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Mathematical Modelling of Comparative Energy Consumption between a Single-loop Curvilinear Escalator (The Levytator) and an Equivalent Pair of Linear Escalators

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INTRODUCTION

This paper describes a technique for mathematically modelling the comparative energy consumption between two types of escalators deriving energy differential functions. Using numerical analysis this paper shows how the energy consumption may vary under different load patterns. The paper concludes that the use of a Levytator is almost always more energy efficient than a pair of conventional straight escalators.

We have focused on energy consumption in operation as we believe the Levytator's carbon footprint in manufacture and disposal would be significantly less than a pair of conventional escalators. If you need details on this, please contact the authors of this paper.

The Levytator: Conventional escalators follow a straight line. The return path of the step travels underneath the useable steps beneath the housing. In order to provide both up and down paths of travel, two conventional linear escalators are needed.

The Levytator is designed to follow any reasonable curve. Its unique patented step design using vertical bearings, allows one Levytator to provide both up and down directions of travel as both set of steps are part of one loop. The Levytator only needs one power source to drive the steps whereas a conventional escalator needs two motors.

Structure: This paper sets out a method for mathematically modelling the differential power consumptions between a single Levytator configuration and a pair of conventional escalators for the same rise. The construction of the mathematical model is set out in Part 1-Overview. The calculations using some simple assumptions are set out in Part 2-How Green is the Levytator. The numerical analysis and the shape of the energy functions are detailed in part 3.

PART 1 OVERVIEW

The performance analysis of the Levytator consists of the comparison of power demand of two escalators that have travelling passengers in two opposite directions and the Levytator with the same geometry. The steps of the process are:-

- To produce the equation of total power demand P^* for two escalators ("up" and "down") with the same geometry (length l and canting angle α) traveling in opposite directions;
- To produce the equation of total power demand P^{**} for the Levytator (the length of incline bands - $2l$, total length – S);
- To calculate the relation between power demands depending on the dynamic parameters.

The calculations based on the Newtonian dynamics and the energy conservation law.

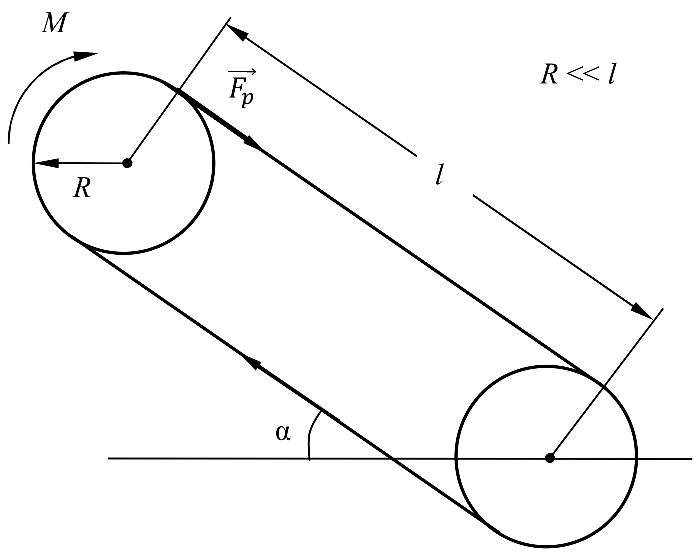

Fig 1 A single conventional escalator

Figure 1 shows a stylized representation of a single conventional escalator rising at an angle of α. The engine has an effective propulsive force of F_p working on an effective radius of R on an escalator of effective length l. Letting m_e be the mass of the escalator, m_1 the mass of passengers going up, m_2 the mass of the passenger going down, V the velocity of the escalator band, η the efficiency coefficient of the engine and μ is the coefficient of friction due to the band of the escalator, we can derive the power demand for a pair of conventional escalators to give the following equation.

$$P^* = \frac{V}{\eta}[\mu g \cos\alpha\,(2m_e + m_1 + m_2) + g\sin\alpha\,(m_1 - m_2)]$$

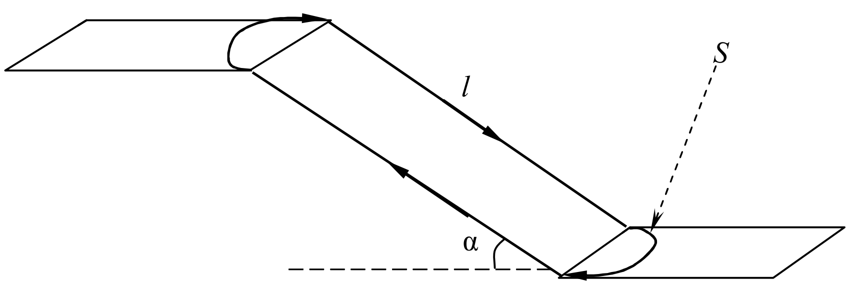

Fig 2 The Levytator

Figure 2 shows the configuration of the Levytator showing both the upward and downward paths of the loop. It is configured to be equivalent to two conventional escalators of effective length l. Since the Levytator's return loop is the downpath, we introduce another variable S, the total length of the Levytator loop. Using the same variables as above, we can derive the power demand for the Levytator as

$$P^{**} = \frac{V}{\eta}\left[\mu m_e g\cos\alpha + \mu m_e \frac{S-2l}{2l} g + (m_1 - m_2) g\sin\alpha + \mu(m_1 + m_2) g\cos\alpha\right]$$

$$= \frac{V}{\eta}\left[\mu g(m_e(\cos\alpha + \frac{S}{2l} - 1) + (m_1 + m_2)\cos\alpha) + (m_1 - m_2) g\sin\alpha\right]$$

Therefore, we can derive the Green Coefficient as follows:-

$$\frac{P^*}{P^{**}} = \frac{\mu \cos\alpha\,(2m_e + m_1 + m_2) + (m_1 - m_2)\sin\alpha}{\mu(m_e(\cos\alpha + \frac{S}{2l} - 1) + (m_1 + m_2)\cos\alpha) + (m_1 - m_2)\sin\alpha)}$$

PART 2 – HOW GREEN IS THE LEVYTATOR

By applying some reasonable assumptions, we can illustrate the 'Greenness' of the Levytator against a pair of conventional escalators by applying these assumptions to the power demand equations derived above in the mathematical models.

We have made the following assumptions in producing the indicative calculations.

The rise for both systems is 7.5m with both systems travelling at a speed of 0.5 m/s. The effective length of the incline l of both systems is 15 m and the number of visible steps is 39. We assume that the step sizes and width are equivalent (1 m wide and 0.38 m deep) and have similar masses. We also assume the average mass of a single passenger is 75 kg. We have assumed the energy conversion efficiency η is the same for both at 90% and the effective coefficient of friction μ is 0.25.

According to the reference paper published by the Royal Academy of Engineering [1], we derive that 1kW per hour in a coal-fired station typically produces 0.9 g of CO_2.

We have modelled the following three cases as an illustration of the relative 'greenness' between the Levytator and a pair of conventional escalators.

Results	Power, P^* and P^{**} (kW)	Green Coefficient, $\frac{P^*}{P^{**}}$	Power per person per trip, $P^*_{per\ person\ per\ trip\ up\&down}$ and $P^{**}_{per\ person\ per\ trip\ up\&down}$ $(kW-hr)$	CO_2 emissions per person per trip, (g)
Escalator	14.91	1.25	0.003148	2.83
Levytator	11.96		0.002525	2.25

Fig 3 Full loaded both up and down

Results	Power, P^*_{UP} and P^{**}_{UP} (kW)	Green Coefficient, $\frac{P^*_{UP}}{P^{**}_{UP}}$	Power per person per trip UP, $P^*_{per\ person\ per\ trip\ up}$ and $P^{**}_{per\ person\ per\ trip\ up}$ $(kW-hr)$	CO_2 emissions per person per trip UP, (g)
Escalator	13.72	1.27	0.0058	5.22
Levytator	10.77		0.0046	4.05

Fig 4 Half loaded with empty downward path

Results	Power, P^*_{UP} and P^{**}_{UP} (kW)	Green Coefficient, $\frac{P^*_{UP}}{P^{**}_{UP}}$	Power per person per trip UP, $P^*_{per\ person\ per\ trip\ up}$ and $P^{**}_{per\ person\ per\ trip\ up}$ $(kW-hr)$	CO_2 emissions per person per trip UP, (g)
Escalator	5.752	2.05	0.00243	2.18
Levytator	2.8		0.0012	1.08

Figure 5 Half loaded with upward path empty

PART 3 – CONCLUSION

From the tables in Part 2, we can show theoretically that the Levytator is more 'Green' than a pair of conventional escalators in a similar configuration. We have also modelled several variations of the assumptions (e.g. different values of μ etc). In the main paper we show diagrams from MathCad using different numerical analysis.

Obviously, the accuracy any mathematical model is dependent on the selection of the main parameters to be modelled. Having completed this model, we could refine it further by breaking down μ to include friction between the step bearings and its guide tracks etc. However, we believe we have modelled the key parameters.

The technique shows that we can develop mathematical models to predict likely power demands even before the system is built. By using simple mathematical tools, we can express our intuition that the Levytator is likely to be more energy efficient in some more reasoned and logically argued form. It is also a powerful method to show the energy efficiency of a system before it is built and Elena is researching the application of such techniques to marine systems.

In our attempts to commercialise the Levytator, we have focused on its unique feature of being able to follow any reasonable curvilinear path. This particular modelling exercise has highlighted to us the opportunity to 'sell' the Levytator as a 'Greener' and more energy efficient solution than conventional escalators.

One final note, in our numerical calculations, there are certain combinations of factors that suggests the Levytator, rather than consume energy, may generate energy!

REFERENCE

[1] "The Mathematics of Escalators on the London Underground", Transport for London, the Royal Academy of Engineering,
http://www.raeng.org.uk/education/diploma/maths/pdf/exemplars_engineering/4_Escalators.pdf