, optimisation

Abstract. Speed reduction of escalators is commonly employed worldwide and has been shown to achieve savings in energy consumption and component wear. However, although London Underground has considered speed reduction, there is not currently a strategy in place to optimise running speed based on quantitative data. This study researches current practices, relevant previous work and state-of-the-art technology to determine the scope for investigation. Energy consumption, component wear, human factors, safety and passenger journey time are all considered. A combination of primary empirical data, theoretical calculations and secondary sources are used to derive models for a chosen escalator. These are then applied to assess possible options and recommend a strategy for London Underground. It has been found that the negative impact on passenger journey time due to a pre-programmed speed reduction during off-peak hours significantly outweighs the savings, even at low passenger flow rates. Automatic stop-start is not considered feasible for a number of reasons including excessive brake operation and the need to overcome static friction. The recommended strategy is to reduce the speed to a crawl when the escalator is unloaded, accelerating to full speed when passengers are present. This reduces the energy consumption and component wear whilst minimising the negative effect on passenger journey time, and, if used in conjunction with regenerative braking, would minimise energy lost during deceleration. Methods for early detection of passenger arrival are suggested to avoid delays during the acceleration phase. An application has been developed using MATLAB that can quantify and compare the impact of different variable speed strategies and visualise predicted cost savings.

1 INTRODUCTION

Speed reduction of escalators has numerous advantages, the main ones being to save energy and extend component life, and it is commonly employed worldwide. Although this has been considered by London Underground, a strategy to optimise running speeds based on quantitative data has not been implemented. The main objective of London Underground is to get passengers to their destination safely and efficiently, so it is within this context that all engineering and business decisions must be made. In this study, speed reduction strategies shall be assessed and models derived to determine the financial and environmental impact of each approach. Consideration shall also be given to legislation, standards and human factors as well as existing practices elsewhere. The most suitable strategy for a chosen escalator shall be recommended, along with a conceptual design of a system, to maximise the benefits of speed reduction.

1.1 Energy use

London Underground's Energy Strategy aims to achieve a reduction in CO_2 of 60% by 2025, from the 1990 baseline, as specified in the high level strategy initiated by the Mayor of London [1]. This has led to various energy saving initiatives which this work contributes to.

The fixed energy losses of an escalator have been focused on i.e. the losses of an unloaded machine [2]. Variable energy losses, due to the effects of passenger loading and behaviour, have not been included. The number of passengers and vertical distance travelled are both independent of running speed so the energy required to lift passengers was assumed to be unaffected by speed. This avoided complexity in data collection and can be confirmed with a trial in service.

1.2 Available technology

Variable Voltage Variable Frequency (VVVF) drives are the most widely used method for speed control of AC motors and maximise energy efficiency by regulating both voltage and frequency. The vast majority of escalators on the London Underground achieve this with *Pulse Width Modulation* inverters which are efficient and have regeneration capability.

Automatic speed control is integral to various designs available from major escalator manufacturers, either reducing to a slower speed or stopping until passenger presence is detected, often using infra-red detection or measured passenger loading. Other widely available technology is 2D video counting, which has the added advantage of providing accurate passenger flow data. This information is essential in determining the optimum running speed, and is currently only available from surveys and ticket gate counts.

1.3 Speed limitations

The limitations of speed are largely safety-related, with BS EN115 [3] specifying a maximum running speed of either 0.65 or 0.75 m/s for the escalator configurations present on the London Underground. The standard also specifies a 0.5 m/s speed limit for rises up to 6 metres where the angle of inclination exceeds 30º. The minimum speed must be sufficient to avoid passenger bottlenecks so it is important that this is taken into consideration. In the event of an evacuation, any reduced speed system should have the ability to be overridden. The running speed is also dictated by physical requirements of the machinery and must be fast enough to produce sufficient air flow for cooling of *Totally Enclosed Fan Cooled* motors where the cooling fan is mounted on the rotor (common on London Underground escalator motors).

1.4 Component wear

Escalators have a large quantity of mechanical components in relative motion including bearings, surfaces in rolling contact and surfaces in sliding contact, and a variety of materials, relative speeds and wear mechanisms. Reduction of the speed of the machine will proportionally reduce the number of cycles undergone in a given time for many components; however, variables such as age, lubrication, alignment, and passenger behaviour all add complexity to the system.

A comprehensive assessment of the effect of running speed on the wear of escalator components requires a significant tribology study as well as a full evaluation of the maintenance strategy which is beyond the scope of this paper, however, a basic model has been derived based on some assumptions to provide a starting point for further investigation.

1.5 Human factors

There are many human factor issues to consider when deciding on a strategy for variable speed. Acceleration, deceleration and jerk (the rate of change of acceleration) have a direct safety implication and require strict adherence to specified limits. There is a minimum safe transition time between speeds, which may cause delays during acceleration, and it is therefore advantageous to bring the step band up to speed before passengers reach the comb plate.

Passenger balance when stepping on and off the machine may actually improve with a reduction in speed, as the relative speeds of the steps and landing will reduce. This will have the biggest impact on passengers who are elderly or disabled, and do not react as quickly to changes in balance. Conversely, passengers who use the Underground regularly may have an expectation of the speed of escalators and overcompensate for the required balance adjustment if it is running slowly.

Whether passengers are aware of a reduction in speed, as well as the likelihood of walking or standing, will influence the optimum running speed. The perception of speed reduction is highly subjective and will vary from person to person, with the demographic of certain locations or times of the day making them more appropriate for a reduced speed strategy than others. Further work in this area would allow the human factor implications to be explored fully.

As well as the motion of the machine, it has been shown that a disorientating visual effect due to the periodic pattern of the step treads known as the *Wallpaper Illusion* is a common cause of accidents on escalators [5], so a comprehensive study should also take this into consideration.

2 OBJECTIVES

Following the research undertaken, the objectives of this study were specified:

- Assess the feasibility of speed reduction on London Underground escalators
- Derive models to predict and quantify the benefits of different variable speed strategies
- Recommend a variable speed strategy and conceptual design for a chosen escalator

An analysis of escalators was carried out against a set of criteria and a machine selected at Gants Hill (escalator number 2). The layout of the station enabled available passenger count data to be used to gauge escalator traffic, and off-peak speed reduction was already approved.

3 METHODOLOGY

3.1 Questionnaire

A questionnaire was submitted to the *Community of Metros* (CoMET). CoMET is an international benchmarking consortium consisting of fourteen large metro systems. The main aims of the questionnaire were to establish what speed reduction methods and technologies were being employed elsewhere, the drivers behind speed reduction strategies and how effective they were.

3.2 Modelling the effects

To assess the impact of each variable speed strategy, it was important not only to identify the effects, but also to quantify them and their relationship to the speed profile where possible. Three effects of running speed were considered in this way; energy consumption, component wear and passenger delays. These outputs were explored separately to derive a model for each in terms of the equivalent financial impact, with all three added together to give the overall financial impact.

To determine the energy consumption, empirical measurements of active power and power factor were taken, using a network analyser, at incremental running speeds with the machine in an unloaded state. Three replicates of each measurement were carried out and the mean average taken. The results were then used to determine the apparent power required to drive the machine and overcome the losses in the system, largely due to friction and inefficiencies in the drive machine. The results were also used to determine the effect of alternative speed profiles on the annual energy consumption and the associated cost and CO_2 emissions.

The cost savings due to reduced component wear were represented as a reduction in depreciation cost per year. A directly proportional relationship between speed and wear rate has been used to create a basic model to use as a starting point to quantify savings [4]. However, it should be noted that this is an oversimplified model, and further work is required to test it and develop it further. As well as extension of component life, it is likely that there will also be a positive impact on the reliability of the assets and associated repair and servicing costs, however this was not included in this scope of this study. The depreciation savings were estimated based the proportion of time that the machine is running at reduced speed along with historical data for frequencies and costs of replacement of the selected subsystems. It would be expected that there would be an increased rate of wear due to the influence of passengers, the magnitude of which will depend on the amount of loading, flow patterns and behaviour e.g. standing or walking, as well as the size and design of machine. Therefore a wear factor has been included in the model to enable adjustment to be made for this, initially set to an estimated value. For off-peak speed reduction, the figure used represents the expected ratio of wear rate from peak to off-peak time, and for automatic speed reduction it was based on the ratio of wear in a loaded to an unloaded state. These figures can be adjusted to observe their effect on the output, and depending on the findings of further investigation and data collection, could be developed into subsystem-specific values based on their different wear characteristics.

London Underground quantifies delays to passengers based on values of time defined by the Department of Transport [6]. This can vary but is around £6 per hour of delayed time, which will be used for the purposes of this study. This value, referred to as a *Lost Customer Hour* (LCH), is multiplied by the quantity of hours and passengers delayed to determine the equivalent financial cost for business cases. Depending on the activity, an additional weighting is applied to represent the magnitude of the impact on the passenger due to the nature of the activity, and this weighting for travelling on escalators is 1.5. These figures were used to model the financial impact on delays to passengers, with the ability to observe the effect of different passenger flow rates on the output.

3.3 Assessment of strategies

Automatic start/stop was not considered to be a feasible option for various reasons. Static friction must be overcome each time the machine starts, repeated operation of the brakes is likely to cause excessive wear of the braking system components, and there would be a risk that passengers may approach machines from the wrong direction or think that they are out of service. Two strategies were compared. The first was a pre-programmed speed reduction in off-peak hours[1]. The second was reduced speed operation, increasing to full speed when passengers are detected. Additional data sources used in the analysis were station plans, passenger count data, records of component replacement costs and frequencies, and train arrival times for the chosen station.

4 FINDINGS

4.1 Passenger flow

Figure 1 shows passenger count data for Gants Hill from surveys undertaken by London Underground [7]. This includes all passenger journeys from the platform concourse to the ticket hall, which equates to the total passenger flow for escalators 1 and 2 and represents a typical weekday.

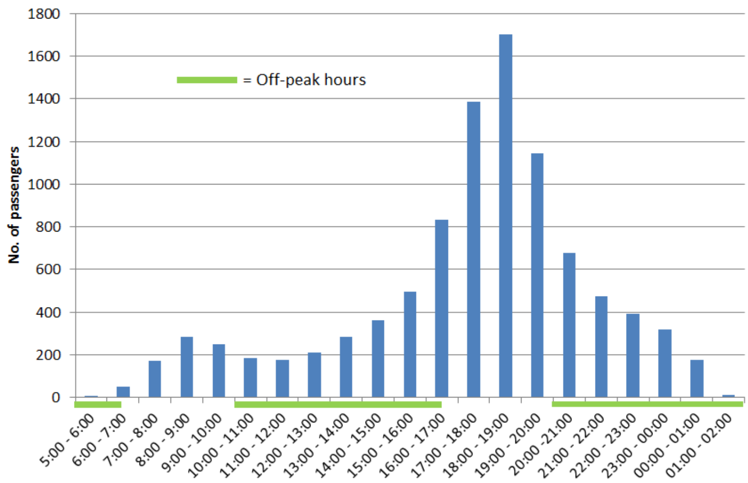

Figure 1: Passenger count data for Gants Hill from platforms to ticket hall

[1] Off-peak hours for reduced speed are weekdays 05:00-07:30, 10:00-16:30 and 19:00-02:00

4.2 Questionnaire

The questionnaire results showed that speed reduction is commonly employed worldwide, with nine out of ten of metro systems surveyed utilising some kind of speed reduction strategy. Although automatic speed reduction is widely used (all nine metros), stop/start is less common, with only five out of the ten responders utilising this approach. None of the responders employ a strategy of pre-programmed speed reduction during off-peak hours.

Most of the stop/start and speed reduction systems take an input from either photocells, pressure sensors or a combination of the two, to detect passengers. One metro system[2] bases its running speed on the number of passengers entering the station, however it was not specified how this is done.

Only one metro system reported a negative impact, whereby passengers entered an automatically starting escalator in the wrong direction, and one actually reported a decrease in accidents after the introduction of reduced speed. The reported experiences with speed reduction strategies were generally positive, with energy saving being the most common, and cost savings and component life extension also reported. The vast majority of the responses were positive, suggesting that speed reduction is tried and tested and widely agreed to be successful.

4.3 Analysis of off-peak speed reduction

<u>Energy Consumption Model</u>

The empirical measurements of active power and power factor are shown in Figure 2.

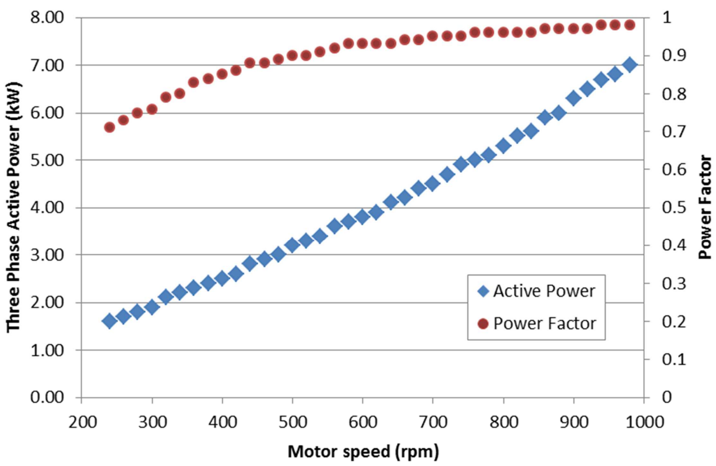

Figure 2: Empirical measurements of three phase active power (kW) and power factor vs motor speed for Gants Hill escalator 2

The above data was converted to apparent power and multiplied by the quantity of off-peak hours per year to predict the annual energy consumption. The difference in energy use between reduced speed and full speed gives the annual energy reduction. The associated cost saving was calculated using the current price budgeted by London Underground of 10.71 pence per kWh and the results are shown in Figure 3 along with a best fit line determined using the *Least Squares* method.

Speeds below 40% will not be included in the proposed strategy to avoid the risk of the motor overheating as discussed in Section 1.3. Also, although power factor correction is present, the power factor drops rapidly below 40% of full speed. Monitoring in service may demonstrate feasibility for slower speed operation.

[2] Due to a confidentiality agreement with CoMET, individual metros have not been named

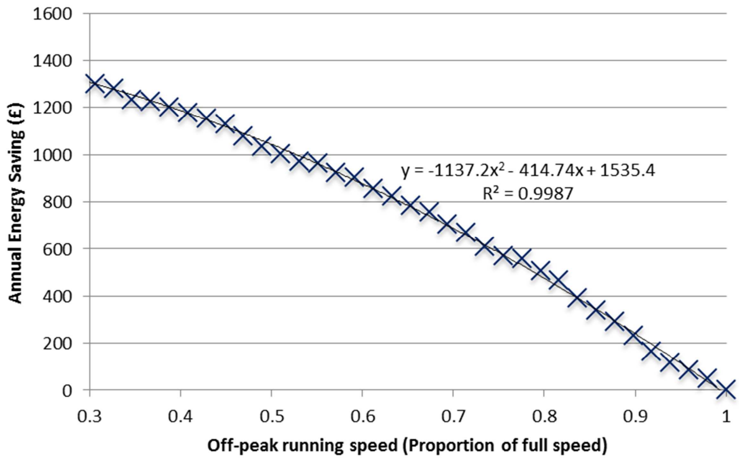

Figure 3: Predicted annual energy cost savings due to off-peak speed reduction modelled from empirical power measurements

The reduction in annual CO_2 emissions can be calculated, based on the electricity generation factor of 0.4585 kg per kWh published by DEFRA [8] to be initially around 1030 kg for each 10% reduction in running speed during off-peak hours, falling to around 500 kg per 10% drop in speed.

<u>Component Wear Model</u>

The subsystems shown in Table 1 have been selected to demonstrate the approach to modelling depreciation savings due to reduced wear.

Table 1: Component replacement data for Gants Hill 2 from maintenance records

Components	Freq, f_n (years)	Replacement cost, c_n (£)	Annual depreciation, c_n/f_n (£)
Handrail sweep track	3.5	4265	1218.57
Chain and trailer wheels	5	21722	4344.40
Handrail system	7.5	62415	8322.00
Step band	10	147000	14700.00
		Total annual depreciation, C_d (£)	**28584.97**

Based on the assumptions in Section 3.2, the total depreciation of *n* subsystems with the machine running at full speed can therefore be modelled with the following formula:

$$C_d = \sum_{1}^{n} \left(\frac{c_n}{f_n}\right) \tag{1}$$

where:
C_d is the total annual depreciation cost of components (with continuous full speed operation)
c_n is the cost of replacement of subsystem *n* (£)
f_n is the frequency of replacement of subsystem *n* (years)

As speed reduction applies to off-peak hours only, the saving in component wear also only applies to this reduced proportion of the total hours run. The total annual depreciation cost is therefore reduced accordingly before calculating the savings. Also, as mentioned in Section 3.2, there will be additional wear due to passengers during peak hours, so the amount of wear attributed to off-peak operation is divided by the previously defined wear factor i.e. the expected ratio of peak to off-peak wear rate at full speed. Equation 1 can then be amended to determine y_d, the saving in depreciation cost per year, by incorporating these factors and subtracting the predicted annual depreciation cost at reduced speed from the annual depreciation due to continuous full speed operation.

$$y_d = \frac{1}{w} \cdot \frac{h_o}{h_p} \left[\sum_1^n \left(\frac{c_n}{f_n} \right) . (1 - x) \right] \tag{2}$$

where:
y_d is the annual saving in depreciation cost per year (£)
h_o / h_p is the ratio of off-peak to peak hours
x is the running speed during off-peak hours (proportion of full speed)
w is the ratio of the wear rate in peak hours to the wear rate in off-peak hours at full speed

With 13 off-peak hours each weekday and a total of 140 hours run per week, the ratio of off-peak to peak hours is 0.464, and an estimated value of 1.5 is applied for the peak to off-peak wear factor. The result, based on the estimated values and assumptions of this model, is a linear relationship between speed and depreciation cost with an increase in predicted savings of approximately £900 per 10% speed reduction during off-peak hours.

<u>Passenger Delay Model</u>

Applying the cost of a *Lost Customer Hour* to the time taken to travel on an escalator gives the equivalent cost of a passenger's time for the journey. This can then be multiplied by the quantity of passenger journeys per hour and a factor of 1/3600 to convert journey time from seconds to hours:

$$C_J = c_{LCH} * \frac{p * t}{3600} \tag{3}$$

where
C_J is the average cost of journeys per hour
c_{LCH} is the cost of 1 Lost Customer Hour
p is the average number of passengers per hour
t is the time for one journey (sec)

To find the total equivalent cost of passenger journeys per year during off-peak hours, C_J (based on the average passenger flow rate) is multiplied by the number of off-peak hours run per year i.e. the weekly off-peak hours multiplied by 52. The time for one journey is calculated from the running speed and length of incline, with the latter derived from the angle of incline and vertical rise. Applying these adjustments to equation (3) leads to the following model for the financial impact of off-peak speed reduction on journey time:

$$y_J = \left(c_{LCH} * \frac{52 h_w . p . r}{3600 . v . sin\vartheta} \right) . \left(1 - \frac{1}{x} \right) \tag{4}$$

where:
y_J is the equivalent cost saving due to passenger journey time per year (£)
h_w is the number of off-peak hours run per week
r is the vertical rise of the escalator (m)
θ is the angle of incline
x is the proportion of full running speed during off-peak hours
v is the step speed at full speed (m/s)

Slowing down the escalator will increase the cost of journey time, making the value of y_J negative, and as the cost of delays are proportional to the inverse of the speed, the magnitude of the impact actually multiplies as the speed decreases, as Figure 4 illustrates.

Combined Model

The savings due to all three of the factors considered are shown in Figure 4a. Passenger delays are based on the average off-peak passenger flow for Gants Hill escalator 2 (353 per hour) [7] and the weighted value of an LCH of £9. The equivalent losses due to passenger delays of running at reduced speed during off-peak hours by far outweigh the savings from energy consumption and component wear resulting in huge losses. Therefore, using this cost benefit methodology, a pre-defined off-peak speed reduction is definitely not a feasible strategy for this machine. To show the energy and component wear savings more clearly figure 4b has the passenger delay plot removed.

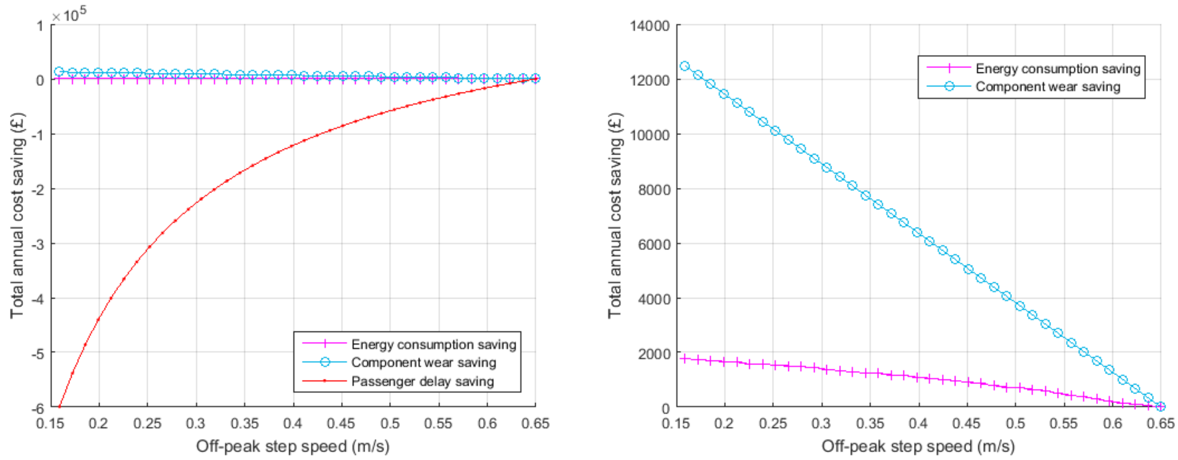

Figure 4: Predicted annual savings for Gants Hill escalator 2 a) All three outputs b) Energy and component wear only

Running the model with a range of passenger flow rates enables other scenarios to be tested, and a series of plots of the total financial savings for each passenger flow rate is shown in Figure 5. It is not until the rate drops below about 30 passengers per hour that the net savings become positive. This means that there may be value in reducing the speed for very quiet periods, for example at the beginning and end of the day, when footfall is particularly low, to achieve a corresponding proportion of the annual savings, but this will not provide significant savings.

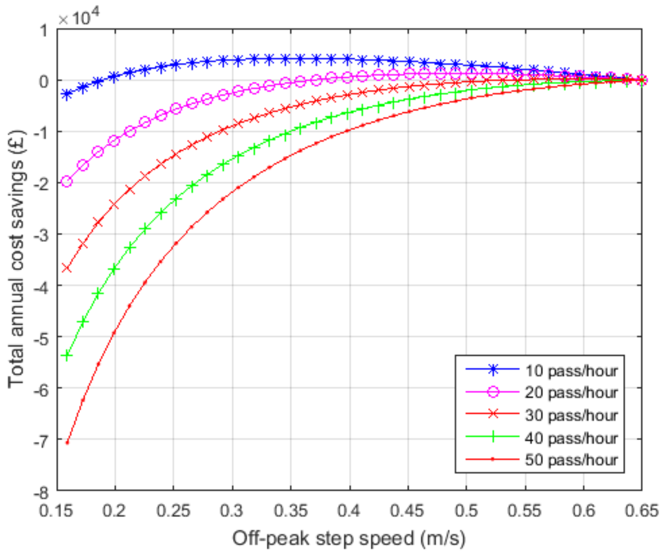

Figure 5: Predicted total annual cost savings due to energy, component wear and delays for pre-programmed off-peak speed reduction with up to 50 passengers per hour

4.4 Analysis of automatic speed reduction

As with the off-peak speed reduction strategy analysed in the previous section, the cost savings for an automatic speed reduction strategy depend on the proportion of time that the machine is running at a reduced speed, therefore a similar approach can be taken to model these. With this approach, the speed will repeatedly alternate between full speed and reduced speed throughout the day, so instead of using the ratio of off-peak to peak hours, the ratio of unloaded to loaded hours was used. For the calculation of depreciation savings, the wear factor applied to the expected ratio of component wear rate between loaded and unloaded conditions instead of peak to off-peak.

To determine the proportion of time that the machine would be required to run at full speed, the time taken for the passenger in the furthest carriage to reach the top of the escalator must be calculated. Based on an average walking speed of 1.34 m/s [9], and the distance from the furthest point on the platform to the escalator (148 metres), the expected time taken for the last passenger to reach the escalator is 110.5 seconds. The journey time on the escalator can be calculated from the full speed of the escalator (0.65 m/s) and the length of the incline (19.66m) to be 30.25 seconds. To avoid causing delays, this approach would be most effective if the machine is able to accelerate prior to the arrival of passengers.

The total of the two calculated durations was added to the train arrival times to determine the theoretical amount of time when the escalator is required to either accelerate or run at full speed. This was found to be 60%, which corresponds to annual cost savings of £5,140 and an annual reduction in CO_2 emissions of around 5.7 tonnes. These figures are based on every train having someone in the furthest carriage, which may often not be the case, particularly during quiet periods. Also, regenerated energy during deceleration will not equal that required for acceleration due to the effects of friction and motor and gearbox losses. With the component wear also based on an oversimplified model, empirical data collection after the system is installed is recommended to determine more accurate estimates of the savings.

4.5 Comparison of strategies

Of the two approaches, automatic speed reduction is the most suitable strategy for the chosen machine, as this eliminates delays to passengers whilst achieving savings due to reduced energy consumption and extended component life. These savings can be made at any time of the day, even in peak hours, utilising periods when the machine is unloaded.

Although the component life model requires further development, it does indicate that the annual savings in depreciation of components are potentially much greater than the electricity cost savings. However, the political, legal and ethical issues of environmental impact due to reduced energy consumption gives the latter added importance.

It should be noted that the increase in power required to accelerate the machine will reduce the overall energy consumption benefits, and this will have a larger impact with the automatic speed reduction option. Regenerative braking therefore should be used to decelerate the machine, thereby utilising the kinetic energy and offsetting it against the excess energy for acceleration. The practical effect of this can be determined from empirical measurements in service.

The predicted savings using an automatic speed reduction strategy require the prevention of any delays to passengers. Therefore, as suggested above, it is desirable to ensure that the speed of the machine is at full speed before passengers reach the landing. This also avoids the risk of acceleration affecting passengers' balance. Detection of the arrival of a train at the platform would be an effective solution.

5 OPTIMISATION TOOL

To enable off-peak and automatic speed reduction strategies to be assessed and compared using quantitative data, an interactive application has been created using MATLAB. It can generate all of the relevant predicted outputs discussed in this paper and was used to generated the savings used in the analysis for this study. It can be used in a number of ways:

- Optimum speed profiles can be determined based on specified conditions
- Alternative scenarios can be tested theoretically before installation or changes to operation (although empirical power measurement data is required to generate predicted energy savings)
- Cost savings can be visualised clearly for effective communication of the benefits of proposed strategies in reports or presentations

A screenshot of the application user interface is shown in Figure 6.

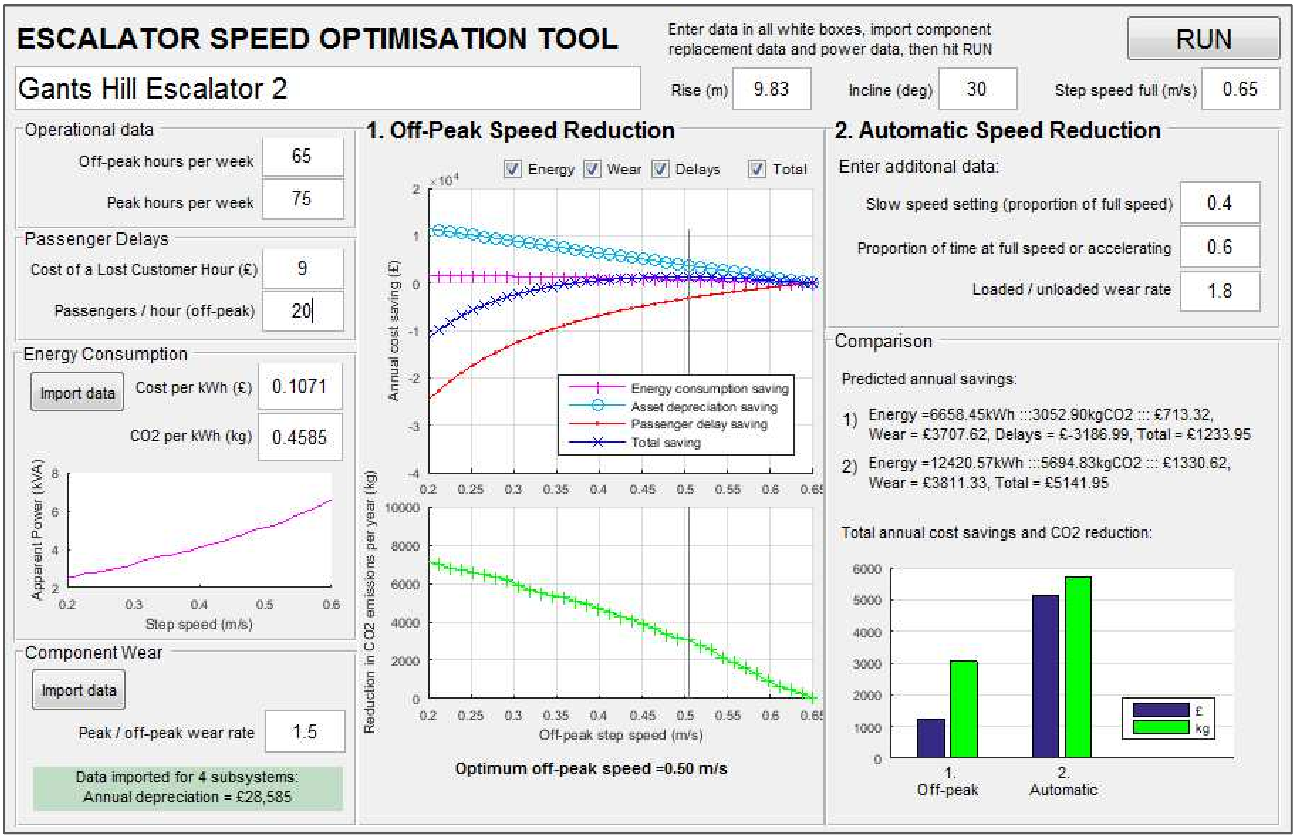

Figure 6: Optimisation tool user interface

6 CONCEPTUAL DESIGN

Based on the findings of this study, the recommended strategy for Gants Hill escalator 2, which can be adapted for other machines and other stations, is an automatic speed reduction system that reduces to a crawl of 40% of full speed when unloaded.

To prevent delays as the escalator accelerates, the input to trigger acceleration should occur prior to the arrival of the first passenger. This could be done when a train enters the platform, either utilising outputs from the signalling system, or a proximity sensor at the platform edge. The layout of the station would allow approximately 25 seconds for the escalator to accelerate before the first passenger arrives at the lower landing, based on an average walking speed. The system should also include a method of detecting when the last passenger has left the machine. An infra-red detector at the lower landing in conjunction with a timer would be a cost effective solution. However, 2D video counting should also be considered as this would provide passenger flow monitoring which could support future strategic decisions.

Using the VVVF drive will ensure that acceleration, deceleration and jerk do not exceed acceptable limits as well as enabling regenerative braking to be used to minimise wasted energy.

7 RECOMMENDATIONS

Following the development of a final design for an automatic speed reduction system at Gants Hill, a trial is recommended in passenger service to gather empirical data. This can then be used to make a full assessment of the system. In the short term, energy consumption can be measured, while component life will require longer term monitoring. Temperature and vibration monitoring of the motor should also be carried out initially to confirm that the motor can function effectively at the reduced speed. The speed setting can then be adjusted if necessary. Monitoring of passenger flow and real time monitoring of power as well as any changes to component failure rates should also be carried out as part of the trial to enable a true assessment of the system to be made.

The recommended method of triggering the escalator based on train arrivals is most suited to escalators situated close to the platforms and running in the up direction, as passenger arrivals will be in groups synchronised to train arrivals. Therefore when considering a variable speed strategy at other locations a full assessment of passenger flow and station layouts is recommended to determine the optimum strategy on a site-by-site basis. This should also consider the benefits of applying speed reduction to down machines, however, the proportion of time where these are unloaded may be considerably less due to the continuous flow of passengers entering stations throughout the day.

Further research and data collection is recommended to test the models derived in this study and develop them further. More comprehensive investigations are also recommended into the impact of running speed on human factors, safety and component wear. This work can be carried out alongside the proposed trial, both of which can provide valuable input into an overall strategy.

8 CONCLUSIONS

From the research, data acquisition and analysis carried out, it can be concluded that speed reduction is feasible on escalators on the London Underground. The technology has proven benefits in terms of energy consumption and component life on metro systems throughout the world. Furthermore, the majority of London Underground’s escalators are already equipped with the required hardware to vary the speed, with only minimal programming required. Therefore, this is an effective way to reduced costs, which will contribute to the overall energy reduction target.

Although reducing the speed can provide cost savings to the business, the savings are considerably less and in most cases negative, when passenger journey time is considered, even with a low passenger flow rate. Therefore, an automatic speed reduction system, reducing the speed to a crawl when the escalator is unloaded, has been recommended. This will achieve reductions in energy consumption, the depreciation cost due to wear of components on the machine will be reduced and delays to the travelling public minimised.

In order to carry out a full business case, the concept should be developed into a detailed design, determining the full cost of implementation. A conceptual design has been recommended for a trial which will enable the effectiveness of the proposed strategy to be assessed and further optimisation carried out. As the scope of this investigation applies to a single machine and includes various assumptions, additional data collection and analysis would be required to develop a complete strategy for London Underground. However, the structure of the investigation and the models and tools that have been created form a starting point for this work to be undertaken.

REFERENCES

[1] Greater London Authority, 2011, Climate Change Mitigation and Energy Strategy

[2] Al-Sharif, Dr. L. R., 2011, Modelling of Escalator Energy Consumption. Energy and Buildings, 43, pp.1382–1391.

[3] British Standards Institution, 2010, BS EN 115-1:2010 Safety of escalators and moving walks: Part 1. BSI: London

[4] Chowdhury, M. A., Khalil, M. K., Nuruzzaman, D. M. & Rahaman, M. L., 2011, Effect of Sliding Speed and Normal Load on Friction and Wear Property of Aluminum, International Journal of Mechanical & Mechatronics Engineering

[5] Cohn, T, & Lasley, D, 1990, Wallpaper illusion: cause of disorientation and falls on escalators. Perception, 19, 573-580.

[6] Department for Transport, 2014, WebTAG: Transport Analysis Guidance (TAG) data book, [Online], Available at https://www.gov.uk/government/publications/webtag-tag-data-book-november-2014

[7] London Underground, 2013, Rolling Origin and Destination Survey

[8] Department for Environment Food & Rural Affairs, 2015, Greenhouse Gas Conversion Factor Repository, [Online], Available at http://www.ukconversionfactorscarbonsmart.co.uk

[9] Health & Safety Executive, 2007, Inspection Pack - Workplace Transport, [Online], Available at: http://www.hse.gov.uk/foi/internalops/fod/inspect/transport.pdf

ACKNOWLEDGEMENTS

Support received from London Underground, Brunel University, Dr. Lutfi Al Sharif and Barwit Control Systems is gratefully acknowledged.

BIOGRAPHICAL DETAILS

Ben Langham has a BEng in Mechanical Engineering from the University of Reading and an MSc in Advanced Engineering Design from Brunel University. He has worked in maintenance on the London Underground since 2006 when he joined the Metronet Rail engineering graduate scheme. For the past 7 years he has been based in lift and escalator maintenance at London Underground, first as a Performance Engineer and currently as a Condition-Based Maintenance Engineer.