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FOREWORD

It is with great pleasure that we present the proceedings of the 5th Symposium on Lift and Escalator Technologies, September 2015, organised jointly by The Lift Engineering Section of the School of Science and Technology and The CIBSE Lift Group.

The Lift Engineering programme offered at The University of Northampton includes postgraduate courses at MSc/ MPhil/ PhD levels that involve a study of the advanced principles and philosophy underlying lift and escalator technologies. The programme aims to provide a detailed, academic study of engineering and related management issues for persons employed in lift making and allied industries.

The CIBSE Lifts Group is a specialist forum for members who have an interest in vertical transportation. The group meets regularly to promote technical standards, training and education, publications and various aspects of the vertical transportation industry. The CIBSE Lifts Group directs the development of CIBSE Guide D: Transportation systems in buildings, the de facto reference on vertical transportation.

The Symposium brings together experts from the field of vertical transportation, offering an opportunity for speakers to present peer reviewed papers on the subject of their research. Speakers include industry experts, academics and post graduate students.

The papers are listed alphabetically by first author details. The requirement was to prepare an extended abstract, but full papers were accepted from the invited speakers where they preferred to offer them. The submissions are reproduced as they were submitted, with minor changes in formatting, and correction of obvious language errors where there was no risk of changing meaning.

We are grateful to organisations that have supported this venture, as highlighted by their logos below.

Professor Stefan Kaczmarczyk, The University of Northampton and
Dr Richard Peters, The CIBSE Lifts Group

CONTENTS

Extracting the Value of the Round Trip Time under Up Peak Traffic Conditions from Simulation

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Keywords: elevator; lift; inter-arrival time; inter-service time; round trip time; interval; Poisson arrival process; system loading; calculation; simulation; Monte Carlo simulation.

Abstract. The round trip time has been traditionally found by using calculation methods, either analytically by the use of equations or numerically by the use of Monte Carlo simulation or Markov chains. This paper explores the use of simulation to extract the value of the round trip time. The main reasons for the difference between the value of the round trip time under calculation and simulation are the three random effects: the randomness of passenger destinations (thus making the value of the round trip time a random variable), the randomness of the passenger arrival (driven by a Poisson passenger arrival model) and the effect of bunching (thus making the value of the interval a random variable). The value of the round trip time has been plotted against the system loading level for the case of a single entrance and incoming traffic only. The system loading level has been varied from values as low as 0.05 (i.e., 5%) up to an overloaded system level of 3 (i.e., 300%). Different conditions have been simulated including constant and random passenger arrivals, as well as queues allowed and queues not allowed conditions. Varying these conditions provides an essential insight into the variation of the round trip time and the reasons for it.

Nomenclature and Acronyms

AR% is the passenger arrival rate expressed as the building population in five minutes
CC is the rated car capacity in passengers
FIFO first in first out (of a queue)
λ the passenger arrival rate in passengers per second
λ_{des} the design passenger arrival rate in passengers per second according to which the system was originally designed
λ_{act} the actual passenger arrival rate in passengers per second to which the system is exposed
L is the number of the elevators in the group
ρ the system loading (where 1 denotes 100% system loading)
RTT or T is the average value of the round trip time in seconds during the total simulation time and averaged over a large number of trials
τ the value of the round trip time in seconds (as a random variable varying from each round trip to the next)
WS is the nominal simulation time referred to as the workspace in seconds

1 INTRODUCTION

The round trip time has been, and still is, the basic tool for designing elevator traffic systems. It has been customary to evaluate the value of the round trip time using calculation or the Monte Carlo simulation method.

A previous paper has outlined six methods for deriving the round trip time [1]. The first five of these are analytical ([2]-[9]) and numerical ([10], [11], [12] and [23]). Numerical methods have also been used to calculate the value of the average travelling time (e.g., using the Monte Carlo simulation method to evaluate the value of the average travelling time [13]). The sixth presented method was based on simulation, although few details were given. This paper outlines a possible methodology for extracting the round trip time from the simulation data.

Queuing theory has been used in order to try to understand the performance of the elevator traffic systems under simulation [14]. Classical queuing theory can be used to estimate the value of some critical parameters such as the average waiting time and the average queue length.

Section 2 presents a qualitative explanation for the reasons of the discrepancy between the values of the round trip time under calculation and simulation. Section 3 provides an overview of the MATLAB code used to run the simulation. Section 4 discusses results for a 12 floor building and shows the variation of the round trip time under increasing system loading. The results from section 4 are discussed in section 5. Conclusions are drawn in section 6.

2 THE CAUSE OF THE DISCREPANCY

In theory, the value of the round trip time found by calculation should be identical to the value found in simulation. However, it is generally acknowledged that the value of the round trip time under simulation is smaller than that resulting from calculation. Differences between calculation and simulation are discussed in [15].

The main reason for this discrepancy is the fact that the number of passengers boarding the elevator car on average is smaller than that assumed under calculation. It is in fact the random effects that arise under simulation that lead to a smaller number of passengers boarding the elevator car under simulation and thus causing a difference between the two values of the round trip time.

The combination of the restriction in the car size coupled with random effects (detailed later in this section) are the reason why the average number of passengers boarding the elevator car is smaller than that expected under calculation. This is explained as follows:

1. In cases where the number of passengers waiting to board the elevator is larger than the car capacity (*CC*), only *CC* passengers can board the elevator car (assuming 100% car loading is possible). The remaining passengers remaining will be added to the queue in order to board a future elevator car under real life simulation (or discarded under the hypothetical *no queuing* simulation introduced later in this paper).
2. In cases where the number of passengers waiting to board the elevator is smaller than the car capacity, the elevator car will collect them and depart (and will not wait for further passengers to arrive in order to fill the elevator car up). This point is what leads to the smaller car loading on average, and thus to a reduction in the value of the round trip time.

The net effect of these two last points is that the effective number of passengers boarding the elevator car in each round trip is smaller than the car capacity (*CC*). There are five sources of randomness, listed below:

1. The randomness of the passenger destinations: In each round trip the passengers boarding the elevator car will select different destinations. These random destinations depend on the relative floor populations. The fact that they are different in each round trip results in different values of the round trip time in each trip. The consequences of this variability in the value of the round trip time are that the elevator car will spend different times away from the main entrance. When the elevator car returns to pick up passengers from the main entrance, the number of passenger waiting to board the elevator car will be proportional to the value of the last round trip time.
2. The randomness of the passenger arrival process: It has been shown that the passenger arrival process in elevators is a random process, whereby the number of passengers arriving

in a specified period of time follows a Poisson probability density function. The consequences of these random passenger arrivals are that a different number of passengers will be waiting to board the elevator when it returns to the main entrance (regardless of the variability in the value of the round trip time itself).

3. The variability in the value of the interval (caused by the phenomenon of bunching): Even if it were possible to prevent the variability in the value of the round trip time, the value of the actual interval could vary. This is due to the phenomenon of bunching ([16], [17]), whereby the elevators are not equally spaced in their movements. Bunching leads to variability in the actual value of the interval. The interval is in effect the time during which the passengers that will board the next elevator car accumulate. If the interval is longer than the average value, more passengers will arrive; if it is shorter, fewer passengers will arrive.
4. Edge effects: When the workspace (*WS*) of the simulation is relatively short (e.g., 300 s) the effect of the first and last journeys can be significant. The elevator car for the last journey of the simulation would usually be carrying the remaining passengers, the number of which would be smaller than *CC*. The first journey could also involve a larger than normal or smaller than normal number of passengers and hence could distort the overall results.
5. The initial conditions: The initial position of the *L* elevator cars can also have a significant effect on the value of the round trip time.

It is relatively easy to overcome the last two sources of randomness. Edge effects can be overcome by removing the first and last journey and increasing the value of the workspace. The initial conditions are overcome, by carefully locating the position of the elevator cars in the round trip cycle such that they are perfectly spaced.

It is worth noting that the effect of the group control algorithm is beyond the scope of this paper. Work has been done in order to amend the formulae for the round trip time to take the effect of the elevator group controller into consideration in [18], [19] and [20].

3 MATERIAL AND METHODOLOGY

In order to extract the value of the round trip time from simulation, a simple MATLAB code was written that can simulate a group of elevator cars under incoming traffic conditions and single entrance. Various software switches can be used to simulate different conditions in order to better understand the effect of different conditions, assumptions and settings. The software runs the simulation for the workspace time (*WS*).

It is based on incoming traffic only from a single entrance. The software contains two parts: a calculation part that carries out the design of the elevator traffic system using the *HARint* Plane methodology ([21], [22]); and a simulation part that receives the parameters of the elevator traffic system design from the calculation part and carries out the simulation for a specified period of workspace (*WS*). The simulation produces graphical outputs as well as spreadsheet data for the following parameters:

1. Average passenger waiting time.
2. Average passenger travelling time.
3. Average passenger queue length.
4. Average value of the round trip time.
5. Average car loading.

The following rules are followed in running the software:

1. The set of passengers are generated at the start of the simulation for the whole period of the workspace (assuming constant passenger arrivals or Poisson passenger arrivals).

2. The car capacity is set to exactly the number of passengers stipulated by the calculation (an integer value is used). Hence, 100% car loading is allowable.
3. When the elevator car returns to the main entrance, it picks up as many passengers as are present, but no more than the maximum number of passengers.
4. The elevator will not wait for more passengers to fill up with the maximum number of passengers.
5. Any passengers arriving while the existing passengers are boarding are also allowed to board.
6. Any passengers arriving after the doors start closing cannot board the elevator and will have to wait for the next elevator to arrive (thus joining the queue).
7. No door re-openings are allowed.
8. Any passengers that cannot board the elevator will remain in the lobby in a queue (or discarded if the switch for no-queuing allowed is active).
9. If there are no passengers present in the lobby when the elevator arrives then the elevator will not leave and will stay at the lobby with its doors open.
10. For the purposes of extracting the round trip time from the simulation, the idle time has to be removed. So if there are no passengers in the lobby, this time does not count as part of the round trip time.
11. In order to remove edge effects, the first and last round trips are excluded from the calculations of the round trip and the average number of passengers boarding the car. The software automatically finds the start and end points of each round trip (e.g., by looking for the door-start-of-closing-point in time and using it as a reference). Once all the round trips have been identified, the values of the first and last trip are excluded from calculating the average value.

4 SAMPLE RESULTS

A numerical example is presented in this section. It illustrates the points introduced earlier in this paper. A sample building is used in order to plot the value of the round trip time against system loading. The system loading is varied in increments of 0.05 starting from the value of 0.05 (i.e., 5%) loading up to 300%.

System loading is varied by varying the actual value of the arrival rate (in passenger per second) (λ_{act}) against the design arrival rate (in passengers per second) denoted as (λ_{des}). Thus a system loading of 100% is represented by passengers arriving at the rate that was anticipated in the original design; an under-loaded system will experience passengers arriving at a rate smaller than the design arrival rate; and an overloaded system will experience passengers arriving at a rate larger than the design arrival rate. This is summarised in Table 1 below.

Table 1: Summary of the three loading conditions.

Under-loaded system	$\lambda_{act} < \lambda_{des}$ or $\rho = \frac{\lambda_{act}}{\lambda_{des}} < 1$ ……….(1)
100% loaded system	$\lambda_{act} = \lambda_{des}$ or $\rho = \frac{\lambda_{act}}{\lambda_{des}} = 1$ ……….(2)
Over-loaded system	$\lambda_{act} > \lambda_{des}$ or $\rho = \frac{\lambda_{act}}{\lambda_{des}} > 1$ ……….(3)

Effectively, varying the value of λ_{act} is a change in the value of the arrival rate *AR%*.

Numerical Example

A building has 12 floors above the main entrance. The total building population is 1000 persons. The floor by floor population and the floor heights are shown in Table 2.

Table 2: The floor populations and the floor heights of the building.

Floor	Floor population (persons)	Floor height (m)	Type of floor (Ent, Occ)
12th	25	N/A	Occupant
11th	25	4	Occupant
10th	25	4	Occupant
9th	25	4	Occupant
8th	50	6	Occupant
7th	75	6	Occupant
6th	100	6	Occupant
5th	100	6	Occupant
4th	125	6	Occupant
3rd	125	8	Occupant
2nd	150	8	Occupant
1st	175	8	Occupant
Ground	N/A	10	Entrance/exit

Other parameters are shown below:

Kinematic parameters:

Rated speed: 3.15 m/s.
Rated acceleration: 1 m/s^2.
Rated jerk: 1 m/s^3.

Passenger data

Passenger transfer into the elevator car: 1.2 s
Passenger transfer out of the elevator car: 1.2 s

Door timing data

Door opening time: 2 s
Door closing time: 3 s

The user requirements are:

Arrival rate: 12% of the building population arriving in five minutes.
Target interval: 30 s

A design for the elevator traffic system for the building is carried out using the Monte Carlo simulation method for finding the value of the round trip time and HARint plane for the design methodology ([21], [22]). The resulting value of the number of passengers boarding the car is not an integer in this design. It is not possible to compare this calculation with simulation. It is thus necessary to round up the number of passengers to the nearest integer, which is equal to 12 passengers in this case. The user requirements have to be revised to suit this such that 12 passengers boarding the car represents a system loading of 100%.

The final design that has been used (which is based on an integer value for the number of passengers) is listed below:

- Number of elevators in the group (L): 5 elevators
- Number of passengers: 12 passengers (thus this is set as the car capacity with 100% car loading allowable).
- Speed: 3.15 m/s.
- Round trip time: 143.381 s
- Actual interval: 28.68 s
- Nominal arrival rate in passengers per second (λ): 0.4 passengers/second
- Adjusted arrival rate in passengers per second (following the adjustment of the number of passengers to an integer number): (λ): 0.418 passengers/second

The value of the round trip time has been plotted against the system loading in Figure 1, for a value of workspace equal to 300 seconds. The value of the round trip time has been normalised in the figure by dividing the absolute values by the maximum value of the round trip time (143.381 s) that attains this maximum value when 12 passengers board the elevator car (which is the maximum allowable car capacity).

It is worth noting that the round trip time does not exceed the nominal calculated value of the round trip time that is attained when the car is full even under high system loading conditions. This can be seen in the *saturation* effect Figure 1 and can be explained as follows. As the system loading increases, more passengers arrive that can be taken by the available elevators. The passengers who cannot board the elevators will join a queue. As the system loading increases, the queue becomes even longer. The number of passengers who can board each elevator is limited to the rated capacity (CC) (assuming that 100% loading is allowed and possible). As the queue becomes excessively long, each elevator car becomes very likely to find a sufficient number of passengers to board it and to fill it up as soon as it arrives in the lobby. Thus the round trip time attains its maximum possible value expected in the design stage, but no more.

The round trip time has been plotted for a number of different conditions listed below. It is accepted that under these conditions the value of the round trip time has become a random variable (τ), and it is in fact the average value of this random variable that is quoted ($\bar{\tau}$) denoted as *RTT* or *T*.

1. Queuing allowed under constant arrival conditions and Poisson passenger arrival conditions: Under these conditions, passengers who arrive join a first-in-first-out queue (FIFO). When the car is available for boarding, passengers leave the queue one at a time and board the car. Once the car is full, passengers who have not boarded remain in the FIFO queue. As can be seen from the figure there is little difference between the constant arrival process and the Poisson arrival process. The reason is that queuing has been allowed, and this effectively decouples the average number of passengers boarding the elevator car from the arrival process. It is also worth noting that the value of the round trip time at a system loading of 100% (i.e., ρ=1) denoted as point C1, C2 is smaller than the maximum possible value for the round trip.
2. Queuing not allowed under constant arrival conditions: In this case, passengers who are prevented from boarding the car because it is already full are not added to the FIFO queue, but are discarded (this is an example of the hypothetical conditions that are used in this paper). This is referred to as the case of "no queuing allowed". It is acknowledged that this condition will not take place in real life. It is shown here as it is easy to calculate using analytical equations or the Monte Carlo simulation method, and can provide a lower analytical bound on the actual value of the round trip time. It is denoted as point E in the

Figure 1, where its value is smaller than the value of the round trip time under queuing conditions at a system loading of 100%.

3. Queuing not allowed under Poisson arrival conditions: In this case, passengers who are prevented from boarding the car because it is already fully are discarded. Passengers arrive under Poisson arrival conditions and this introduces a new source of randomness further reducing the effective car load and thus the value of the round trip time. At a system loading of 100% (ρ=1), the value of the round trip time under these conditions is denoted by the point F in Figure 1.

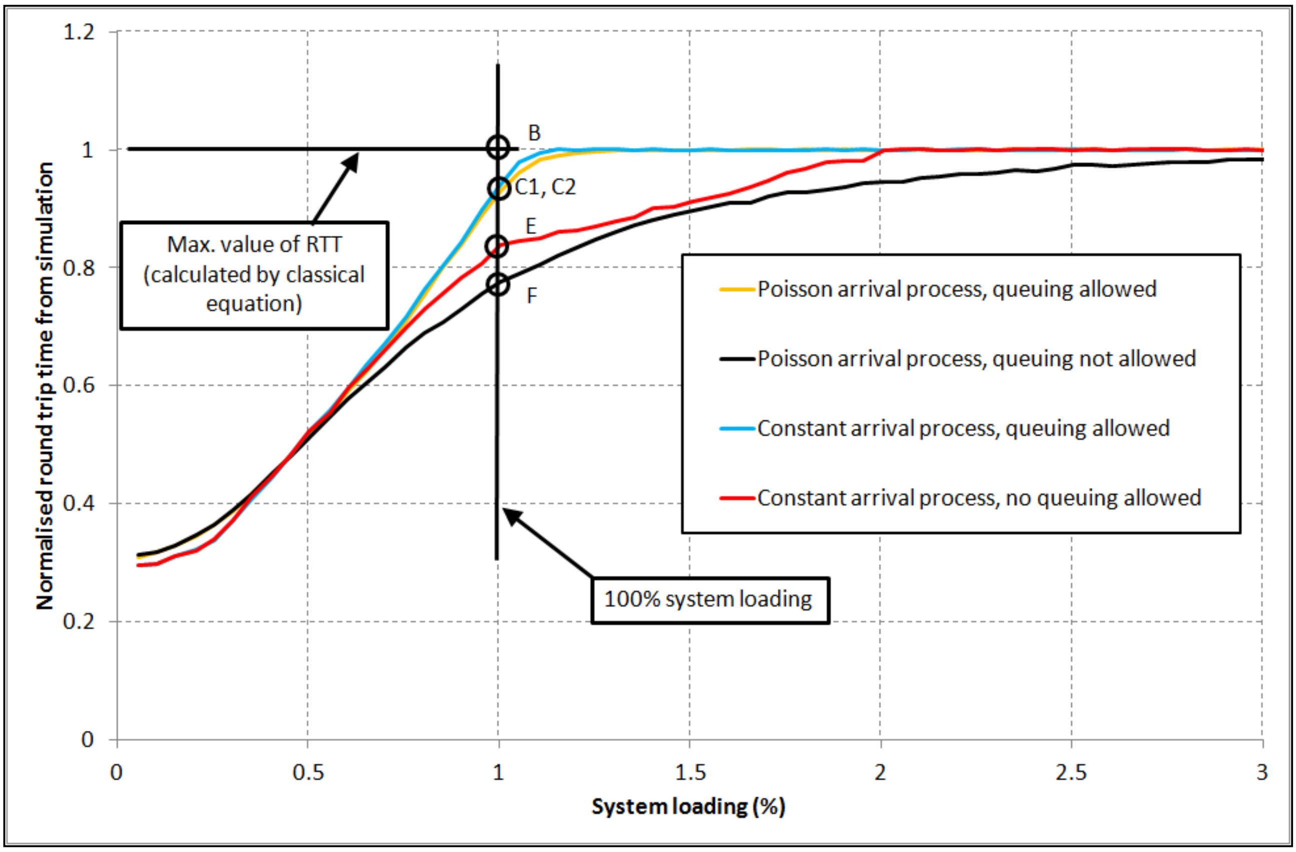

Figure 1: The normalised value of the round trip time against system loading under different conditions (the value of the workspace is 300 seconds).

The effect of the value of the workspace has been investigated and the results are shown in Figure 2. The round trip time under simulation conditions has been plotted against system loading for three values of workspace: 300 s, 600 s and 900 s. The passenger arrival model has been assumed to follow a Poisson process. From the figure the following two conclusions can be drawn:

1. Under the condition of queuing allowed the value of the workspace has virtually no effect.
2. Under the condition of "no queuing allowed" the increase in the value of the workspace forces the values of the round trip time to settle down to the lower bound. The explanation for this is that the larger the workspace, the more random edge effects and transient behaviour are diminished and become less pronounced.

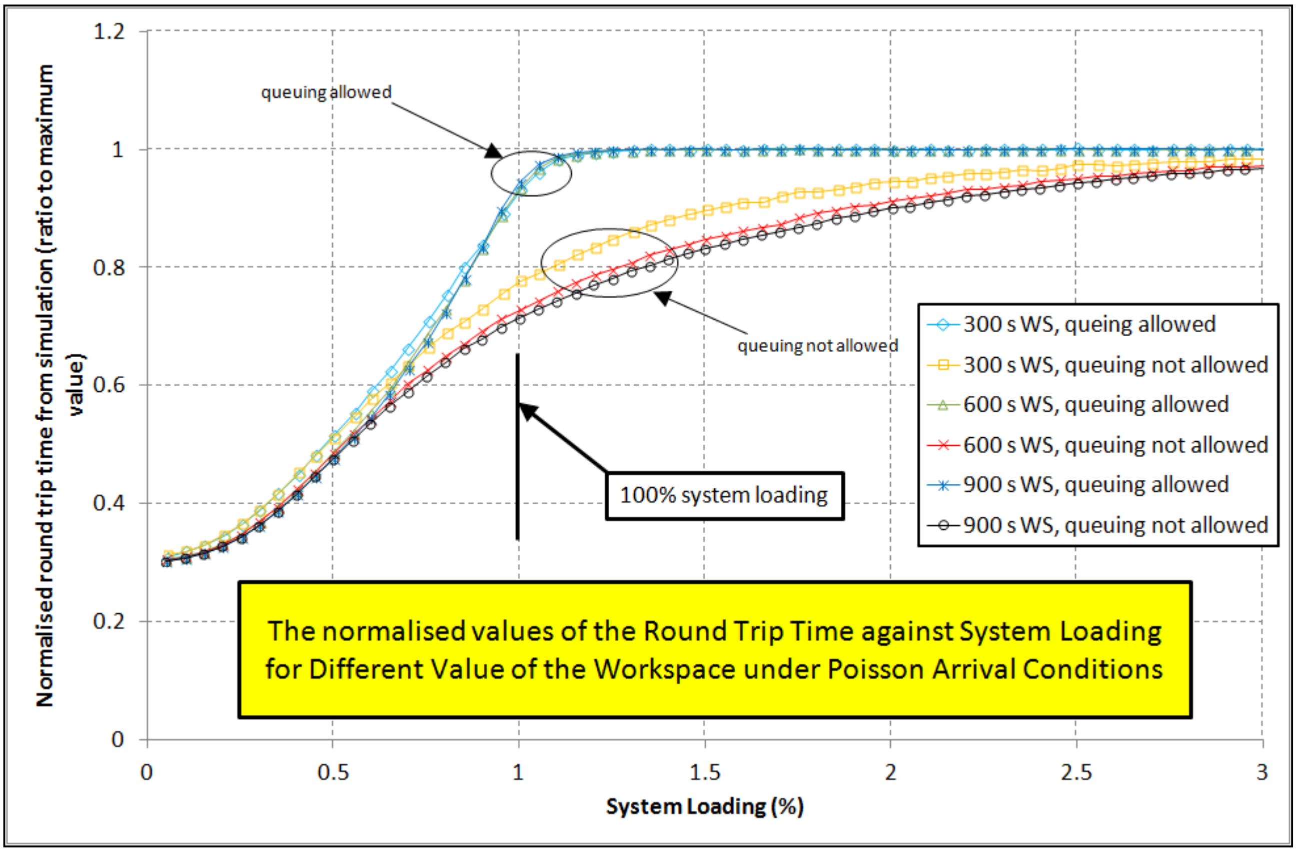

Figure 2: The normalised values of the round trip time against system loading for different workspaces.

5 DISCUSSION

As seen in the last section and in Figure 1 the value of the round trip is different between calculation and simulation at a system loading of 100% ($\rho=1$). There are a number of factors that affect this final value of the round trip time. It is possible to think of the value of the round trip time as starting from the value found in calculation and then being transformed by a number of effects into the final value under simulation, as follows:

1. The round trip time value under calculation is based on the value of the number of passengers boarding the elevator car in each trip and vice versa (point B in Figure 1). It is worth noting that this value is based on a number of assumptions:
   a. The value of the round trip time is a constant (T) rather than a random variable.
   b. The passenger arrival process is constant, with a constant inter-arrival time.
   c. The value of the round trip time is constant and does not vary as the passenger destinations vary.
   d. There is no bunching.
   e. With the ideal conditions above, no queues will ever develop and hence queuing in effect is irrelevant.
2. When the random effects of bunching and the randomness of the passenger destinations are taken into consideration and no queuing is allowed, the value of the round trip time drops to the value shown on point E in Figure 1. In this case, passengers who are unable to board the full elevator cars are discarded. Bunching is caused by the random destinations of passengers, as these lead to variations in the values of the round trip times of the different elevators.
3. When the random effects of the passenger arrival process (Poisson process) are added, this leads to further randomness in the value of the round trip time, which in turn leads to a

reduction in the number of passengers boarding the elevator car in each trip, and thus to a reduction in the value of the round trip time (shown as point F in Figure 1). As in the previous point, the value of the round trip time is a random variable and no queuing is allowed.

4. Finally, once the effect of queuing is added, the value of the round trip time rises back to a value shown as point C1/C2 in Figure 1 which is the actual value of the round trip time expected under simulation. This value is still smaller than that given by the initial calculation shown as point B in Figure 1.

This discussion has elucidated how the different effects under simulation gradually change the value the round trip time from that found in calculation to that achieved under simulation at a system loading of 100% (ρ=1).

6 CONCLUSIONS

There has long been an acceptance among vertical transportation system designers that a discrepancy exists between the value of the round trip time evaluated by calculation and that extracted from simulation. The main reason for this discrepancy is the lower average value of the number of passengers boarding the elevator car in each trip in simulation compared to the value assumed in calculation.

It suggested that the reason for this lower value of the number of passengers than expected is the combination of the restricted car size and the random effects. There are five random effects: the randomness of the passenger destinations (that lead to variable values of the round trip times); the randomness of the passenger arrival process (assumed to follow a Poisson probability density function for the number of passengers arriving in a period of time); the variability of the value of the interval caused by the bunching phenomenon; the edge effects (at the start and the end of the simulation); and the assumed initial conditions regarding the phases of the elevators in the group. In addition, the presence of a FIFO queue of the arriving passengers and those who are unable to board full elevator cars has a very strong effect on the final value of the round trip time (as it can potentially lead to a plentiful supply of passengers in the lobby and completely decouple the value of the round trip time from the passenger arrival process).

Hypothetical scenarios have been run in simulation (e.g., no-queuing allowed scenario). While it is acknowledged that such scenarios will not take place in real life, they are very insightful in presenting a qualitative explanation and aiding the understanding of the underlying mechanics of the elevator traffic system during simulation.

The value of the round trip time has been plotted against system loading under simulation for different conditions. The effect of queuing is analysed by plotting the value of the round trip when queuing is allowed for passengers unable to board a full elevator, and when queuing is not allowed (where passenger unable to board a full elevator are discarded). A comparison is also made between constant arrival conditions (where the inter-arrival time between successive passengers is constant) and random arrival conditions (where the inter-arrival time between successive passenger arrivals is random) following a Poisson arrival process. The values of the round trip time extracted from simulation at a system loading of 100% are found to be smaller than the maximum value of the round trip time evaluated by calculation assuming a full car. It is also shown that the value of the round trip time under constant arrival conditions and no queuing allowed is larger than the value of the round trip time under Poisson arrival conditions and assuming that no queuing is allowed.

Finally, the effect of the workspace has been investigated. It is shown that under queuing allowed conditions, the workspace length has no effect on the value of the round trip time. Under no queuing conditions, the increase in the value of the workspace allows the value of the round trip time to settle to its steady state value, due to the fact that edge effects and transient effects are diminished by the longer workspace.

The results shown above are insightful in understanding the random nature of simulation and can have practical effects in the process of designing vertical transportation system and sizing its components.

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Optimum Design of Traction Electrical Machines in Lift Installations

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Keywords: lift, comfort, vibration, noise, electrical machine, machine design.

Abstract. Improper operation of the traction machine of a lift installation causes energy waste, vibrations and noise. The design of the machine must be optimum if energy efficiency and comfort specifications have to be satisfied. The vibrations and noise frequency spectra of electrical machines present manifest peaks at certain frequencies, multiples of the fundamental electrical frequency, that depend on the machine topology and its rotation velocity. Changes in its topology or in its mechanical properties (geometry, size, materials…) must be done in order to reduce the magnitude of peaks at certain excitation frequencies or to locate the excitation frequencies far from the natural frequencies of the structure or the lift installation. Machine designers need tools to calculate their vibroacoustic response once a certain design has been proposed, so they can modify it before a prototype is built in case the response is not acceptable. Numerical and analytical models to calculate the vibroacoustic response of electrical machines have been developed and experimentally validated. In this paper, the authors summarise the state of the art in modelling the vibroacoustic performance of electrical machines and show some of the results obtained in their research work.

1 INTRODUCTION

The traction machine of a lift installation is a source of vibrations and noise that cause discomfort to the lift passengers and of the neighbours living at flats close to the lift well. Therefore, the machine design must be optimised (power, size, cost, vibrations and noise…) in order to conform to the riding comfort standards. Furthermore, the machine should not be designed without considering the lift installation, the whole assembly, because vibrations generated at the machine are born through the structure to the cabin. Consequently, the machine design is also conditioned by the lift installation in which it will be placed.

Tools to predict the vibroacoustic performance of an electrical traction machine in a certain lift installation are necessary to achieve an optimum design and to avoid, as much as possible, the prototyping stage. The first step is to predict its performance on a test bench but the final goal must be to predict it in the installation.

This document reviews the state of the art corresponding to that first step and describes the procedure to be carried out to compute the vibroacoustic performance of an electrical machine.

2 VIBROACOUSTIC PERFORMANCE OF AN ELECTRICAL MACHINE

Vibrations and noise of an electrical machine can be originated by the electromagnetic forces at the air-gap, by mechanical defects associated to the rotating parts (bearings, shaft), or by the air flux, when the machine has a fan for cooling purposes (see Fig. 1). Below 1000 Hz and in low to medium speed rated machines, electromagnetic forces are the main sources of vibrations and noise [1]. The frequency spectra of electromagnetic vibrations and noise are very tonal and particularly annoying for lift passengers and neighbours close to the installation. This paper reviews the procedure followed to calculate the vibroacoustic response of electrical machines due to the radial electromagnetic forces generated at the air-gap.

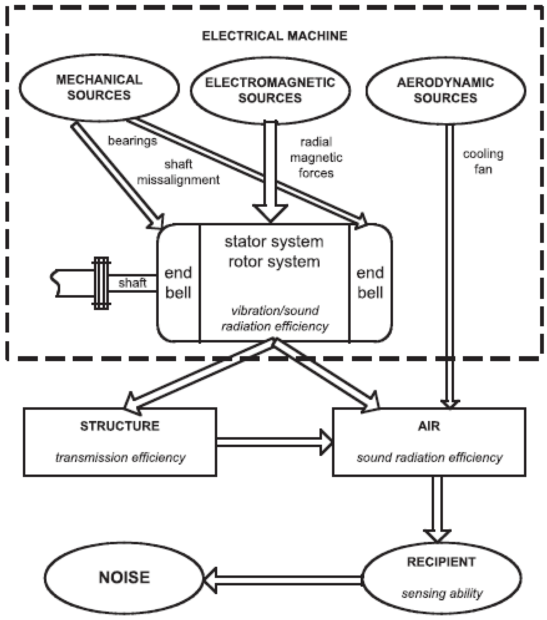

Figure 1: Noise generation and transmission in electrical machines [2].

The procedure consists of three parts (see Fig. 2). First: calculating the radial electromagnetic forces. Second: applying them to the machine structural model to obtain the vibratory response of its outer surface. Finally, computing the acoustic power it radiates [2].

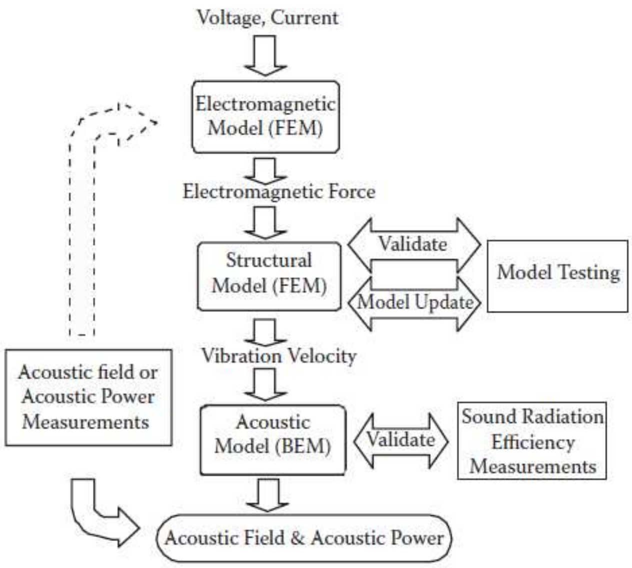

Figure 2: Procedure for predicting acoustic power from an electric machine [2].

2.1 Computing the Maxwell Forces

According to Le Besnerais, Maxwell forces [3], normal to the front surface of the stator teeth, are the main contributors to the machine vibrations [4], particularly in Permanent Magnets Synchronous Motors (PMSM) [5], very common in lift installations. If the rotor is not skewed and the end effects are neglected, the pressure distribution is independent of the motor axial direction. The electromagnetic field at the air-gap is calculated either by Finite Element Models (FEM) or analytical ones, and a reasonable agreement between them is achieved [6]. Next to be calculated is the pressure applied on the surfaces at the air-gap, due to the electromagnetic field. The pressure, by the two-dimensional Fourier transformation, is converted into separate rotating force waves, defined by frequency, spatial harmonic number on the circumference, amplitude, phase angle, and rotation direction [7].

2.2 Structural Model

The electrical machine is composed of static (stator-windings) and rotating parts (shaft-rotor). The transversal section of the stator is constant in the axial direction and has a particular shape with a number of teeth and slots, where the windings are inserted.

Regarding the mechanical behaviour of electrical machines, it is worth mentioning some particularities.

The stator and rotor consist of a stack of laminates, electrically isolated, and consequently they show an orthotropic behaviour. Because of this orthotropic nature, there is uncertainty in the values of some mechanical properties. Axial stiffness of the stator increases if the clamping pressure applied when joining them is increased [8]; high axial stiffness implies high values of the natural frequencies associated to the axial modes; however, natural frequencies of the radial modes hardly vary [9].

In addition, there is no elastic connection between adjacent stator sheets and some slip is allowed between them. The slip is the main contributor to damping, not only in the case of the axial modes but also in that of the whole structure [10]. Damping is another key parameter, uncertain as well, that is expected to affect the amplitude of vibrations.

Some authors [8, 9] provide approximate values of those uncertain parameters of the machine; otherwise, the model of the structure can be updated based on the results obtained from common modal analysis [9, 11], which provides the natural frequencies and mode shapes of the structure (see Fig. 3).

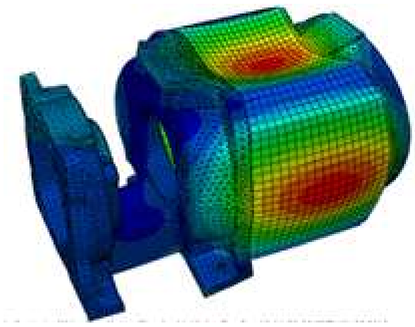

Figure 3: Modal shapes of the structure [11]

When the windings are added to the stator, the values of the natural frequencies of the assembly decrease, but they increase again when the assembly is impregnated with the isolation varnish [8].

With respect to modelling the mechanical structure, either finite element (FE) or analytical models have been proposed. FE models are closer to the real structure, but they require much bigger computation effort than analytical models. In consequence, analytical models could be convenient for machine design optimisation purposes, although less accurate.

A number of analytical models have been proposed in the literature to calculate the natural frequencies of electrical machines. The stator-windings assembly is commonly modelled as a lumped parameter model, with two circular cylinders attached to each other, one of them corresponding to the stator and the other one to the teeth-windings part [2]. For the case of short machines (the machine length to diameter ratio less than or equal to one) [2], the axial dimension is negligible and a two-dimensional ring model can be used. If the machine is not short enough, instead of as a double ring, it is modelled as a double cylinder, either of infinite [2] or finite length [12, 13].

Mechanical properties are commonly assumed to be isotropic. The values assigned to the material of the outer ring are those of the steel, but those assigned to the inner ring are estimated. A more accurate model should consider that the components are orthotropic and assign different values to the radial and axial elasticity moduli. For a laminated structure, the elasticity modulus in the axial direction is much smaller than that in the circumferential direction [15].

Two-dimensional models neglect several aspects as three-dimensional mode shapes, axial vibrations and rotor vibrations, and, consequently give inaccurate results in the case of machines with significant axial and rotor vibrations [14]. For these cases FE models can be more appropriate, as they allow considering other components as end-shields [15], the rotor [16], the frame or the support, and provide the possibility to assign orthotropic properties to the materials (see Fig. 4).

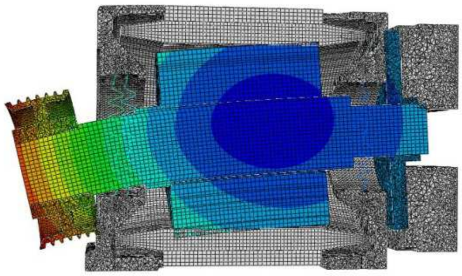

Figure 4: a FE model of the whole machine.

Once the structural model has been developed, previously computed forces are applied on the surfaces of the teeth and poles, and the vibratory response of the outer surface of the machine is obtained. The modal superposition theorem [17] is used to compute the global displacement of a certain point of the outer surface. This theorem uses the mode shapes as a vector basis to calculate the response of the system to a harmonic forcing load vector. The method allows computing the global displacement of a given point by summing the displacements caused by individual modes [18].

2.3 Acoustical Model

If the vibratory response of the outer surface of the machine is known, the acoustic power radiated by it can be obtained. The key parameter to determine the acoustic power is the sound radiation efficiency, defined as the ratio between the acoustic power and the radiation power of the surface [19].

If the geometry of the machine is idealised, analytical expressions to obtain the sound radiation efficiency are available. If the length of the machine is similar to its circular section diameter, an acoustic spherical model can be assumed (the radiated sound waves approximate to the spherical waves radiated by a vibrating sphere) [20]. If the length to diameter ratio is much bigger than one, an infinitely long cylindrical model can be used [21]. If it is not so big, the finite length circular-section cylindrical shell model [22] is usually a better approach.

To deal with complex topologies and to take end-plates and other details into account, numerical methods have to be used to calculate the sound radiation efficiency and radiated acoustic power [23].

3 ACCURACY OF SIMULATION RESULTS AND CURRENT RESEARCH

From a quantitative point of view, there are usually differences between the computed and measured acoustic power spectrum, at least at certain third-octave bands, due to the assumptions considered at the modelling phase. There is uncertainty regarding the electromagnetic forces applied; validation tests reported in the literature are commonly based on vibration measurements but not on measurements of the forces themselves. In the structural model, there is uncertainty too regarding certain mechanical parameters (elasticity modulus, damping…) and in the boundary conditions assumed. Nevertheless, the developed tools provide interesting results regarding relative analysis, that is to say, to compare different designs, to make sensitivity analysis, to understand which modes are excited by which forces, to choose the best slot pole combination…

Let us show some results for the sake of illustrating the previous paragraph. Fig. 5 shows an experimental set up to test vibrations of the machine in operation. Fig. 6 shows the comparison between the power spectral densities (PSD) of the measured (blue line) and calculated (green line) accelerations (by a FE model) at the top surface of the machine. We have orders in the horizontal axis instead of frequency. One order corresponds to the rotation frequency of the machine multiplied by the number of pole pairs. Only vibrations of electromagnetic origin are calculated but all vibrations are measured, including those of mechanical origin.

Figure 5: Experimental set up.

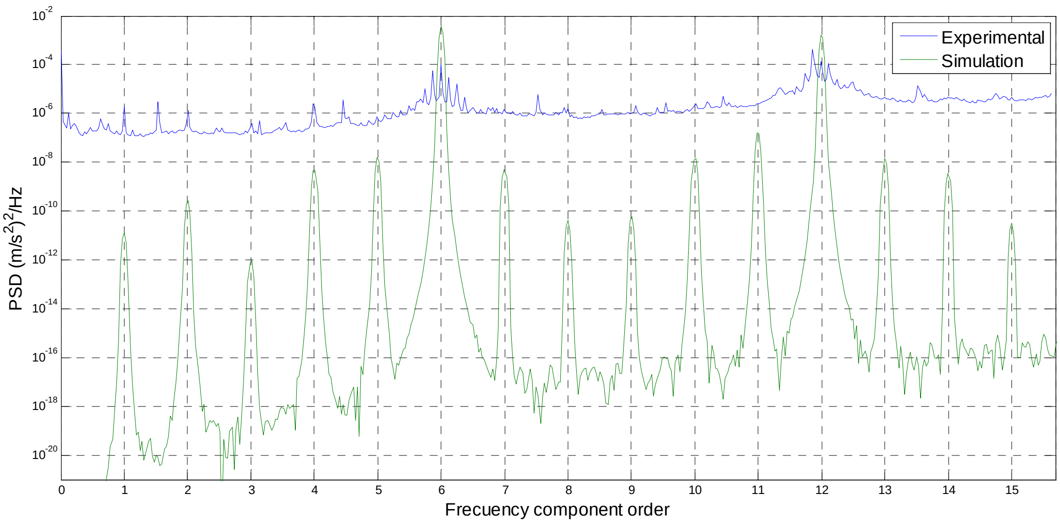

Fig. 6: Comparison between measured (blue) and calculated (green) accelerations.

The model identifies the vibration frequency components with the highest amplitudes (orders 6 and 12), although there are considerable differences in the amplitudes of most of the peaks. Close to the two highest orders smaller peaks can be observed. They are due to certain eccentricity of the axis.

Eccentricity always causes the increase of the amplitude of the peaks, particularly at the main orders. As the measurement includes all vibration (not only that of electromagnetic origin), its spectrum was expected to be over that one of the calculated vibration at all intervals between orders.

With respect to the results provided by the analytical models compared to those provided by the FEM (displacement vs. orders), see Fig. 7, where the vibration responses provided by several models of only the stator-windings assembly of the machine are compared. The continuous red line corresponds to the FEM. Three analytical models have been used: a double ring of circular shape (ring means that axial modes are not considered), a single cylinder (including stator and windings whose properties have been assigned average values) and a double cylinder. All properties are assumed to be isotropic.

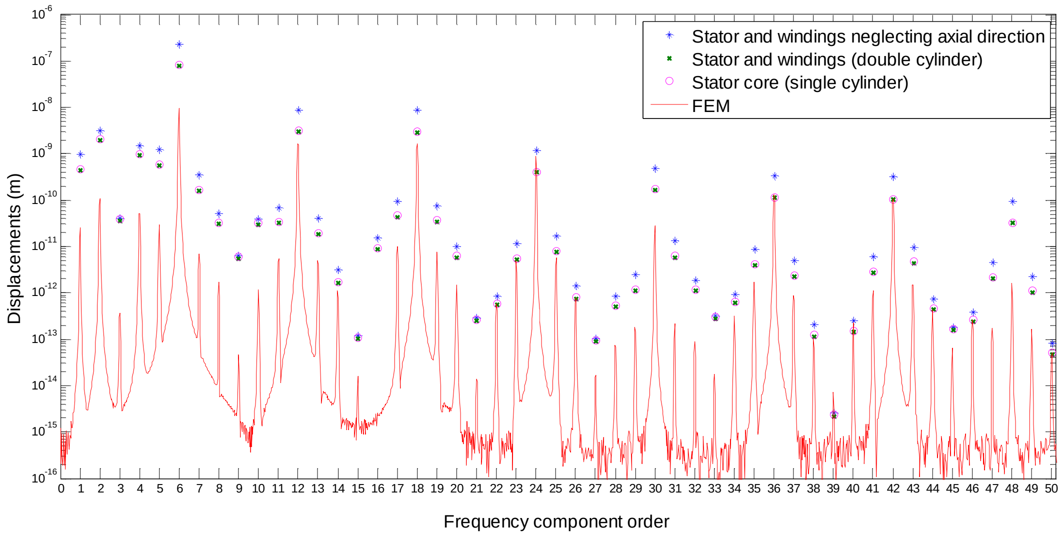

Figure 7: Comparison between analytical and FEM models.

There are considerable differences in the amplitudes of the peaks, but it can be observed that the results of the models considering axial modes are closer to the FEM.

To conclude, it seems difficult to obtain accurate models from a quantitative point of view, but interesting conclusions can be obtained from a qualitative one (main frequencies, shape of the response, comparison between different designs…).

The final question is how the machine will operate once it has been installed, because a discarded machine, based on tests carried out on a test bench, could behave properly in a certain installation. Thus, any tool developed to compute the machine behaviour should consider the whole assembly it belongs to.

Consequently, nowadays, there are two main areas of research: improvement of the machine models regarding all uncertainty aspects previously mentioned and behaviour of the whole installation due to electromagnetic excitations generated at the air-gap of the machine.

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BIOGRAPHICAL DETAILS

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Experimental Studies on Guide Rail Fastening System

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Keywords: Lift guide rails, fasteners, bolts, clips.

Abstract. Lift systems consist of many components that must have high strength and a high factor of safety. Rail brackets and steel clips are used for fixing guide rails to shaft walls, sustaining the loads and providing linearity for the guide rails; they are essential elements of the complete rail fastening system.

In this study, in order to determine the loads to the bolts and clips complete rail fastening systems were designed. Stresses and deformations occurring in the guide rails, brackets, steel clips, and bolts are examined by experiments carried out. Results are interpreted with respect to the complete rail fastening system. The experimental results for clips and bolts and their impact on the complete system are interpreted separately.

1 INTRODUCTION

With the increase of urbanization and high-rise buildings, the importance of lifts has increased in our daily lives and lifts have become an essential which are used for vertical transportation. In terms of providing safe and comfortable travel guide rails and their fastening systems used in lift installations. Rail brackets and steel clips are used for fixing guide rails to shaft walls, and provide the linearity of the guide rails. These are the main elements of the complete rail fastening system. The basic functions of the guide rails and rail fasteners are to guide the car and counterweight during their vertical travel, and to minimize the horizontal movement of the car as much as possible, and to prevent tilting of the car due to eccentric load. Besides they provide safe stance and to stop the car by means of safety gear which is activated in case of emergency. Forces occur during the lift car travel and in the event of activation of safety gear on the guide rails and rail fasteners.

Previous studies are generally stress and deflection analysis of guide rails [1]. Studies about brackets and steel clips were limited in the literature [1-7]. In this study, stresses and deformations occurring on the guide rails, brackets, bolts and steel clips, are examined by experiments carried out in the laboratory and the results are interpreted.

2 GUIDE RAILS, AND RELATED EQUIPMENT

The guide rail is one of the important components of the lift installation. It must have strong structure, because it bears all the loads and forces of lift. Guide rails are used to guide the vertical movement of the car and counterweight separately, and minimize their horizontal movement [1-3]. In this study T 90 B type of guide rail were used.

Brackets are used as auxiliary elements in terms of provide linearity of guide rails which connect the guide rail to the wall. These brackets must have enough strength to prevent horizontal movement of the rails. Metric bolts used on the brackets are as important as others. They sustain the same forces and loads as the guide rails brackets. For this reason, bolts occupy an important place, because these small parts bear all the loads and forces of the lift.

Clips are used for fastening guide rails and brackets. They have a different structure and dimensions, compared to the bolts. They are manufactured with aid of the casting, because of their structure. In this study T3 type of clips were used. British Standard BS A305 taken for bolt about tensile and shear testing system, and then it used to test for clips. Figure 1 shows how to anchor the guide rails and brackets to a wall [1-3].

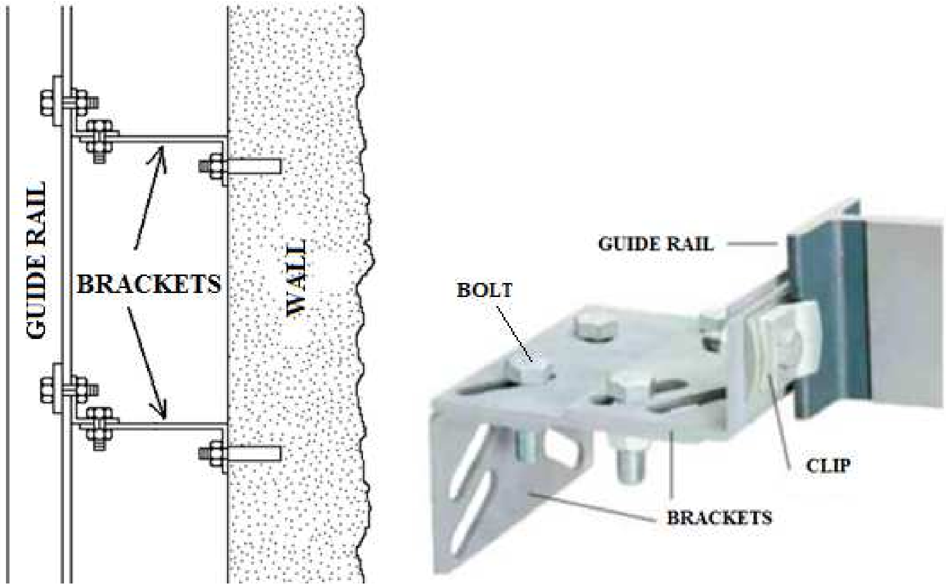
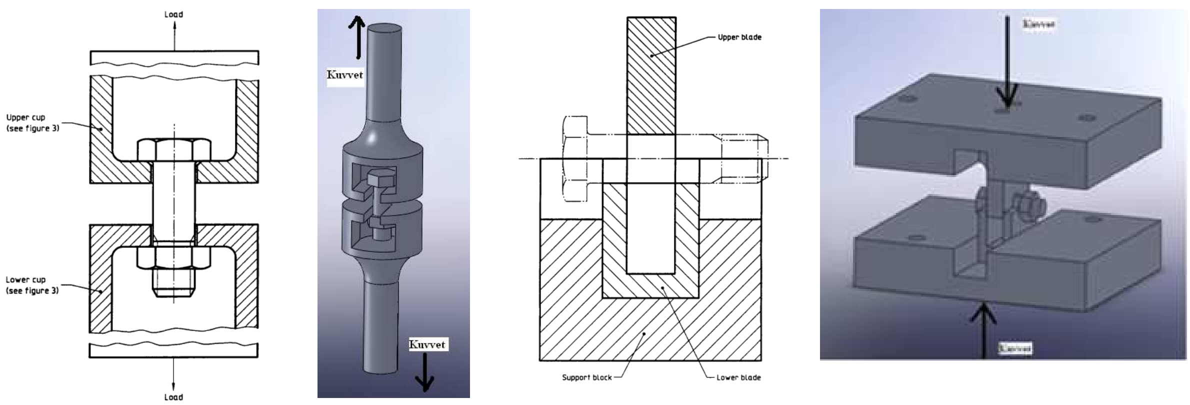


Figure 1: Assembly of guide rail, brackets with fasteners

3 TEST PROCEDURE OF FASTENERS

In this study, bolts and clips are used as fasteners. The equipment for the tensile test is modelled as cylindrical shape, taking into account the machining process. Besides this, heads of equipment are designed according to the grips of the machine. The slot part where bolts and clips are fixed is formed in a channel-shape. The tensile test apparatus, for bolts and clips is shown in Figure 2a. The load speed of the experiment is taken from standard BS A305. To perform tensile tests for a bolt and clips sample with 12 mm in diameter, the rate of load should be 80kN/min [4].

In order to perform shear test for bolts and clips, the test apparatus are proposed with three separate parts. These tests are made with pressing and this changed the structure. For this test, thicker materials are used for the bottom part and upper part which are connected to the test machine. The third parts as known connector, related to metric threat is modelled and machined separately. Figure 2.b shows the complete shear test apparatus. According to BS A305 to perform double shear test for bolts and clips 12 mm in diameter, the rate of load should be 160kN/min [4].



a) Tensile test apparatus b) Shear test apparatus

Figure 2: Test apparatus [5]

4 TEST PROCEDURE OF COMPLETE RAIL FASTENING SYSTEM

Throughout the service life of the structural system, designed not to break down under estimated load has critical importance complete rail fastening system analysis is fairly complex, but it is valuable design and design of modern structural systems. In the literature on this issue, particularly with respect to the complete rail fastening system, experimental studies are not in sufficient number and scope.

The brand new convenient test machine as shown in Figure 3 consists of four main groups which are carrier block that made by St37 materials and it was formed by welding construction. (1), a hydraulic actuator that provides applying variable loads (2), control units were used to perform to provide desired load combination to the system, sensors were used to arrange, measure and record to loads and displacements. This test machine that is supported by Turkish Lift Industrialists is under development. After developing PLC codes the tests will be conducted.

Experimental studies will be performed in Lift Technologies Laboratory (ITU). When setting up the experimental set up, the idea in comprehensive paper of Dr. Merz from HILTI Company was examined and adapted for the test rig [6,7].

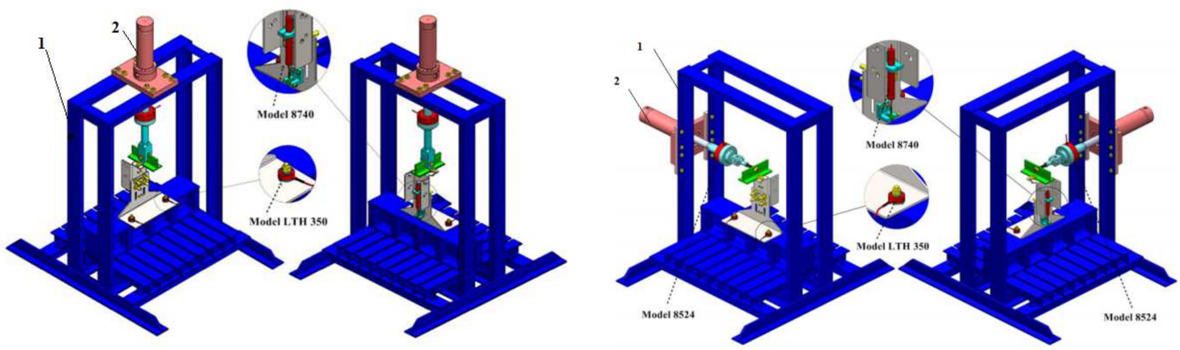


Figure 3: Experimental setup for complete rail system with vertical and horizontal installation [2]

In this test machine metric bolts and clips will be used for variety of guide rails. There are two types of sensor used in the experiment load measurement sensors and displacement sensors.

Fasteners can make displacement or relative motion under load. In order to prevent from these movements bracket's bolts are assembled with preload. Namely, by applying the force (F), $\mu F_{preload}$ friction forces between the parts occur. Theoretical principle of fasteners is provided for making effective mechanical connections.

$$F_S = \mu F_{preload} \geq F/i \quad \text{or} \quad \mu F_{preload} = c_0 F / i \qquad (1)$$

where $F_{preload}$ is preload force, Fs is friction forces, i is number of bolts, i; $c_0 = 1{,}1 - 1{,}5$ is safety factor against to shear. From this equation the connection force can be calculated.

$$F_{\text{preload}} = \frac{c_0.F}{\mu.i} \qquad (2)$$

Additionally fasteners used in the guiding system were tested on the indoor test tower. The experimental set up was designed and established in order to examine the behaviour of different load cases. Designed experimental set up are given the opportunity to examine variety of guide rails and brackets more extensively in the future. With this design it is possible to apply tensile and compressive forces. Sensors and data collectors were assembled on guide rails fasteners. Real time data was obtained by examining the situation in different loads of the test car. Figure 4 shows the properties of test tower. Under different loading conditions of the lift car, the forces affecting the guide rails bracket and fasteners were examined. In these experiments, a test tower which is 7.3 meter in height was used.

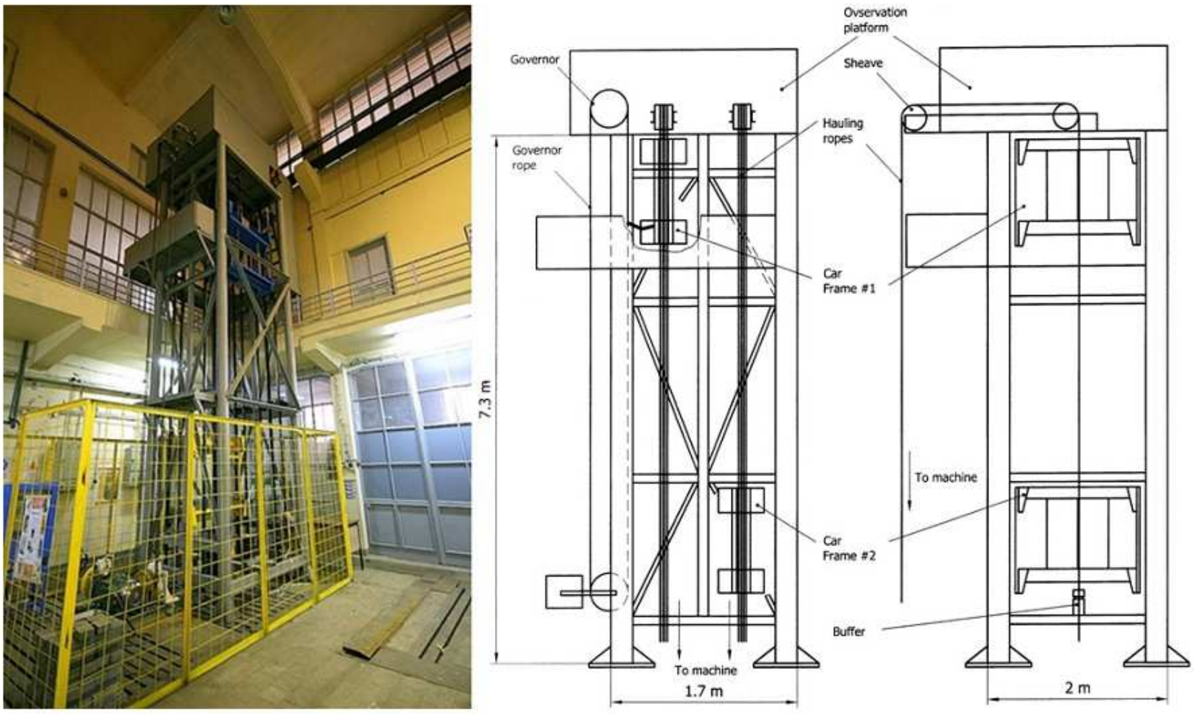


Figure 4: Indoor lift test tower [2]

USB data acquisition device (sensor interface), was used for transfer data from sensors (load cells) to computer. DigiVision software was utilized for the processing the data. This system has 16 bit resolution and it allows up to 2500 measurements per second (See Figure 5).

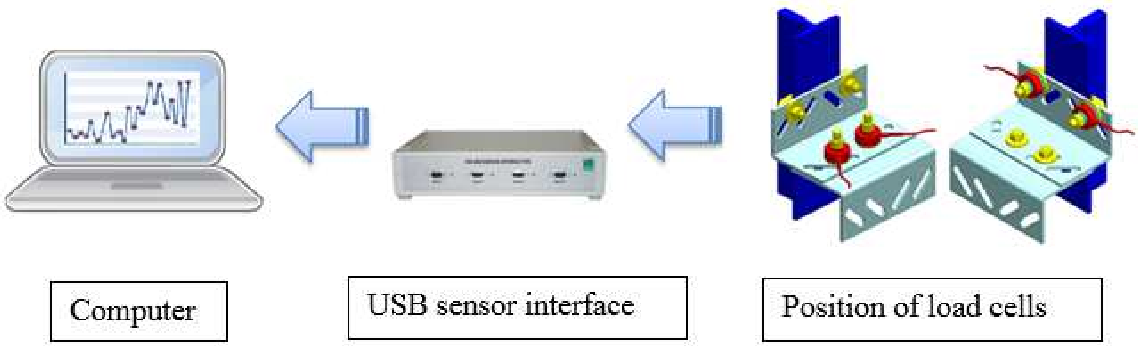
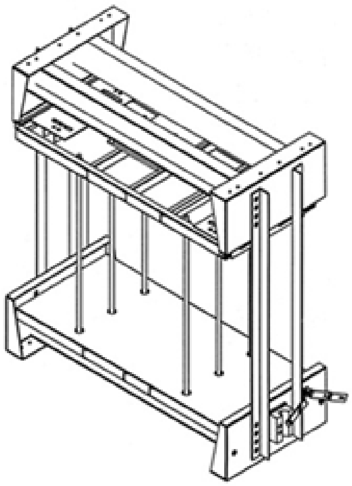


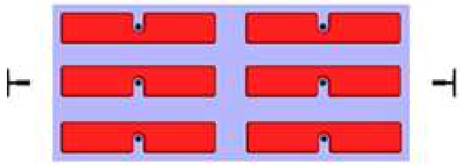
Figure 5: Data acquisition and signal processing [2]

In this study, stress and compression load cells and donut shape load cells were connected to the fasteners (See Figure 6). Donut shape load cells were used in order to investigate the compression load on the bolts.

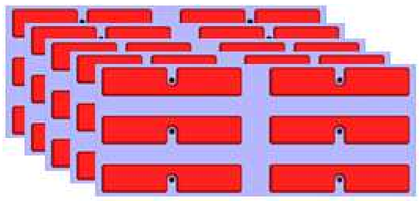
Figure 6: Donut shape load cells installation [2]

In this test car for 8 people, empty and loaded (%100 full) cases were investigated. Steel casting weights (each 17.3 kg) were used to ensure that the car frame empty and loaded cases. Each of them 17.3 kg steel casting weights were used for providing car empty and loaded cases (See Figure 7).





Empty case: 10 pieces of steel casting weights

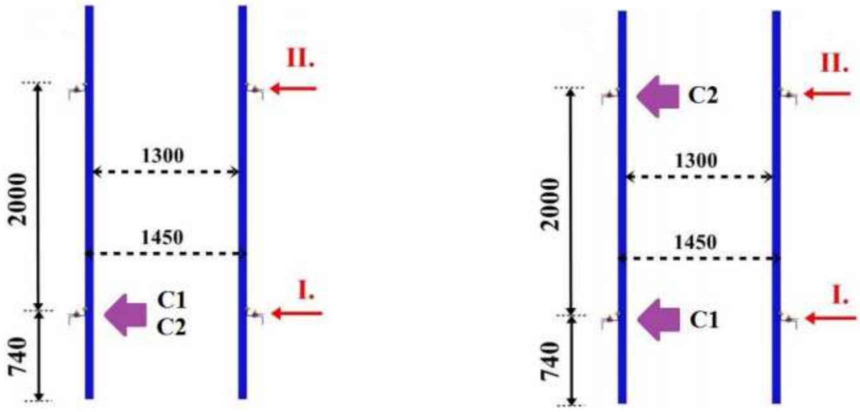


Loaded case: 46 pieces of steel casting weights

Figure 7: Different load condition of lift car

T90 / B type standard guide rail was used for guiding the test cars. Guide rails assembled from 4 points and the distance between brackets on the guide rails was 2000 mm. Different test condition and configuration can be seen from Figure 8.

In Figure 8 the donut shape load cells are depicted with C1 and C2. In the Test 1 condition, load cells are placed on the same bracket. In the Test 2 condition C1 and C2 load cells are placed separately on a lower bracket and upper bracket.



Test 1 **Test 2**

Figure 8: Two different test configurations

In this study, bolts and clips which are used as fasteners for anchoring the guiding system are examined under certain loads experimentally. The experimental set up can be seen from Figure 2. It is observed from experiments result, that the shear test value is negligible compared with the tensile tests. Each experiment was performed 5 times and observed each experiment has given close values. Tensile test results for bolts and clips can be seen from Table 1 and Table 2 respectively.

Table 1: Test result for bolts 12 mm in diameter

Test number	Yield point kN
1	46.1898
2	47.4258
3	47.1053
4	45.4344
5	47,8149

Table 2: Test result for clips 12 mm in diameter

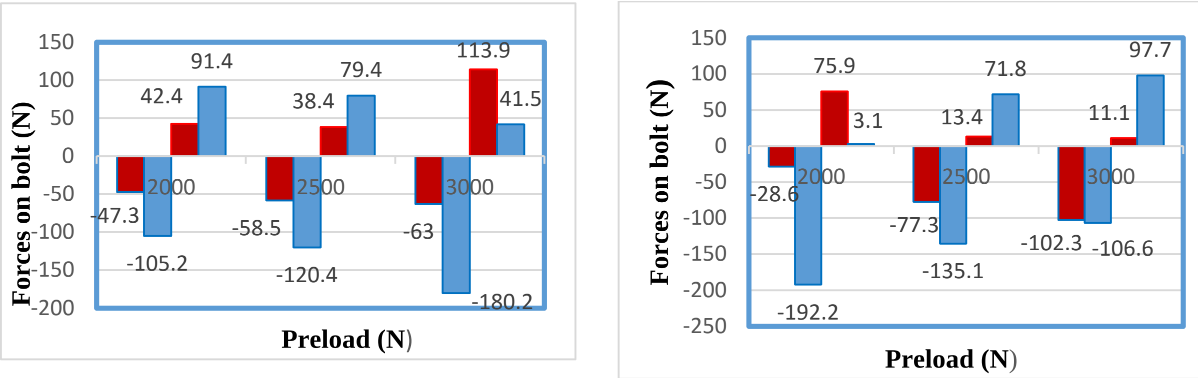
Test number	Yield point kN
1	32.8684
2	34.1044
3	35.5922
4	37.0342
5	36.8053

The bolts are tightened with three different preload conditions: 2000, 2500, and 3000 N. The zero point was calibrated in accordance with these preloads. The forces under the preload were negative, the above values were positive.

The following forces on guide rails shall be taken in account for the case of safety gear operation with different load distributions:

The horizontal forces from the guide shoes due to masses of the car and its rated load, travelling cables, etc. taking into consideration their suspension points and dynamic impact factors. The vertical forces are from the braking forces of the safety gears; weight of guide rail, and □push through forces of rail clips. The vertical load is carried by the rail itself and partially by the brackets whenever the guide rail is not fixed at the pit.

The first set of tests was performed for empty car condition for Test 1 and Test 2 load cell positions. The results from Test 1 and Test 2 load cell conditions are shown in Figure 9. In the graphs the red bars and blue bars depict the maximum and minimum data that are collected from C1 and C2 sensors respectively. X axis shows the preload conditions 2000, 2500, and 3000 N.

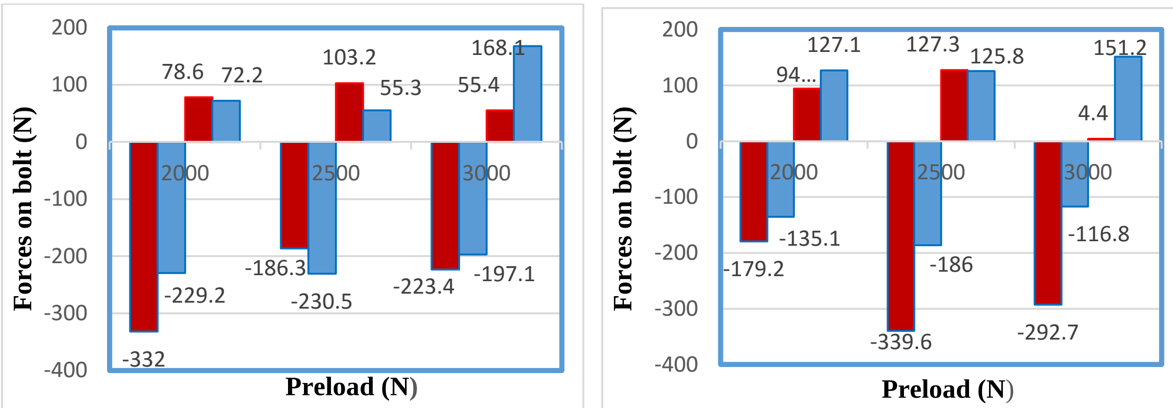


Test 1

Test 2

Figure 9: Forces on bolts empty car [N]

The second set of tests was performed for fully loaded car condition for Test 1 and Test 2 load cell positions. The results from Test 1 and Test 2 load cell conditions are shown in Figure 10.



Test 1 **Test 2**

Figure 10: Forces on bolts loaded car [N]

5 CONCLUSION AND DISCUSSION

In this study, T90/B guide rail and its fastening elements are examined experimentally. The forces exposed to the clips and brackets during operation was measured and recorded. According to the test results maximum force is in (C1 sensor, 3000N preload) for fully loaded car condition, was measured as -328,9 N. According to individual tests for bolts the yield point was measured around 47 kN and for clips it was measured around 36 kN. Whereas the tests conducted on the complete fastening system allowed for the performance of the entire system under various preload and assembly conditions to be assessed. Additionally, on unique test machine for bracket and fasteners designed and built. After adapting hydraulic driving and operation codes via PLC test results will be reported.

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BIOGRAPHICAL DETAILS

Suhan Atay Mr. Atay received the BSc degree in Mechanical Engineering from ITU in 1995 and MSc degree in Mechanical Design from ITU in 2013. He is working as a Design Engineer.

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C. Erdem Imrak has been employed as a fulltime Professor in ITU. Prof. Imrak received the BSc, MSc, and PhD degrees in Mechanical Engineering from ITU in 1990, 1992, and 1996 respectively. He has carried out research into materials handling and especially lift systems. Currently his activities include: a Member of the IAEE; a Member of the OIPEEC; a Member of Chamber of Mechanical Engineers in Turkey; a Member of Steering & Consulting Committee of Asansor Dunyası Magazine and a Member of International Committee of Elevatori and Rapporteur from Turkey.

The Trouble with Mobility Scooters

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Keywords: Mobility Scooters, Invalid Carriages, Electric Wheelchairs, EN81-20, EN81-71.

Abstract. A fatal accident in South Korea in August 2010 with a mobility scooter user was the first known mobility scooter fatality involving lifts. Products already exist which are said to be designed to withstand the forces exerted by mobility scooters. This paper examines the possible forces involved using actual measurements and video evidence, and compares the likely forces with the requirements for the strength of landing doors contained in EN81-2050 and 71. The conclusions of the paper include implications for designers, specifiers and owners of lifts.

1 INTRODUCTION

Mobility Scooters are the commonly used term for class 2 and 3 Invalid Carriages as defined by the Use of Invalid Carriages on Highways Regulations 1988 as amended 2015 [1]. The regulations consider that mobility vehicles are divided into three main categories. These include:-

- "Class 1 invalid carriage" which means an invalid carriage which is not mechanically
- propelled i.e. a wheelchair.
- "Class 2 invalid carriage" which means a mechanically propelled invalid carriage which is so constructed or adapted as to be incapable of exceeding a speed of 4 miles per hour on the level under its own power;
- "Class 3 invalid carriage" which means a mechanically propelled invalid carriage which is so constructed or adapted as to be capable of exceeding a speed of 5 miles per hour but incapable of exceeding a speed of 8 miles per hour on the level under its own power;"

Research carried out by the Research Institute for Consumer Affairs (Rica) [8] found that:-

Use of mobility scooters has increased significantly over the last 15 years and today there are thought to be over 350,000 units in the UK. The increase can be explained by the reduction in manufacturing costs making the retail prices more generally affordable as well as the emergence of a second hand market, and a growth of overall demand due to increased obesity and an aging population. The market is expected to continue to grow and we can expect more than 500,000 units by 2016.

Other key findings of the Rica research were:-

a) fewer than 10% of scooter users were aged under 45
b) 88% of users used the scooters within buildings.
c) Class 3 scooters made up only 35% of the survey sample.

Although incidents involving electric wheelchairs have been known for many years on lifts in hospitals and residential nursing homes mostly the focus has been on the damage to the lift rather than to the passenger.

There were fatalities involving the failure of lift landing doors in Shirley Towers Southampton in 2001[11]. In that incident two men fighting in a lift lobby fell against the landing door with enough force to push the landing door shoes out of the retaining slot in the sill or bottom track. This became commonly known as a "cat flap" incident. In a resulting prosecution the route cause was attributed by the Court to poor maintenance and the maintenance company was fined £400,000.

Soon after this incident pr EN81-71 appeared and for the first time a test procedure for the resilience of lift doors to impact by deliberate misuse was outlined in a European Standard. The full standard was published in 2005.

In Berlin in May 2010[10] Elzie G, a 66 year old diabetic amputee drove her mobility scooter at full speed into the landing doors of the lift in her apartment block. She had become unwell and was trying to get home to her medication. The landing doors broke free of the door shoes and she and the scooter fell in to the shaft falling about 5 metres. She was rescued by the fire service and survived the incident albeit with severe injuries.

In August 2010 in a South Korean shopping centre [9] Mr. Lee, a 40 year old Mobility Scooter user, tried to enter a scenic lift car whilst the doors were closing. At the time of impact the doors had fully closed and the impact could not have broken the landing door electrical interlock as the lift set off in the down direction. Mr. Lee placed a call on the landing call not realising that the lift was already in transit. Mr. Lee then reversed about 1.2 metres and accelerated his scooter into the doors. The landing doors were two panel centre opening of the stainless steel framed glass type and on the second impact the left hand door panel broke free of the landing sill and swung into the shaft. Not deterred by this Mr. Lee reversed about 1.5 metres before accelerating in to the landing door for a third time. On this occasion the left hand door panel also broke free of the landing sill and the momentum of the scooter pushed up both door panels and Mr. Lee, still aboard the scooter, fell about 6 metres down the lift shaft to his death. The Korean Police investigation held that Mr. Lee's anger was the main cause of the incident.

2 LAWS AND CODES

2.1 S.I. 2015 No. 59 The Use of Invalid Carriages on Highways (Amendment)(England and Scotland) Regulations 2015.

In March 2015 the limit on the maximum unladen weight of a Class iii invalid carriage was increased to 200kg to allow for the additional weight of medical equipment. The basic machine however is still limited to 150kg. Class i and ii invalid carriages are limited to unladen weight of 113.5kg

Class 2 mobility vehicles are designed to be used on pavements and class 3 vehicles are equipped to be used on the road as well as the pavement.

2.2 BS EN 12184:2014 Electrically powered wheelchairs, scooters and their chargers — Requirements and test methods(5)

This standard allows for a single passenger weighing up to 300kg (48 stones) but allows the designer to define the limit for each design and subject it to a suitable test.

Wheelchairs and scooter are classified in one or more of the following three classes, dependent upon their intended use: —

Class A: compact, manoeuvrable wheelchairs not necessarily capable of negotiating outdoor obstacles;

Class B: wheelchairs sufficiently compact and manoeuvrable for some indoor environments and capable of negotiating some outdoor obstacles;

Class C: wheelchairs, usually large in size, not necessarily intended for indoor use but capable of travelling over longer distances and negotiating outdoor obstacles. NOTE Scooters are included within the classes above.

The maximum speed allowed is 15km/hr (9.32mph)

It is therefore clear that there is little consistency between the constraints of UK law and the British and European Standard for these products. UK users of mobility scooters may be operating machines which do not satisfy the legal requirements for invalid carriages and may be breaking the law by using them.

3 FORCE AND ENERGY

Before considering the forces and energy applied by mobility scooters and the forces and energy lift doors are designed to resist under the EN81series of standards let us consider the requirements of other standards controlling the design of building barriers.

BS EN 1991-1-1 2002 [12] requires that balustrades around atria and building perimeters are tested by both pendulum shock tests and applied forces. The requirement for a balustrade is that it can withstand a force of 1.5kn per metre at a height of 1100mm and 1.5kn as a point load on an infill panel. BS 6180:2011 [13] also considers the effect of vehicle impact on barriers.

3.1 A worst case scenario

The worst case scenario is for a 200kg Mobility Scooter carrying a 300kg passenger hitting a landing door at 15km/hr (4.166 m/sec) energy on impact $=1/2MV^2 = 0.5*500* 4.166^2 = 4.39KJ$

$E=1/2\ mv^2$ formula (1)

Where:-

m = the mass of scooter and passenger

v = the rated speed of the scooter assumed to be the velocity of the scooter at the point of impact.

Under BS EN 1991-1-1:2002 barriers in car parks are required to resist the horizontal characteristic force F (in KN), normal to and uniformly distributed over any length of 1,5 m of a barrier for a car park, required to withstand the impact of a vehicle is given by:

$F = 0{,}5mv^2 / (c +b)$ formula (2)

Where:-

m is the gross mass of the vehicle in (Kg)

v is the velocity of the vehicle (in m/s) normal to the barrier

c is the deformations of the vehicle (in mm)

b is the deformations of the barrier (in mm)

If we apply this method to the mobility scooter's impact on a landing door and for example we assume it is a multi-panel door:-

The deformation of the door is limited by design to its clearance from an adjacent panel (usually 5mm).

The deformation of the scooter bumper itself can be ignored as it is a rigid component in most cases.

Then using formula (2) this mitigates the force to $0.5 * 500* 4.166^2/5 = 867N$ acting at 250mm above sill level.

From test results carried out by Thomas Lernet formerly of Meiller and currently head of R&D for door systems at Wittur [6] and the Author it is clear that the maximum acceleration is developed by the motor from start and peaks at 3.33m/sec^2. If the batteries were able to supply the necessary current this would be a worst case scenario of F=M*A = 500*3.333 = 1.66kN.

F= m*a formula (3)

Where:-

m= the mass of scooter and passenger

a= the maximum acceleration of the scooter at a point of impact

The impact of the bumper on a mobility scooter is approximately 250mm above the door sill over an area of approximately 400m2.

In theory these are the worst conditions that a lift door could face from a mobility scooter impact.

3.2 The Requirements of the EN81series of standards

Standard	Force (N) =m*a formula (3)	Energy (J) from pendulum test =m*g*h formula (4) Where: m= mass g=acceleration due to gravity h= height at release above bottom dead centre
EN81-20 without glass	Static force of 300 N, being evenly distributed over an area of 5 cm² in round or square section, is applied at right angles to the panel/frame at any point on either face they shall resist without: 1) permanent deformation greater than 1 mm; 2) elastic deformation greater than 15 mm; After such a test the safety function of the door shall not be affected. Static force of 1000 N, being evenly distributed over an area of 100 cm² in round or square section, is applied at right angles at any point of the panel or frame from the landing side for landing doors or from the inside of the car for car doors they shall resist without significant permanent deformation affecting functionality and safety (See 5.3.1.4 [max. clearance 10 mm]	45*9.81*0.8 =353J applied 1 metre from sill level.
EN81-20 doors with glass	As above	Hard pendulum m.g.h = 49.05 J

EN81-71	As above	Category 1 309J Category 2 442J Retaining force 618J

EN81 does not address or consider the scale of forces applied by mobility scooters or other causes of heavy impact in the way that BS EN 1991does. This means that the balustrade adjacent to a lift in a shopping mall will be more likely to resist mobility scooter impact than the lift doors themselves.

3.3 Reasonably anticipated forces and energy

To be pragmatic in the evaluation of likely forces and energy applied to lift doors by mobility scooter impact the following assumptions could be made

Many lifts are installed in buildings where it will not be possible to accelerate from rest to maximum speed. Therefore if it is unlikely that the straight line acceleration distance is more than 2 metres, the maximum speed is unlikely to exceed 1.4M/sec. This assumption is based on research carried out by Thomas Lernet using high speed video cameras to measure the distance covered by a loaded mobility scooter in fixed time intervals. The findings were corroborated by measurements taken by the author using a Henning tri-axial accelerometer. If a landing door is so placed to be at risk of a high speed collision other measures may need to be considered by either the lift designer or the building designer.

Most Class 3 mobility scooters currently sold in the UK have a maximum weight of 120kg and a maximum passenger load set by the designer of 220kg giving a total load of 340Kg.

The maximum likely force using formula (3) is therefore 340 * 3.333 = 1132N. This is only slightly greater than the static force required in EN81-20 1000N over 100cm^2

The maximum energy is therefore 0.5*340*1.4^2 = 333J which is only slightly more than the force required under EN81-71 category 1 and less than the retaining force 618J.

Wittur have patented a system for testing lift doors for mobility scooter impact which assumes a combined scooter and passenger weight of 220kg. In the UK as previously stated many mobility scooter users weigh in excess of 75-100kg and so the test weight may not be adequate. However the test methodology used by Wittur is appropriate and could be easily adapted as it allows a single test rig to verify that both force and energy applied in mobility scooter collisions are adequately dealt with by the door design.

4 IMPLICATIONS FOR DESIGNERS

4.1 Risk Assessment.

To follow the methodology of BS EN ISO 14798 [7] the consequence of an accidental impact of a mobility scooter at high speed (like the Elzie G incident cited earlier) is foreseeable in a residential building for the elderly. It has a level of probability somewhere between remote and highly improbable (level D and level E). The level of harm is undoubtedly high (level 1). This means that some form of protective action is required. In public access buildings particularly those which allow a longer acceleration distance in long corridors such as shopping centres (like the Mr Lee incident) and hospitals there is a greater probability of impact incidents with forces and energy greater than allowed for by EN81-20.

In the case of Mr Lee there were two simultaneous acts of imprudence:-

a) repeated attempts to ram the lift doors
b) repeatedly running the scooter on high speed inside a building.

Under the assumptions of EN81-20

"0.4.9 A user may, in certain cases, make one imprudent act. The possibility of two simultaneous acts of imprudence and/or the abuse of instructions for use is not considered."

A point for further consideration may be (taking this case in mind): has a designer done enough by complying with EN81 to satisfy his or her duty of care? Indeed building owners should consider whether mobility scooters can be used within a building that contains lifts

4.2 Implications for lift door design

Lift doors and lift cars have improved impact resistance under EN81-20 but as has been shown this is not quite enough to protect against low speed mobility scooter impact. Sematic, Meiller, Wittur, and Fermator, all have existing products developed for EN81-71 Category 2 applications. Meiller has developed these products further to resist mobility scooter impact and this was demonstrated at Interlift 2013 and there are testing devices that have been developed to verify door performance.

There are some simple changes all manufacturers can make which can improve the impact resistance:-

a) Use of stainless steel or cast iron door sills.

b) Improved strength of door shoes and fixings to door shoes.

c) Retaining plates located in between the door shoes to prevent the door panel from cat flapping.

d) Use of 2 panel side opening door arrangements which provide greater impact resistance at the centre of the door entrance.

e) Use of spring fixings to allow temporary deflection of top tracks and sills to dissipate impact energy.

NB The rear walls of single and adjacent entry lift cars will also need to be suitably strengthened.

4.3 Implications for mobility scooter design

Mobility scooters main braking is by the retardation provided by the motor when disconnected from the battery. Operator error and unintended operation of controls (by shopping baskets etc.) are common and predictable events. It would be inexpensive and would greatly improve safety if proximity sensors were fitted as standard to all Class iii scooters and as an option on Class ii scooters.

The spirit of the UK legislation which requires a device to limit a Class iii scooter to 4 mph except when on the road is being flouted. All that is normally supplied by manufacturers is a separate switch for high speed operation which many scooter passengers use as their default speed. A greater safeguard is required if further accidents including those not related to lifts are to be avoided.

4.4 Implications for Building Designers, Managers and Owners.

Can the building reasonably refuse access for mobility scooters? If so this is a simple building management solution.

If not is the lay out of the lift such that it is possible to have a straight line journey greater than 2 metres and impact the landing door panel at any landing? This is likely to apply to most hospitals, shopping centres, supermarkets, large retail outlets, Airports etc. In these cases consideration should be given to either:-

a) Creating a lift lobby to reduce the risk of full speed impact or

b) Improving the resilience of any applicable landing doors to the parameters suggested in 3.1 above.

NB in the buildings cited above other vehicles such as luggage carts, food trolleys, portable X ray machines, pallet trucks etc. may also present risks in the same environment.

5 CONCLUSIONS

With the growth of mobility scooter usage inside buildings the risk of accidents increases, albeit from a very low base.

Usage of mobility scooters is not currently restricted in the UK by capability or improved by training and the registration system for Class iii scooters is ineffective. The UK government is not minded to tighten laws but to the contrary has recently relaxed them.

The UK has an aging population and one which is becoming increasingly obese. All of this means that the frequency of risk is increasing and in the circumstances identified appropriate control measures are required for all lifts.

Laws and Standards do not address the issue so it is for specifiers, designers and building managers to assess the risks on a site specific basis and adapt designs appropriately.

In buildings where space does not permit mobility scooters to accelerate to an impact speed of more than 1.4m/sec (have more than a 2metre run up) doors manufactured to EN81-71 category 2 should be sufficiently robust to prevent door failure.

In buildings where space permits mobility scooters to accelerate to an impact speed of more than 1.4m/sec additional measures are required to prevent further fatalities.

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See also http://www.gainesville.com/article/20080607/NEWS/854300487 details of an earlier incident in the USA in 2008.

BIOGRAPHICAL DETAILS

Michael Bottomley joined MovvéO Ltd. formerly Lerch Bates Ltd. in 2002 after working for Gregson & Bell Lifts for 21 years. He holds a degree, with honours, in Engineering and Marketing from the University of Huddersfield, and has over 34 years' experience in lift engineering and lift design. In 1999 he was the second lift designer in the UK to achieve Notified Body approval under the Lifts Regulations. He is a member of the International Association of Elevator Engineers and a Past Chairman of the CIBSE lifts group.

Impact of Design Methods and Maintenance Policies on the Dynamic Behaviour of Escalators

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Keywords: Escalators; Multi-body Dynamics (MBD); Design Of Experiments (DOE); ANalysis Of VAriance (ANOVA)

Abstract: Throughout their service life, escalators undergo wear and tear that disrupt their dynamic behaviour and lead to faster deterioration or collision between components. Therefore, balancing the dynamic behaviour of escalators is one of the keys to longer life expectancy and safety. This requires thorough adjustments and regular part replacements. This paper assesses the impacts of internal and external parameters on the dynamic behaviour of escalators in order to enhance maintenance policies and design methods. Given the wide range of maintenance, design and environmental variables, this paper solely focuses on studying the most common parameters, the step chain lubrication and tension, the step design, the guide rail lubrication and the number of passengers carried on each step. For this purpose, a model is created using a multi-body dynamics' (MBD) system. Conducting Taguchi-designed experiments, the main effects of these factors and their interactions on the stress distribution and displacement of each moving parts of the model are studied. The results are then compared using ANOVA to determine the significant effects for each response. Heavy passenger flows greatly alter force distribution throughout the system, leading to reduced fatigue life of the steps, rollers and guide rails. Poor step chain lubrication and a maladjusted tensioning station have a significant impact on the step chain tension, yielding a higher collision risk between the steps and the combplates. Guide rail lubrication does not seem to significantly affect the system dynamics. No significant interaction between the studied parameters has been found and the responses are for the most part linear. This study showcases the major impact of passenger flows on the stresses applied on the moving parts and calls for an improved assessment of effective passenger flows in the dimensioning of escalators.

1 INTRODUCTION

Escalators undergo wear and tear throughout their service life, which inevitably leads to broken components, endangering users and reducing equipment availability. In addition, they are composed of thousands of moving parts connected to one another. Consequently, wear and tear not only damages the components but also modifies the force distribution through the entire system, altering its dynamic behaviour [1]. This can cause faster deterioration and collisions between components.

Balancing the dynamic behaviour of escalators throughout their service life is therefore one of the keys to longer life expectancy and safety [2].

This process requires thorough adjustments, the effectiveness of which when combined with design or environmental factors is not yet known.

This paper assesses the impact of design methods and maintenance policies on the dynamic behaviour of escalators under normal conditions of use.

2 METHOD

2.1 Selection of the study parameters

Design and maintenance parameters vary from one manufacturer to another but also throughout the escalator's service life. As a first approach, only the factors impacting the maintenance costs of the equipment were studied in this paper. Common environment configurations were also taken into account in order to study the impact of these parameters on escalators under normal conditions of use. The environment parameters were selected according to their occurrence.

Thus, the factors selected for this study are:

- The friction between the plates (which reflects the effectiveness of the step chains lubrication) is modelled as a viscous rotational damping moment in the link joints, as shown in the simplified model in Figure 1 :

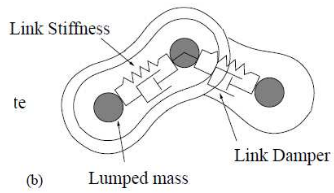


Figure 1: Simplified model of the chain link stiffness and damper

- The rolling friction of the polyurethane rollers on the steel step tracks (which depends on the step track lubrication),
- The steps weight,
- The tensioning station adjustment,
- The number of passengers carried and their position on the steps.

2.2 Creation of the dynamic model

To perform dynamic analyses, a model was created using a multi-body dynamics software enabling the modelling of fully functional chain driven systems.

This model represents a 4.8 meter rise escalator with a nominal step width of 1 meter. It operates in the upward direction at a speed of 0.6 m/s. These are currently the most common characteristics of the RATP fleet.

Given the high number of moving components in escalators, only the essential parts enabling transportation of passengers from the lower to the upper landings were modelled. This enabled simulation cost savings. Thus, the model is composed of:

- Two independent step chain systems (210 chain links, four sprockets, four chain guides) connected to each other by the use of two shafts,
- Two independent damping systems used as a tensioning station to pre-charge the step chain systems,
- Seventy steps and their rollers,
- One rail assembly.

Figure 2 shows the bottom part of the chain systems, the bottom shaft and the dampers.

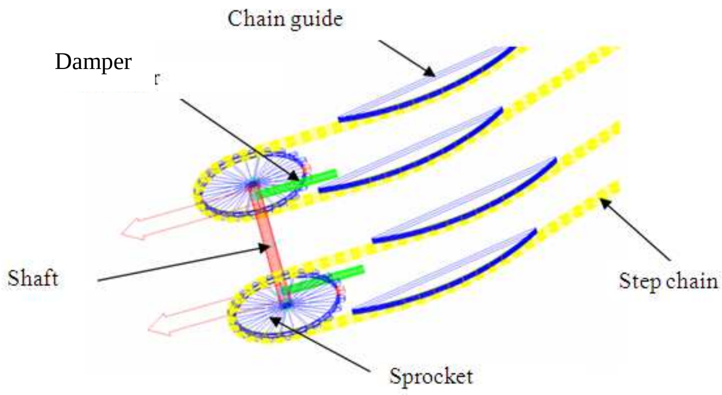


Figure 2: View of the tensioning station

The passengers loading, transport and unloading were modelled by applying a uniform distributed load on each step located between the lower and the upper combplates. The passengers' position on the steps was also taken into account by enabling the possibility to apply the distributed loads on the right half of the steps.

Figure 3 shows the complete model fully loaded. The green arrows represent the distributed loads applied to the steps, the red ones the reaction forces of the sprockets on the step chains.

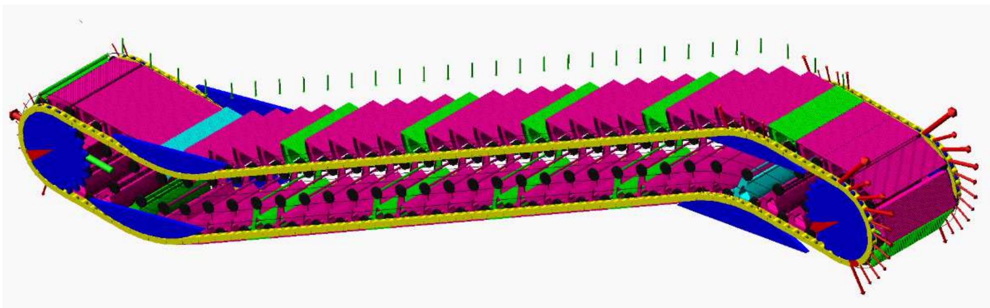


Figure 3: Fully loaded model

2.3 Validation of the simulation model

Part of the study was dedicated to ensure the simulation model was sufficiently accurate for the set of parameters previously identified.

The validation approach focused on comparing the outputs of the dynamic model described earlier to the outputs of a theoretical model specially built for the validation process [3]. This theoretical model was established using the manufacturers' static and dynamic design equations enabling the calculation of:

- The nominal motor torque required to run the escalator up to a speed of 0.6m/s,
- The steps chain links maximum dynamic tension,
- The normal contact forces of the steps and steps chain rollers on the rails.

These equations mainly depend on the following variables:

- The number of passengers,
- The step weight,
- The tensioning station adjustment,
- The rolling friction of the rollers on the rails.

Given that the design equations available do not take the step chains lubrication efficiency into account, the input-output transformation could not be validated for this particular parameter using this method and additional trials had to be run to determine the step chains rotational damping characteristics.

A Design Of Experiments (DOE) was conducted to optimize the simulation process [4, 5]. Considering that a first full factorial multilevel design had shown no significant interaction between the study parameters [6], a Taguchi method was used based on a L16 (2^{15}) orthogonal array, allowing the study of four parameters on two levels and taking into account all their possible interactions (up to the second order). This table requires 16 experimental runs.

The values assigned to each factor are the most commonly used by manufacturers in their design equations. They are given in Table 1.

Table 1: Factor levels defined for the validation runs

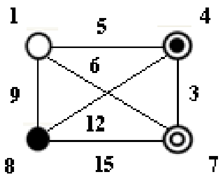
Level	Number of passengers carried [passengers/step]	Tensioning station adjustment [mm]	Steps weight [kg]	Rolling resistance coefficient of the rollers on the tracks
1	0	Min 169	Aluminium 15	Lubricated 0.04
2	2	Max 171	Steel 35	Non-lubricated 0.05

Table 2 gives the column assigned to each factor in the selected orthogonal array.

Table 2: Column of the L16 (2^{15}) array assigned to each factor

Parameter	Number of passengers carried	Tensioning station adjustment	Steps weight	Rolling resistance coefficient of the rollers on the tracks
Column	1	4	7	8

Figure 4 gives the linear graph selected of the interactions for the L16 array.



The dots are labelled with the corresponding array column number for factors and the connecting lines are labeled with the corresponding array column number used for the interaction. These arrays are determined using the Taguchi interaction table for the L27 (3^{13}) orthogonal array.

Figure 4: Linear graph for the Taguchi design matrix

Results show a mean disparity of 10% between the dynamic model and the analytical model. This disparity principally impacts the nominal torque output: the 3D model takes into account coefficients of friction in the joints connecting parts whereas the theoretical model only considers the rolling friction between the roller and the rails. Therefore, the rolling friction variations have more impact on the analytical model than on the dynamic model.

This validates that the simulation model correctly reproduces the system behaviour (i.e. within acceptable bounds).

No significant interaction between the studied parameters has been found.

2.4 Impact evaluation of the study parameters

The same DOE process was conducted to assess the impact of the five study parameters but using a Taguchi method in order to optimize the number of simulations.

Since the passenger's position on the steps is a non-linear factor, it was important that our table provided for the study of the linearity of the system. At the same time, given that no significant interaction between the studied parameters has been found during the validation process, it was not necessary that the Taguchi table selected enabled the study of all the interactions between the parameters.

Thus, a L27 (3^{13}) orthogonal array was selected, enabling the study of five factors on three levels and the study of four interactions. This requires 27 simulation runs.

Table 3 summarizes the values assigned to each factor. Since our simulation model is not used for design purposes, the rolling resistance coefficient was set to its theoretical literature values [7].

Table 3: Factor levels defined for the Taguchi design matrix

Level	Number of passengers carried [passengers/step]	Tensioning station adjustment [mm]	Steps weight [kg]	Rolling resistance coefficient of the rollers on the tracks	Step chains rotational damping[1] [N.mm.s/rad]
1	0	Min 169	Aluminium 15	Highly lubricated 0.015	Highly lubricated 1
2	1 Standing on the right side of the steps	Mean 170	Heavy Aluminium 25	Lubricated 0.0225	Lubricated 2000
3	2	Max 171	Steel 35	Non-lubricated 0.03	Slight corrosion damages 4000

[1]The step chain lubrication effectiveness and thus the factor levels are determined by increasing the step chain rotational damping up to the point where a discontinuity appears in the rotational oscillation of the step chain links.

Table 4 gives the column assigned to each study parameter in the L27 (3^{13}) orthogonal array.

Table 4: Column of the L27 (3^{13}) orthogonal array assigned to each factor

Parameter	Number of passengers carried	Tensioning station adjustment	Steps weight	Rolling resistance coefficient of the rollers on the tracks	Step chains rotational damping
Column	1	4	6	8	9

Figure 5 gives the linear graph selected of the interactions for the Taguchi design matrix. The confounding scheme chosen is considered acceptable since the previous validation array revealed that there was no significant interaction between the main study parameters.

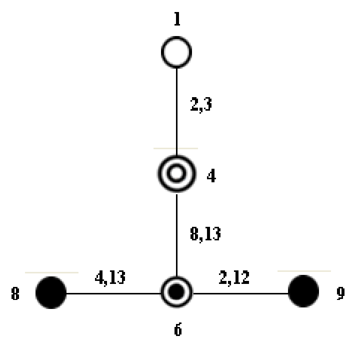


Figure 5: Linear graph for the Taguchi design matrix

3 RESULTS

3.1 Selection of the study outputs

Studying the system's dynamics involves going through the forces and displacements of each component all the way along the escalator. Given the high number of outputs, this study mainly focuses on covering the following aspects, selected according to their impact on the maintenance costs:

- The life expectancies of the steps chains, chain guides, steps, rollers and tracks,
- The risk of collision between the steps and the combplates,
- The nominal torque required to operate the system.

The following table lists the effects analysed during this study and briefly explains how they were used.

Table 5: Studied effects and examples of use

Studied effects [Unit]	Example of use
Nominal torque applied on the shaft [N.m]	Evaluation of the motor power required to move the escalator in the upward direction at a nominal speed of 0.6m/s
Step chain links tension [N]	Determination of the step chain fatigue life : the tension is used as an input to determine the cycle stress
Normal contact forces of the step rollers on the rails [N]	Evaluation of the risk of collision between the steps and the combplates : the steps have a higher propensity to raise and hit the combplates when the contact forces of the rollers on the rails are low
Projected contact forces of the step rollers on the rails [N]	Determination of the step rollers deformation: the contact forces are used as inputs to determine the polyurethane deformation
Restoring forces and displacements of the damping systems [N]	Determination of the tensioning station behaviour
Normal contact forces of the steps shaft on the steps [N]	Determination of the step fatigue life (normal contact forces used as inputs)
Normal contact forces of the steps chains on the chain guides [N]	Determination of the step chain fatigue life (normal contact forces used as inputs)
Roller speed variations [m/s]	Evaluation of the track wear which can be caused by the rollers variation of speed

3.2 Impact of the parameters on the studies effects

To reduce the simulation time, the outputs of only two steps (coloured in blue in figure 3) and their four attached chain links were recorded. This way, the behaviour of the steps and the step chains can be assessed by only computing half of an entire cycle run.

Figure 6 shows an example of the tension evolution within the step chains from the bottom to the upper landings on an escalator moving in the upward direction.

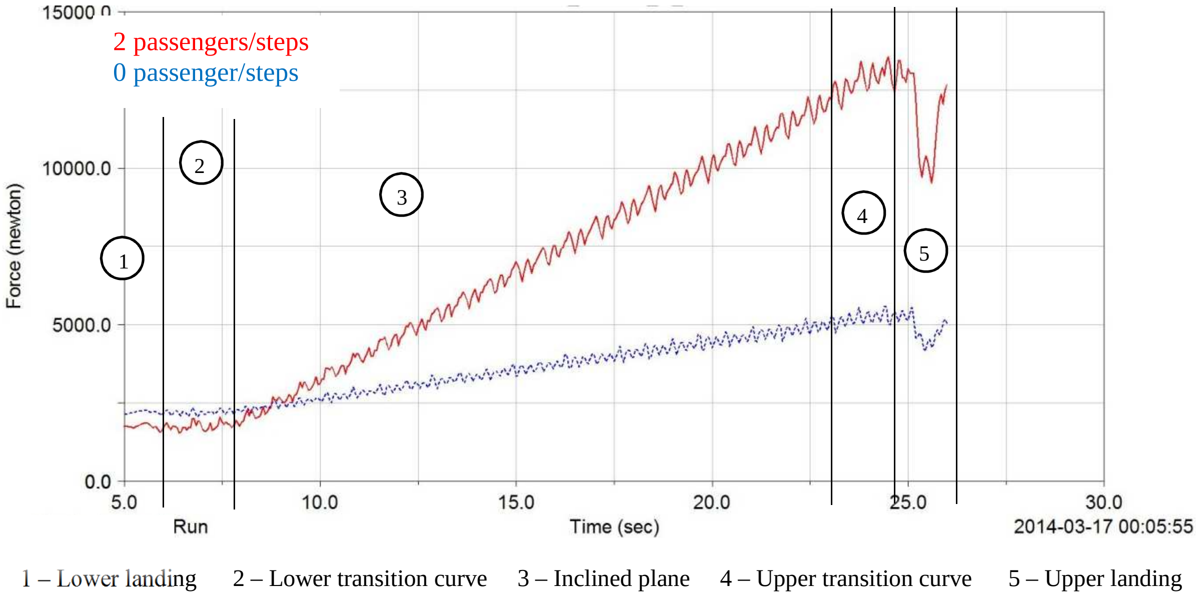


Figure 6: Step chain tension evolution under two different load cases

The blue curve represents the chain tension when no passengers are using the escalators and the red one shows the tension evolution when two passengers are standing on each step. The regular vibration on the curves is due to the polygon effect.

Depending on the output, the min, max or mean value of these graphs was used to complete our DOE table.

An ANalysis Of Variance (Chi² test) was used to determine which factors were significantly impacting our studied effects. The following table gives the percentage relative to the contribution of each significant parameter to the outputs.

Table 6: Chi-square contribution

Output \ Input	Number of passengers carried	Tensionning station adjustment	Steps weight	Rolling resistance coefficient of the rollers on the tracks	Step chains rotational damping
Nominal torque	98.0 %	Negligible[1]	Negligible	Negligible	2.0 %
Step chain links tension	97.1 %	Negligible	2.4 %	Negligible	Negligible
Normal contact forces of the step rollers on the rails	97.1 %	Negligible	2.7 %	Negligible	Negligible
Contact forces projection of the step rollers on the rails	89.8 %	Negligible	Negligible	Negligible	9.2%
Normal contact forces of the steps shaft on the steps	75.5%	Negligible	2.4%	Negligible	21.6%
Restoring forces and displacements of the damping systems	59.1%	16.8%	7.7%	Negligible	16.4%
Normal contact forces of the steps chains on the chain guides	71.7%	Negligible	2.7%	Negligible	24.8%
Rollers speed	Negligible	Negligible	Negligible	Negligible	Negligible

Once more, no significant interaction between the studied parameters has been found.

[1]The level of significance is set to 0.02.

4 DISCUSSION

The number of passengers carried is the most significant factor of the study in terms of impact on the dynamic behaviour and stresses of the escalator. The high variation of stress passengers create while standing on the steps transfers through the step chains and its connected parts. It modifies the forces distribution within the whole model and impacts the life expectancy of all the components connected to the loaded steps and to the steps chain.

The passengers' location on the steps, however, does not seem to imbalance the dynamics of the escalator, although it affects the stress distribution in the steps.

To a lesser extent, the step weight significantly impacts the dynamics of the system.

However, evidence that the use of lighter step material could increase the steps unexpected rising leading to the collision between the steps and the combplates has not been found.

The use of lighter steps (e.g. aluminum steps instead of steel steps) does not affect the nominal torque.

The step chain lubrication does not have a significant impact on the step chain tension. However, poor lubrication generates unpredicted forces on the step chain increasing the stress and displacement of its connected parts, potentially reducing their life expectancy and increasing the risk of collision.

The tensioning station has a negligible impact on all of the studied effects according to the one-way ANOVA table. This result contrasts with the forces distribution mechanism observed under steps load, steps weight and steps chain lubrication quality variations. For these three factors, the forces transfer through steps chains and are then absorbed by their connected parts, putting the steps chains at the centre of the dynamic mechanism. Due to the fact that the tensioning station's purpose is to preload the steps chain, a similar effect should occur when the tensioning station is adjusted to a different value. However, this did not occur in any of the DOE simulation runs. It can be explained by the fact that the three millimetre range of adjustment selected for the DOE is the one specified by the manufacturer; consequently, no chain tension adjustment within this range should disturb the dynamics of the system.

Additional simulations in which the tensioning station was incorrectly adjusted were run to tackle this issue. They tend to showcase that the tensioning station adjustment is the non-environmental parameter that has the greatest impact of the study.

Rails lubrication is a quite recent maintenance operation in the field of escalators. Manufacturers recommend lubricating the tracks to prevent premature damages caused by the rollers' speed variations. However, over the 27 simulations, no variation of the roller speed was noticed.

5 CONCLUSION

Because they are composed of a high number of moving parts, escalators require thorough adjustments to help control their dynamics. A better understanding of these adjustments when combined with design or environmental factors is a key to longer life expectancy and safety.

This study solely focuses on assessing the impact of the most expensive maintenance operations and common environmental parameters:

- The step chains lubrication efficiency
- The lubrication of the tracks
- The weight of the steps
- The tensioning station adjustment
- The number of passengers carried

To perform dynamic analysis, a model composed of the essential parts enabling transportation of passengers from the bottom to the top landing platforms was created using a multi-body dynamics software enabling the modelling of fully functional chain driven systems.

Part of the study was dedicated to validating this model by comparing its outputs to the outputs of a theoretical model established using the manufacturer's static and dynamic design equations. The disparity between the dynamic and the analytical model outputs is mostly due to the more complex definition of the simulation model.

Once the simulation model was validated, a series of 27 simulations was run using the DOE Taguchi methods to assess the impact of the 5 study parameters on 7 effects previously identified. These effects were selected according to the amount of information they give about the force distribution variations through the entire escalator system.

The steps chain appeared to be the main component of the mechanism controlling the escalator's dynamics. All the forces applied to one of its connected parts are transmitted through the steps chain impacting the stresses and displacements of the entire system.

This study showcases the *major impact of passenger flows on the force distribution through the whole model* and calls for *an improved assessment of effective passenger flows in the dimensioning of escalators* [8]. Finally, this study invites us to *optimise the maintenance policies regarding step chain lubrication and tensioning station adjustments* in order to reduce the escalator cost of ownership.

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BIOGRAPHICAL DETAILS

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Boat lifts in the UK

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Keywords: Boat lift, canal, waterway, river

Abstract. Once upon a time England's canals and rivers were the motorways of their days and all sorts of goods were transported from one end of the country to the other. These days canals and rivers are generally used for recreational pursuits but raising and lowering boats from one level to another, be it on the same waterway or between two different waterways, still remains an engineering issue. This paper looks at three very different boat lifts found around the UK: the Anderton Lift, described as the "cathedral of the canals" was opened in 1875 and still survives today; The Foxton Lift in Leicestershire was built in 1899 and only saw a few years' service; and the most recent acquisition to the canal network, The Falkirk Wheel in Scotland, which opened in 2002.

1 INTRODUCTION

At one point the canals and rivers of the UK were the motorways of the time and cargo was transported up and down the country in working boats. Famous companies such as Fellows Morton & Clayton were formed and had fleets of working boats upon which whole families would live in the traditional back cabin measuring less than 10ft long and in which you had to cook, wash and sleep. The children, who were mostly uneducated due to the nomadic lifestyle of their families, often slept on top of the cargo being carried. Many boats increased their carrying capacity by double breasting or towing a "butty" which was essentially a boat with no engine. The early canals were "contour canals" and would stay at the same height for miles on end thus negating the need for locks. This was very often a long and torturous way of covering just a few miles. Locks were installed to raise and lower boats but these were time consuming especially if you arrived at a lock that was against you (water level not set so you can enter the lock immediately). In some cases flights of locks were built where one gate was the top gate for one lock and the lower gate for another. Passage through flights of locks was costly and places such as the Caen Hill flight near Devises in Wiltshire on the Kennet & Avon Canal (see fig 1) could take a day to get from top to bottom or vice versa. The answer was a boat lift and there are 3 famous lifts ranging from Victorian times to a relatively modern installation in Scotland.

Fig 1: Caen Hill Locks

2 THE ANDERTON LIFT (1875)

Initially a flight of locks was considered for the task but this was discounted due to the time it would take boats to passage, the amount of space required and the large amount of water that would be lost from the canal to the river.

The Anderton Boat lift (see Fig 2) is often referred to as the "Cathedral of the Canals" and was designed by Edwin Clark. It was built in 1875 and was built an impressive 60 feet high, allowing it to clear the 50-foot difference in height between the two water levels of The River Weaver and the Trent & Mersey Canal. The entire structure was 85 feet long and 49 feet wide, while the aqueduct was 165 feet long. Each tank or caisson weighed a staggering 91 tonnes empty and 252 tonnes when flooded. These giants were 75ft long, 15 feet 6 inches wide, and 9 feet 6 inches deep in the middle. They were big enough for 2 narrow boats.

Fig 2: The Anderton Boat Lift

In 1908 the addition of a machinery deck brought the overall height to 80 feet, while the A-frames added for support widened the lift to 75 feet at its base. Each tank was counterbalanced by 252 tonnes of cast iron counterweights, attached by wire ropes. This gave a balance of 1:1. There were 36 stacks of counterweights on each side, weighing 7 tonnes each. The lift boasted 72 geared pulley wheels in all, and the largest ones, which took the lifting and safety ropes, weighed 3.5 tonnes each. There were 8 on either side. There were a further 20 pulley wheels taking 2 lifting ropes each, and 36 wheels with one lifting rope each. The shafts bearing the pulleys were 8 inches in diameter and the pulley pedestals weighed in at between 193 and 466lbs each. All in all, a good breakfast for the fitter weighing in all the scrap!

In 2001 the lift was restored to full hydraulic operation. The 1908 structure and pulley wheels were retained as a static monument.

The replacement hydraulic ram shafts replicate the original 3-foot diameter rams and are 56 feet long when retracted and 106 feet long when fully extended. The ram shafts are 56ft deep. Each ram weighs approximately 50 tonnes.

Edwin Clark, the designer of the lift, went on to design bigger lifts on the Continent including the lifts at La Louviere in Belgium.

3 THE FOXTON BOAT LIFT (1901)

The Foxton Inclined Plane (see Fig 3) was installed on the Leicester Branch of the Grand Union Canal. The Lock flight at Foxton was built in 1810, and the top summit route opened four years later, celebrating its anniversary in August 2014. A trip through the ten locks takes about 45 minutes to negotiate the 75 ft (just under 23 metres) hill and uses 25 thousand gallons of water, but if there is a queue you can be held up for hours. In the days when canals were used as a means of transporting cargo and were significantly busier than their relatively new use for leisure this could be bad for business. Boat width in the locks is restricted to seven feet so working boats with a “butty” would have to negotiate the flight separately. Boats using the locks were restricted to a maximum load of 20 tons. A solution was needed!

With the coming of the railways, competition was starting to bite. Fellows Morton and Clayton (FMC) wanted to use bigger boats to take coal from the north to the London factories. They promoted a take-over of the Leicester line of the canal by the Grand Junction Canal Company. The takeover was successful and FMC promised to put more narrowboats on the canal until the locks at Watford Gap and Foxton could be widened. GJCCo engineer Gordon Cale Thomas was put in charge of the project however wide locks were dismissed as using too much water from the canal's summit pound. His solution was to build a boat lift to his patented design.

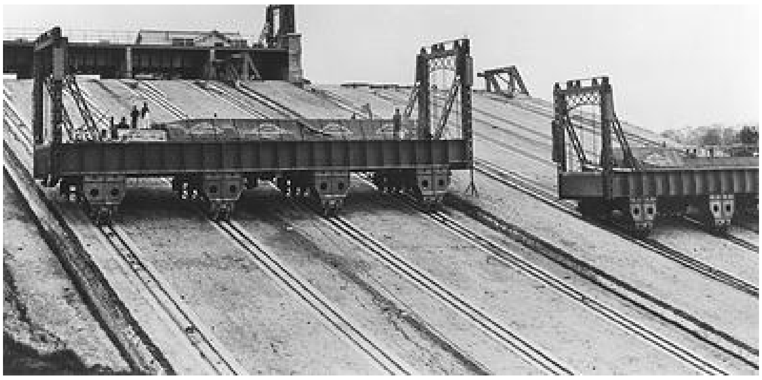

Fig 3: Foxton Inclined Plane under construction

The lift was built in 1901 by J & H Gwynne of Hammersmith, London. They got the job as they proposed using hydraulic power for the gates and ancillary equipment. It consisted of two tanks or caissons linked by wire rope (see Fig 4). A steam driven winch at the top wound the rope on to one side of its drum and simultaneously let it off the other, raising and lowering the tanks. Each tank was full of water and weighed 230 tons with or without a boat as boats displace their own weight in water. Two boats could fit in to each tank. The gradient of the system was 1 in 4. At the top level the caisson was hauled over a slight hump thus taking the weight off the system and also allowing the bottom caisson to overcome being suspended in the water at the bottom.

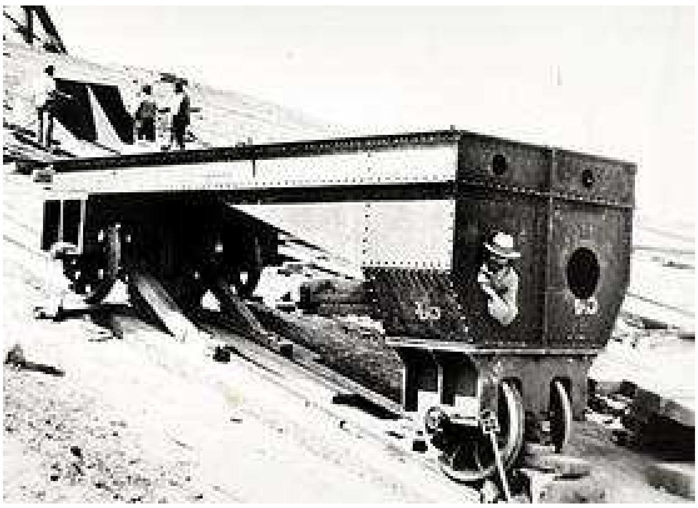

Fig 4: A caisson under construction

Its operation was fairly simple. Assuming your boat is at the bottom, you took your boat(s) into the tank. The operator would close a guillotine gate behind you and signal the engine room with a ship's telegraph. The 25 horsepower steam engine was turned on and you ascend the hill. The other tank descends either loaded with boats or just full of water. The descending tank simply sinks into the water at the bottom where the guillotine gate is opened by the operator. However, the immersion of the descending tank effectively makes it lighter in weight, upsetting the balance between the two tanks. To compensate for this, when the tank nears the top of the Incline, an ingenious change is made to the angle of ascent. The top of the slope curves off, effectively making it easier for the tank to ascend. On the leading edge of the tank, extra wheels come into contact with extra rails either side of the normal track. At the same time the rear wheels descend into a pit. This arrangement keeps the tanks upright. The tank has wooden seals fixed on the end of each top dock. Once at the top, hydraulic rams push the tank on to the wooden seal, and the guillotine gates on the end of the tank and on the dock are opened. The horse is re-attached and off you go. The entire operation took 12 minutes, and could move 2 boats up and 2 down. A big saving against the time taken to use the locks. The lift also saved a tremendous amount of water, because the only water lost was that trapped between the gates at the top.

The lift had worked well but the locks at Watford Gap were never widened, and the traffic didn't increase as railways were the new mode of transport. This made the lift uneconomic. There were problems with track bolts pulling out of the sleepers, but nothing that could not have been overcome. The lift was capable of moving a massive amount of traffic compared with the actual usage. FMC's promise of increased traffic hadn't been fulfilled. In 1911 the lift was mothballed to save money, the traffic returning to the locks which have been in use ever since. The decision was probably due to the need for substantial maintenance repairs on the 10 year old structure - it probably needed new cables which are expensive and the cost of keeping the lift in steam with a minimum of three operators. The fact that a fully working set of locks was available alongside the lift would not have helped. The lift was maintained for a few years, surviving the first world war, and sank into a slow decline. In 1928 the machinery was sold for scrap.

4 THE FALKIRK WHEEL

The Millennium Link was an ambitious £84.5m project with the objective of restoring navigability across Scotland on the historic Forth & Clyde and Union Canals, providing a corridor of regenerative activity through central Scotland.

Fig 5: Falkirk Wheel during operation

A major challenge faced was to link the Forth and Clyde Canal, which lay 35m (115ft) below the level of the Union Canal. Historically, the two canals had been joined at Falkirk by a flight of 11 locks that stepped down across a distance of 1.5km, but these were dismantled in 1933, breaking the link.

What was required was a method of connecting these two canals by way of a boat lift. British Waterways (now Scottish Canals) were keen to present a visionary solution taking full advantage of the opportunity to create a truly spectacular and fitting structure that would suitably commemorate the Millennium and act as an iconic symbol for years to come.

The various parts of The Falkirk Wheel (see Fig 5) were actually constructed and assembled, like one giant Meccano set, at Butterley Engineering's Steelworks in Derbyshire. A team there carefully assembled the 1,200 tonnes of steel, painstakingly fitting the pieces together to an accuracy of just 10 mm to ensure a perfect final fit.

In the summer of 2001, the structure was then dismantled and transported on 35 lorry loads to Falkirk, before all being bolted back together again on the ground, and finally lifted by crane in five large sections into position. The total 600 tonne weight of the water and boat filled gondolas imposes immense and constantly changing stresses on the structure as it turns around the central spine. Normal welded joints of steel would be susceptible to fatigue induced by these stresses, so to make the structure more robust, the steel sections were bolted together. Over 15,000 bolts were matched with 45,000 bolt holes, and each bolt was hand tightened.

The result is a perfectly balanced structure that is The Falkirk Wheel. Completion of The Millennium Link project was officially marked by Her Majesty The Queen on 24 May 2002.

The Falkirk Wheel (see Fig 6) lies at the end of a reinforced concrete aqueduct that connects, via the Roughcastle tunnel and a double staircase lock, to the Union Canal. Boats entering the Wheel's upper gondola are lowered, along with the water that they float in, to the basin below. At the same time, an equal weight rises up, lifted in the other gondola.

This works on the Archimedes principle of displacement. That is, the mass of the boat sailing into the gondola will displace an exactly proportional volume of water so that the final combination of 'boat plus water' balances the original total mass.

Fig 6: Falkirk Wheel

Each gondola runs on small wheels that fit into a single curved rail fixed on the inner edge of the opening on each arm. In theory, this should be sufficient to ensure that they always remain horizontal, but any friction or sudden movement could cause the gondola to stick or tilt. To ensure that this could never happen and that the water and boats always remain perfectly level throughout the whole cycle, a series of linked cogs acts as a back up.

Hidden at each end, behind the arm nearest the aqueduct, are two 8m diameter cogs to which one end of each gondola is attached. A third, exactly equivalent sized cog is in the centre, attached to the main fixed upright. Two smaller cogs are fitted in the spaces between, with each cog having teeth that fit into the adjacent cog and push against each other, turning around the one fixed central one. The two gondolas, being attached to the outer cogs, will therefore turn at precisely the same speed, but in the opposite direction to the Wheel.

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BIOGRAPHY

David Cooper has been in the lift industry since 1980 when he started an apprenticeship with British Railways. He has been involved with many of the rail mounted inclined lifts around the UK including Hastings East, Hastings West, Babbacombe, Scarborough Central, Scarborough South Cliff, Scarborough St Nicholas, Padstow, Lizard, Southend, Urbis Centre, Machynlleth, Bridgnorth. Internationally he has also been involved with the Angels Flight inclined lift in Los Angeles. In 2008 he appeared in the BBC programme “Flog It” as the expert showing Paul Martin over the Inclined Lift at Babbacombe in Devon. He has won awards for his involvement with inclined lifts including the Association for Consulting and Engineering Awards for the projects at Babbacombe and Hastings. He has also been involved with aerial suspended cableways and was the winning project in the Elevator World Project of the Year in 2013 for the London Emirates Airline Cable Car on which he presented a paper at the 2013 Symposium.

How to Approach Lift Doors Modernization and Refurbishment Projects

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Keywords: Lift doors, Modernization, Refurbishment, Lift components, EN 81-80

Abstract. Millions of lifts are in use today in Europe. In many countries, more than half of the existing lifts are 25 years old or older. Few of them have been modernized to meet current safety and performance requirements. Nevertheless the aging of lifts can be made more effective, safer, more reliable and more comfortable through improvement and regular maintenance. EN 81-80 defines measures to be taken for existing elevators to bring them up to state-of-the-art standards. The objective is to reach, in existing lifts, the safety level prescribed in the EN 81 series of standards.

There are also special requirements for lift doors, which should be refurbished according to the characteristics described by the latest operational safety regulations, including fire and vandal resistance. A dedicated approach, as well as a rehabilitation plan and schedule for lift door modernization can be established using the regulations in EN 81-80. These can include specialized services for the analysis of risk levels in existing lifts and refurbishment needs, including on-site surveys, as well as different solutions according to the type of modernization required: complete product substitution, single component replacement or customized solutions.

1 INTRODUCTION

If we present a lift modernization project to an average lift passenger we will explain that the refurbishment's aim is to improve accessibility, reliability, efficiency, performance and comfort in existing systems, whilst simultaneously lowering maintenance activities and energy consumption.

From a sales and marketing point of view, this is a comprehensive description that already includes the full set of advantages for choosing to upgrade an existing lift. Anyway, something significant is missing: the focus on safety. This is clear to any industry expert who, when they start their analysis of how to approach refurbishment and modernization projects, looks to the most relevant safety norm for existing lifts: the EN 81-80 standard.

2 EN 81-80 SNEL [1,2]

The upgrading of the existing lifts in Europe, which are the oldest in the world, has been a top priority for the European lift industry for many years. The actual beginning of this can be considered to be the 1995 “10 recommendations to make existing lifts safe” document (see Fig.1) that was published by the European Commission in addition to the Lifts Directive 95/16/EC.

The recommendations had no legal force but they were the starting point considered by industry experts for the analysis and the identification of all the risks that an existing lift could pose. This process stood as the basis of the drawing up of the EN 81-80 standard in 2003.

1. Car doors to be fitted and a floor-level indicator to be fitted inside the car.
2. The car suspension cables to be inspected and possibly replaced.
3. The stop controls to be modified in order to achieve a high degree of precision in the stopping level of the car and a gradual deceleration.
4. Make the controls in both the cars and lift wells intelligible and usable by unaccompanied disabled persons.
5. Fit human- or animal-presence detectors to the automatic doors.
6. For lifts which travel faster than 0,6 m/s, fit a parachute system allowing them to decelerate smoothly when stopping.
7. Modify the alarm systems to establish a permanent link with a high-speed breakdown service.
8. Eliminate any asbestos in the braking systems, where this exists.
9. Fit a device preventing uncontrolled movements towards the top of the car.
10. Provide cars with emergency lighting that operates in the event of a main power supply failure. It must operate for long enough to enable the rescue services to intervene in a normal manner. The installation must also enable the alarm system provided for in item 7 to function.

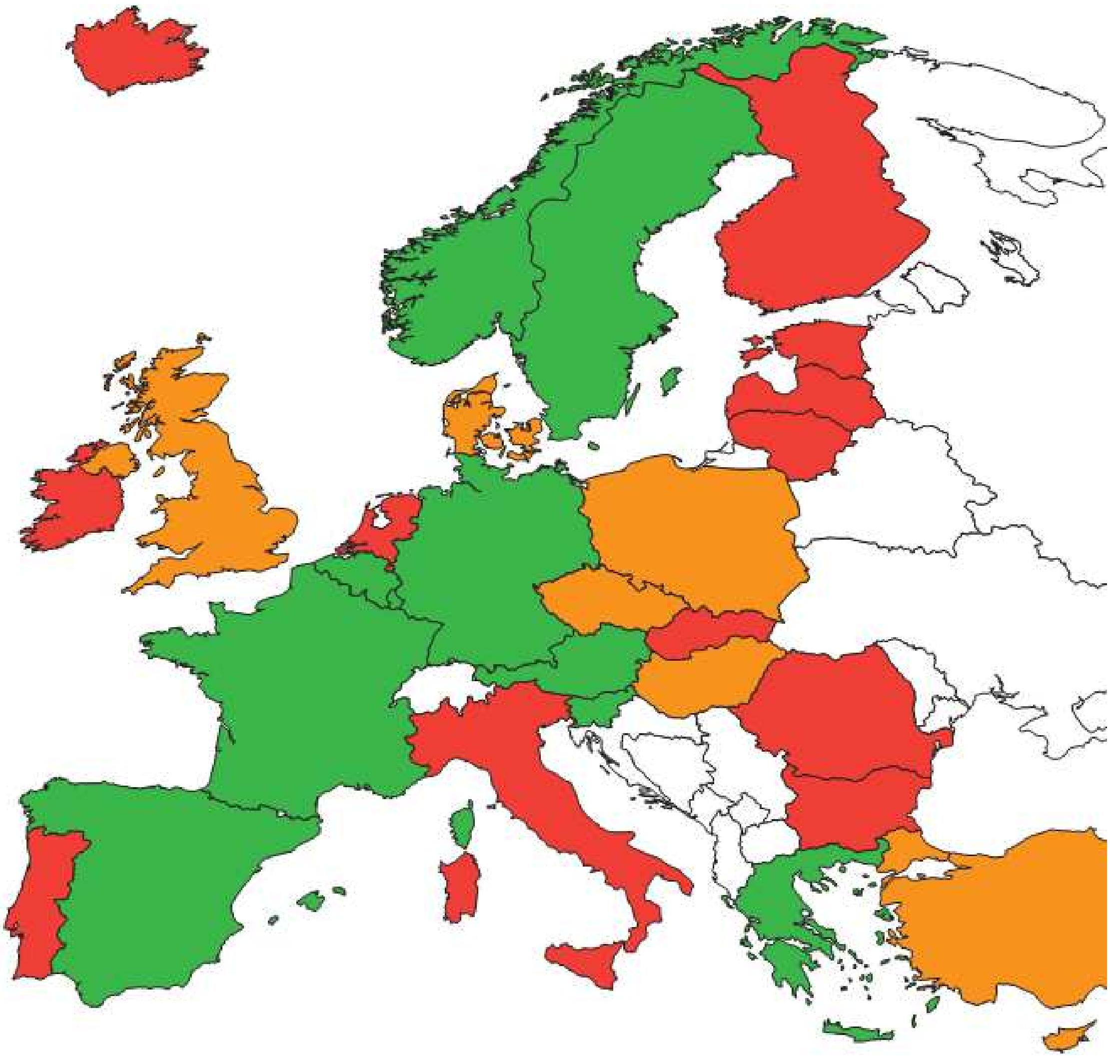
Figure 1: 10 recommendations to make existing lifts safe

Relevant indications related to lift door modernization, such as the need for car doors in any lift, or for adapting existing lifts to be usable by disabled persons, or for efficient detectors for preventing hits during the automatic door closing phase, were already present in the 10 recommendations. But it is only with the addition of EN 81-80 to the well-known European Standard for new lifts, EN 81 Part 1/2 in 2003, that the safety for existing lifts and their components became a crucial topic for the entire elevator industry.

The new standard, introduced by the European Committee of Standardization, was the result of a team composed of CEN safety experts from the lift industry, government authorities, third party inspection bodies, consumer organizations and insurance companies, and derived from the in-depth study of the 1995 “10 recommendations”.

From 2003 on, SNEL implementation has been different from country to country (applied through the national filtering method) since this European standard does not give directly binding requirements for improvement actions to be carried out on lifts. Such obligations are subject to national legislation.

So the implementation of EN 81-80 varies in content and scheduling for each country (see Fig.2), and is subject to local differences, for example, in the definition of risk levels, categorized as extreme, high, medium or low, which depend on previous country history of lift regulations and applied standards, accident statistics, specific product knowledge and social expectations.



GREEN: standard EN 81-80 has been implemented through a national law, including a defined position for the SNEL filtering

YELLOW: national legislation or guidelines in preparation

RED: a rather slow progress or nothing has been undertaken so far or no information received/available for the EN 81-80 implementation

Figure 2: SNEL survey table– source ELA

EN 81-80 can be seen as a technical guide that supports the progressive and selective improvement of the safety in existing lifts and it still remains the standard reference for refurbishment and modernization projects, even if the main lift norm EN 81-1/2 has being replaced by the new EN 81-20/50.

Starting from the analysis of international statistical data on accidents, specific risk assessments and the estimated life cycle of lifts, the EN 81-80 standard identifies and categorizes various hazards and hazardous situations that can be present in existing lifts, classifying them also by priority levels through the correlation between frequency and severity (high risks have to be addressed in the short term).

Table 1: EN 81-80 risk profile with priority levels

Frequency	Severity I	Severity II	Severity III	Severity VI
	Number of hazardous situation			
A	Extreme	Extreme	High	Low
B	Extreme	High	High	Low
C	Extreme	High	Medium	
C-D	High	High	Medium	
D	High	Medium	Low	
D-E	Medium	Low		
E	Low	Low		
F				

Frequency (hazard cause level): A Frequent, B Probable, C Occasional, D Remote, E Improbable, F Impossible	**Severity** (hazard effect category): I Catastrophic, II Critical, III Marginal, IV Negligible

Table 1: Correlation between hazard frequency and severity – source ELA

Furthermore, EN 81-80 provides a detailed checklist of more than 70 items for the safety audit of any existing lift and its components (which can be performed only by qualified technical experts) and gives a complete description of corrective actions to progressively improve lift safety and accessibility for both lift users and workers.

The safety checklist is one of the key tools to be used when starting a modernization project. It results in a clear picture of the status of the lift and groups all of the significant hazards, identified by the EN 81-80, by their position in the lift (well, machine and pulley rooms, landing doors and car doors, car, counterweight and balancing weight, suspension, compensation and over speed protection, guide rails, buffers and final limit switches, etc.). Furthermore this facilitates the risk analysis for component manufacturers and provides relevant suggestions for preparing a stepwise upgrading, which can also be supported by preventive maintenance actions and repairs, for each specific lift component.

3 SAFETY REQUIREMENTS AND PROTECTIVE MEASURES FOR LIFT DOORS

EN 81-80 lists all the hazardous situations to be checked in any landing and car door of an existing lift, defining the priority level of intervention and the protective / risk reduction measures to be implemented. Hazardous situations are mostly linked to the ability of the doors, and of their safety components (door locks, door fixings, apron, protective devices), to act as reliable, safe and protective barriers with the main goal of preventing persons from falling into the well. Nonetheless specific actions are also required to upgrade existing components in order to make them compliant with other EN 81 standards and guarantee accessibility for disabled persons (EN 81-70), as well as resistance to vandalism (EN 81-71) and fire (EN 81-72).

Table 2: Hazardous situations for landing and car doors

Hazardous situation	Cause - Trigger	Incident / Effect	Priority level
Perforated landing and car doors	Person passes limbs through openings	Shearing and crushing of limbs, serious injuries	High
Inadequate design of landing door fixings	Person pushes the door, door collapses	Person falling into well, serious injury or death	
Inadequate glass in doors	Glass is broken by impact, person passes limbs through opening	Falling into well, shearing of limbs, serious injury or death	
No or inadequate protective devices on power operated doors	Person is passing the doors when door starts closing	Person is hit or jammed by the door, serious injury	
Unsafe locking device of landing door	Landing door closed but not properly locked, person opening the door	Person falling down the well, serious injury or death	
Unlocking of landing door possible without special tool	Person unlocks and opens a door	Person falls into the well, serious injury or death	
Well enclosure with perforated walls near door locks	Person is unlocking the landing door without a special tool, e.g. stick	Person falling into well, serious injury or death	
No automatic closing device on sliding doors	Door remains open after emergency unlocking or when car leaves the floor due to creeping	Person falls into the well, serious injury or death	
Inadequate length of car apron	Rescuing of trapped persons when car is stopped above landing	Falling down the well	
Car without doors	Goods in car hit sill or recesses on wall and tip; Person (child) enters gap between car sill and wall	User crushed, serious injury or death; Shearing and cutting of limbs, serious injury or death	
No or inadequate lighting on landings	Users entering or leaving the lift	Tripping and falling	Medium
Inadequate mechanical link between panels of	Mechanical link fails, one panel remains open	Shearing or falling of persons, fatal or serious	

landing doors		injuries	
Inadequate fire resistance of landing doors	Fire in front of landing door spreads into well and up to next floor	Person in upper floors killed by fire and smoke	
Car door moving when landing door is opened	Person entering the car before the car door is fully opened	Trapping and shearing of hands	
No or inadequate protection against dragging of fingers on sliding doors with glass	Person (child) touches glass and door start to move	Fingers are dragged into gap between door panel and frame	Low

Table 2: Hazardous situations, cause, effect, priority level for lift doors – source ELA

For all the items to be checked, the EN 81-80 defines the safety requirements that each part/component has to satisfy and suggests corrective actions to be implemented in order to fulfill these requirements. In many cases, the protective measures refer directly to specific paragraphs of the EN 81-1 and 2, quoting their references, prescriptions and measures. In others they are linked to specific norms or measures which are referred to directly in the EN 81-80 text.

For example, the SNEL suggests fitting landing doors according to the fire rating as required by national/local regulations, or to fit car and landing door protective devices according to EN 81-70. This would be so as to have them covering the opening over the distance between at least 25 mm and 1,800 mm above the car door sill (e.g. light curtain) and to prevent physical contact between the user and the leading edges of the closing door panels.

Table 3: Items to be checked and protective measures (EN 81-80)

Items to be checked	Protective measures
Strength of landing door fixing	Replace door fixings according to EN 81-1:1998, 7.2.3.1 and 7.4.2.1 or EN 81-2:1998, 7.2.3.1 and 7.4.2.1
Car door and landing door protective devices on a lift intended to be used by disabled persons	Fit a device according to EN 81-70:2003, 5.2.3 and 5.2.4
Non-accessibility of landing door locking devices from outside the well by unauthorized persons	a) Fit imperforate wall enclosure, or b) Fit protection around landing door locking device

Table 3: Examples of items to be checked and protective measures for lift doors – source EN 81-80

4 APPROACH TO COMPONENT MODERNIZATION

Even if each existing lift has its own specific characteristics (to be assessed individually) and each EU country has applied the EN 81-80 to a different extent, all the information included in the SNEL provides a precise, common framework that can guide companies and workers during modernization and refurbishment projects.

The starting point for any lift refurbishment project should always be the auditing of the existing lift on the jobsite by a qualified, competent technical expert, who should gather all the relevant information related to the audited components.

There are three main ways to approach the upgrading of a component in an existing lift:

- Complete refurbishment. This includes the replacement of the entire component and gives the advantage of upgrading it to a state-of-the-art model in terms of safety, reliability and performance. It has a higher cost compared to the other approaches.

- Partial refurbishment. This includes the replacement of only specific parts of a component in order to guarantee its compliance to specific requirements of the EN 81-80 standard. Usually partial refurbishment requires additional effort in product engineering and in the adaptation of the existing parts to the new ones.

- Refurbishment kit. As partial refurbishment it includes the replacement of specific parts alone, but in addition it can only be used for specific product lines of specific manufacturers. Costs are lower than for complete refurbishment and product engineering efforts are lower than for partial refurbishment.

The selection between the three types of approach is always guided by safety first but as soon as the compliance to EN 81-80 standard is satisfied, the main variables to be considered are costs and shaft configuration and accessibility.

5 APPROACH TO LIFT DOOR MODERNIZATION

Lift door modernization projects are even more critical because both the dynamic and static elements of the doors have to be analyzed, including installation characteristics, component integration (car-car door-landing door-shaft), shaft dimensions, finishes and materials.

Door manufacturers have developed specific refurbishment services that always start from the collection of data through to dedicated forms to fill in (see Fig.3). Dimensions, type of panels, position of door fixings, and skate and rollers are some of the key information to be collected.

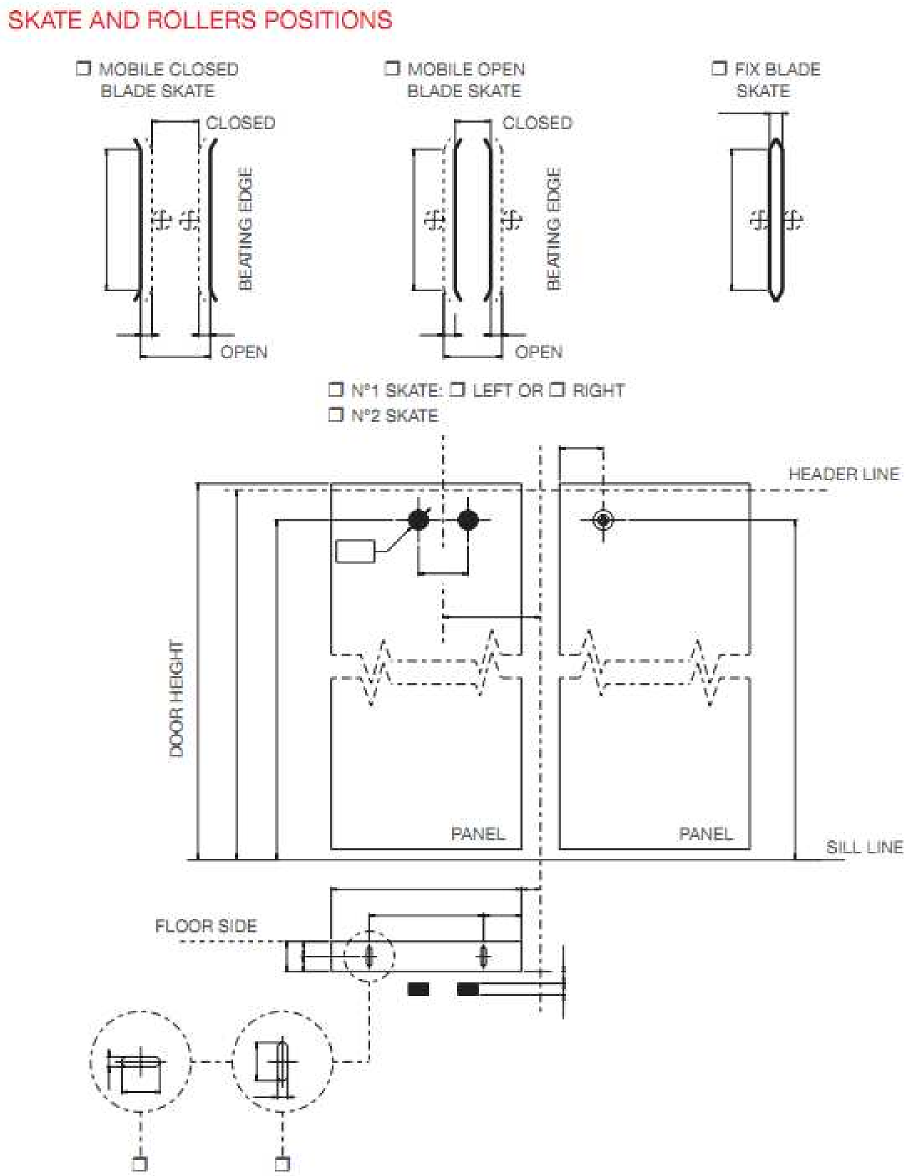


Figure 3: Lift door assessment – skate and roller positions – source Sematic

Seeing as every lift differs from one another, the collection of data (including jobsite pictures – see Fig.4) is needed in order to design a specific solution for each single refurbishment project. Taking into consideration the EN 81-80 prescriptions and the results of the assessment, door manufacturers are able to offer a wide range of solutions for the complete replacement of old lift doors (both manual and automatic), as well as of some of their key components (fixings, skates, operators, protective devices). The products offered in the modernization business are suitable for an extensive range of existing installations and can be customized according to the different destination markets and their characteristics, such as shaft dimensions or local regulations.

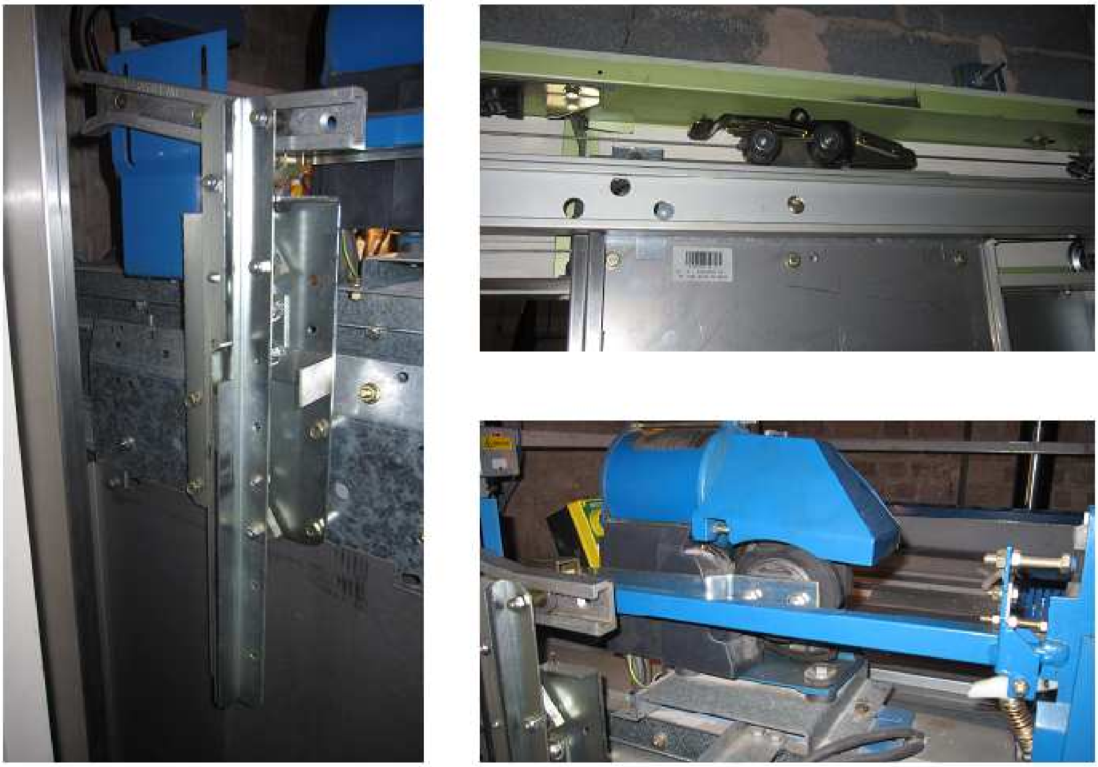


Figure 4: Jobsite survey pictures – source Sematic

For partial refurbishment and refurbishment through specific kits, additional services are provided after data collection, jobsite surveys and analysis. The solutions that door manufacturers can offer in terms of customized products have always to be verified through specific product engineering activities, including conversion of collected data into one-of-a-kind drawings (see Fig.5).

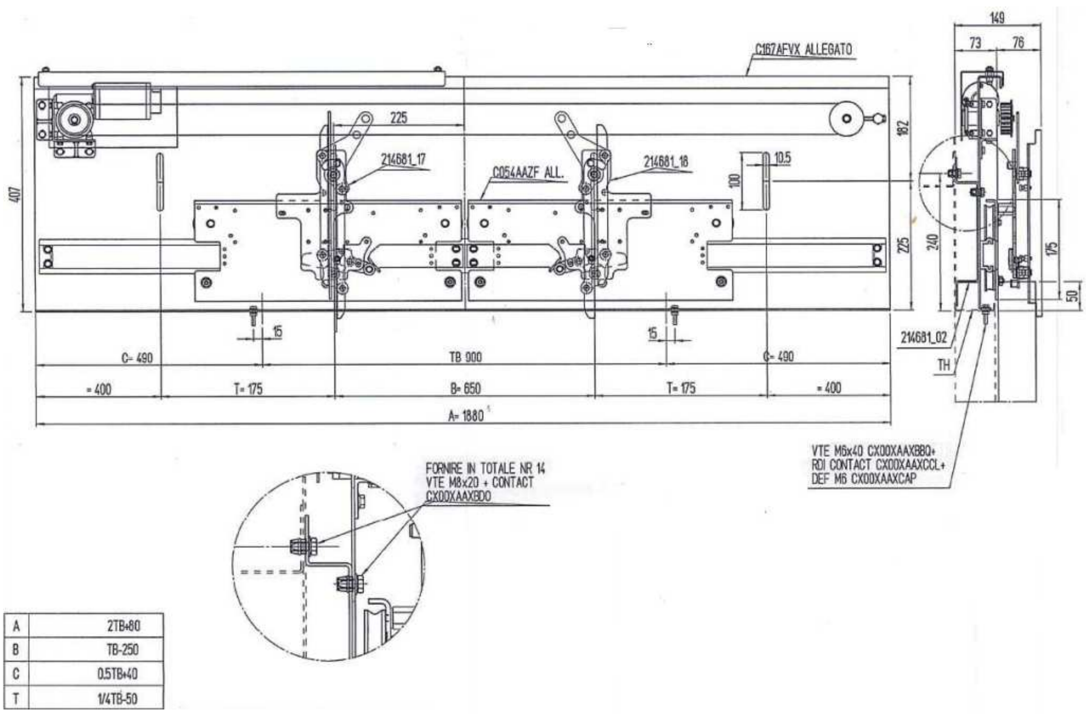


Figure 5: Product engineering – source Sematic

6 CONCLUSIONS

Lift doors are one of the most critical components for the safety and accessibility of any existing lift due to their complex integration with all the other lift components. Hazardous situations that, if not avoided, will result in death or serious injury are strictly linked with their malfunctioning or not updating to present-day standards. EN 81-80 offers all lift door manufacturers a well-defined path to follow during modernization projects, starting from lift assessment up to solution design and product definition. Safety and compliance to SNEL standards are always the guiding criteria of any lift door modernization and refurbishment project, even if technical and economic issues can direct the type of approach chosen.

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BIOGRAPHICAL DETAILS

Giuseppe De Francesco

Born in 1973, Giuseppe De Francesco holds a degree in Electronic Engineering from the Politecnico of Milan. Since 2002 he has worked in the Sematic Group, holding positions of increasing responsibility in the Engineering and R&D areas of the company. Nowadays he is responsible for all the product development activities of Sematic worldwide. Having a 13-year experience in the elevator industry, Mr. De Francesco has gained significant know-how and expertise in the development of innovative solutions for the design and manufacturing of automatic elevator doors, including glass and fire-resistant executions, in any application context: from high-rise to modernization.

Tommaso Sala

Born in 1979, Tommaso Sala holds a Master’s degree in Public Relations and Communication from the IULM University of Milan. He has worked in the Sematic Group since 2009, holding positions of increasing responsibility in the Marketing and Communication areas of the company. Nowadays he is responsible for all the brand promotion activities of Sematic worldwide.

Key Dynamic Parameters that Influence Ride Quality of Passenger Transportation Systems

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Keywords: Lift, Escalator, Noise and Vibration, Design, Components, Dynamic Interactions

Abstract Ride quality is a measure of the comfort level experienced by passengers and is intimately associated with their subjective perception and sensitivity to motion and to sound. This measure is affected by noise and vibration of a running system. On the other hand, ride quality is the measure of the product quality of a Passenger Transportation System (PTS) manufacturer. Ride quality of passenger transportation systems is critical for a PTS manufacturer to determine the subjective and objective quality of PTS. This is especially important in high rise (high end) systems. The paper investigates the dynamic interaction of PTS system components and their influence on ride quality.

1 INTRODUCTION

All humans are different and so the perceived performance of a PTS ride, either vertical using a lift or horizontal using a moving walkway or with an escalator in horizontal and vertical direction, is not the same. The acceptance levels of a given PTS assessed by a user group varies from user to user and typically show a wide variance [1].

A PTS contains of a large number of components which interact with each other. These components or sub-systems influence the ride quality of the system [2] and it is the interest of the PTS manufacturer to install and run a systems that makes the ride as smooth as possible. How these components dynamically influence the PTS and how humans respond to it will be investigated. Based on these results, measures to improve the ride performance will be suggested.

2 DEFINITION OF RIDE QUALITY

Ride quality of a PTS is a measure of the comfort level experienced by passengers and is intimately associated with their subjective perception and sensitivity to motion and to sound. For example, in the case of a lift system, to motion and noise levels of the car [3]. Ride quality is then affected by motion and sound quantified using the following parameters:

- Horizontal vibrations [measured in m/s²]:
  Horizontal vibrations are lateral motions (in x- or y-direction). These motions are quantified in terms of the frequency (measured in Hz) and the amplitude (measured in m/s²). However, the amplitude is typically measured in milli-g (1 milli-g = 0.00981 m/s²) [4].

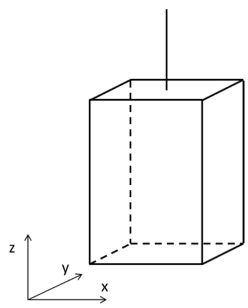


Figure 1 – Arrangement of x-, y- and z-axis

- Vertical vibrations [with the amplitude measured in m/s^2 and the frequency measured in Hz]: Vertical vibrations represent motions in the direction of the z-axis (for a lift: into or opposite to the direction of travel). A typical cause of this vertical vibration is the elastic behavior of the suspension mean, e.g. a steel-wire rope.
- Acceleration [measured in m/s^2]: This is the rate of change in speed in upwards or downwards direction (direction of travel).
  Positive acceleration: increase of speed. Negative acceleration: speed decreases.
- Jerk [measured in m/s^3] (time-derivative of acceleration = rate of change of acceleration): The rate of change in acceleration is called jerk.
- Sound pressure [measured in Pa] and Sound pressure level = defined as a logarithmic measure of the effective pressure of a sound relative to a reference value [measured in dB(A)]: Sound corresponds to vibrations which are transmitted through a solid, liquid or gas-form medium. A human being can hear frequencies in the approximate range of 20 to 20,000 Hz.
- Tympanic pressure [measured in Pa] (effect of dynamic change of ear pressure in the middle ear causing discomfort)

The acceptance levels of these aspects not only vary from human to human, but are also different in terms of product range (e.g. low-cost low-rise – middle segment - high-speed/high rise). Therefore, case-specific pass/fail or assessment criteria for PTS are put aside from this paper.

3 IMPACT TO HUMAN DISCOMFORT

Obviously, the response of the complex active structure of a human body to the multiple facets of ride quality is unique from human to human.
The application of (noise and) vibration to a human body can create various subjective effects and at the end cause human discomfort.
Humans are different in terms of body mass, portion of muscles, physical ability or overall condition [5]. And of course, the sensitivity for external stimulation is again different from person to person. If it comes to extrems, very poor ride quality with human over-sensitivity, vibrations can cause stress effects to following physiological areas: Cardio-vascular system, Nerves system, Muscles, Respiratory system.
It is common practice in the Lift Industry to stay within certain limits for critical ride quality aspects to ensure good ride quality:

- Humans are more sensitive to jerk rates than to acceleration, and jerk rates under 1.0 m/s^3 are assessed as comfortable. [2]
- High rise/high speed travel (e.g.: travel distances of 400 m and more with maximum speed of 7 m/s usually cause an uncomfortable trip in a PTS.
- Acceleration rates of 0.8-1.6 m/s^2 improves passenger comfort, however, especially for high rise application these limits are disregarded due to transportation capacity requirements.
- Horizontal vibrations are typically specified below 25 milli-g (peak to peak in x- and y-axis).
- Maintaining the maximum limit sound level of 55 dB (A) is desired in the lift cabin.

In the context of '*human-machine/lift*' a unique person interacts with the lift car. The person stands on the cabin floor, typically wearing shoes. These represent the coupling or damping element between the human being and the lift system (cabin). The effects of different damping types (shoes) and the theoretical and experimental transmissibility has been compared in another paper [6]. The dynamic response of the lift cabin can substantially been influenced by the characteristics of the passenger and his behaviour during the lift travel. The dynamic interaction of lift components is defined by and finally counts in that human-machine context: Mass-Damping-Stiffness characteristics.

4 COMPONENTS THAT AFFECT RIDE QUALITY

4.1 Sources of vibrations

The operation of lift systems is affected by vibrations and associated vibro-acoustic noise. This affects ride quality and results in a high level of dynamic stresses in lift components. A good understanding and prediction of vibration phenomena occurring in elevator installations is essential for developing vibration suppression and control strategies in order to design a system which satisfies ever more demanding ride quality criteria.

Vibration sources affecting a lift car involve the car guiding system, suspension and compensating ropes and air flow [7,8]. The underlying causes of vibration are varied, including poorly aligned joints and imperfections of guide, eccentric pulleys and sheaves, systematic resonance in the electronic control system, and gear and motor generated vibrations [9,10].

In high-rise applications elevators are subject to extreme loading conditions. High-rise buildings sway at low frequencies and large amplitudes due to adverse wind conditions and the load resulting from the building sway excites the elevator system. This leads to large vibratory motions of elevator ropes [11,12]. The taller a building, the higher the rated speeds of elevator systems are needed. The dynamic responses become more adverse as the speed increases. Torque ripple generated in the motor causes vertical vibrations of the car [13]. At high speeds guide rail deformations induce large lateral vibrations of the car [14,15]. Furthermore, large aerodynamic loadings due to the airflow around the car result in excessive noise and flow-induced vibrations of the car structure [16,17].

The effects of component dynamics to the ride quality of a PTS are the subject of a number of previous investigations. These show evidence of the complexity of the interaction of multiple components.

A variety of sources affect the lift car and – if a passenger travels in the cabin – the passenger. The primary sources that affect ride quality are:

- guiding system (faulty guide rails and joints)
- suspension and compensating ropes
- air flow

Furthermore, imperfect pulleys and sheaves, a systematic resonance in the electronic lift control system, and motors and gears all generate vibrations which are transmitted into the system. Finally, the very slow excitation of building sway to the lift systems (mainly the ropes) can cause vibration in the cabin [13].

Guide rails: The most essential elements affecting ride quality of a lift are guide rails and their installation condition. Due to the T-profile design and the manufacturing process, guiderails are never perfectly straight and totally rigid [2]. The guide rail irregularities (poorly aligned joints, bends and unevenness) introduce lateral excitation to the car during its travel. The range of excitation frequencies depends on the speed. The fundamental frequency of this excitation is given as

$$\Omega = \frac{2\pi}{\gamma} V \frac{rad}{s} \left(or\ f = \frac{\Omega}{2\pi} = \frac{V}{\gamma}\ Hz\right) \tag{1}$$

where γ represents the wavelength corresponding to the guide rail profile.

For example, in a standard arrangement the two lengths of guide rail are connected together with rectangular cross section fishplate bridging the joint. The joint interface is the critical area as it is extremely difficult to arrange for the second moment of area (*I*) of the fishplate–joint interface to be the same as that of the guide rail. Thus, the bending stiffness (*EI*, where *E* is the Young's modulus) of the guiding system is non-uniform in respect of bending deflections. Therefore, during lift travel with a given speed of V, the excitation frequency *f* transmitted to the car frame can be calculated as

$$f = \frac{V}{L}\ [Hz] \tag{2}$$

where *L* is the rail length. Thus, using the standard rail length of 5 m and the speed range of 10 - 18 m/s this would yield the frequency range of 2 – 3.6 Hz. On the other hand, taking into account the fact that the wavelength due to manufacturing bends are about 0.1 m [8] the frequencies calculated from equation (1) can be over 100 Hz (100 – 180 Hz). In general, the nature of guide rail imperfections should be classified as *nondeterministic*. If the unevenness of guide rails is measured then the record for one rail will be different from that for another one. A nature such as this is referred to as being random or stochastic [15]. Consequently, the response of a car – hoist rope system is also a random phenomenon.

Roller Guides: Roller guides are available in various types and configurations for all kinds of application, such as high speed traction lifts or low rise hydraulic systems.
Under the consideration of stiffness and damping characteristic of these rotating or non-rotating components, it is obvious that they directly affect the vibration and thus the ride performance of a lift car.

Imperfections of rotating components such as traction sheave, diverter pulleys: Rotating components can only be made to its ideal round condition with huge manufacturing efforts. As a consequence, the rotating components deviate from the geometrical dimensional data and an imbalance excites the system with a frequency of its rotational velocity.

Rope dynamics: Due to their flexibility, hoist (suspension) and compensating ropes are susceptible to vibrations. These vibrations are transmitted to a lift car which often results in a ride quality which is unacceptable [18,19]. Elevator ropes can vibrate in the vertical (longitudinal) direction and lateral (horizontal) in-plane and out-of-plane directions (see Figure 4). An important feature of an elevator system is that the ropes are of time varying length. Furthermore, the number of passengers on board (load) changes. Consequently, the dynamic characteristics of the system vary during travel. In particular, the natural frequencies of the ropes vary slowly during the elevator car motion rendering the system non-stationary. An adverse situation arises when one of the slowly varying rope frequencies approaches near the frequency of a periodic excitation existing in the system. This results in a passage through external resonances.

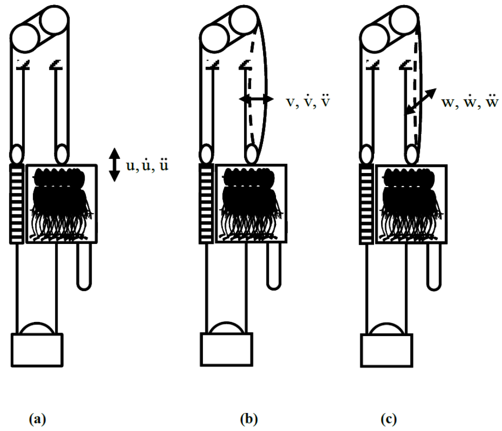


Figure 2 - Longitudinal (a), lateral in-plane (b) and lateral out-of-plane (c) vibrations of elevator ropes [19]

Overall, during the system operation the range of resonance frequencies of the ropes may vary from below 1 Hz to over 100 Hz. As far as the interactions between the ropes and the car are concerned, an elevator will not vibrate throughout its travel at high amplitudes but will 'pass through' a resonant vibration at some particular stage in the travel. An important excitation source relevant the rope – car assembly interactions is the low frequency building sway. This excitation will affect the modes below 1 Hz [21].

4.2 Human frequency band

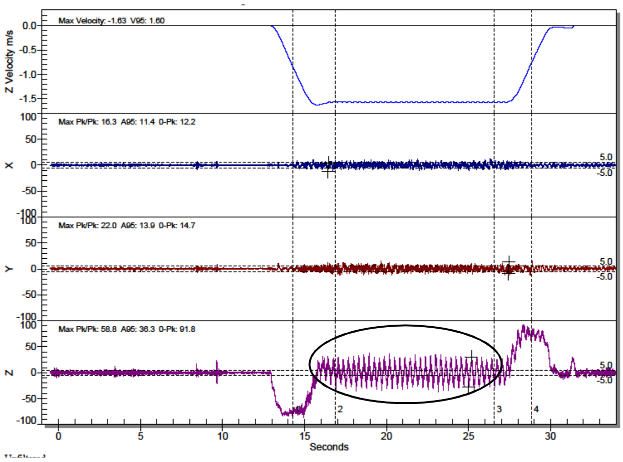
The human hearing range defines the band of frequencies that humans can hear and is usually mentioned as 20 to 20,000 Hz, whereas there are substantial variation between individuals, especially at high frequencies. The sensitivity for noise also varies with frequency. However, the noticeable range of vibration for human beings is even below the minimum of hearable noise.

5 DYNAMIC INTERACTIONS

It is the physical effect of resonance that causes issues with noise and vibration in PTS. The primary external resonance arises when the frequency of external excitation becomes close to one of the natural frequencies of the system. The natural frequencies of a given component is associated with one of the many standing wave patterns by which that component could vibrate. Any component can be forced into vibration at one of its natural frequencies (harmonics) if another interconnected object acts upon it with one of those frequencies.

With focus on the issue of resonance and its influence to the dynamics of lift cars the following practical example is considered.

- The system comprises a lift system with a car of rated speed 1.6 m/s and travel height 23.6 m with multi-reeving roping arrangement.
- The car sufferes from excessive vertical (z-axis) vibrations (peak-to-peak acceleration amplitude of over 58 mg; please see the time measurement record in Figure 3 and the corresponding FFT frequency spectrum in Figure 4)
- The fundamental frequency of the response is about 3.25 Hz which is close to the rotational speed in the diverter pulley system determined as 3.18 Hz.



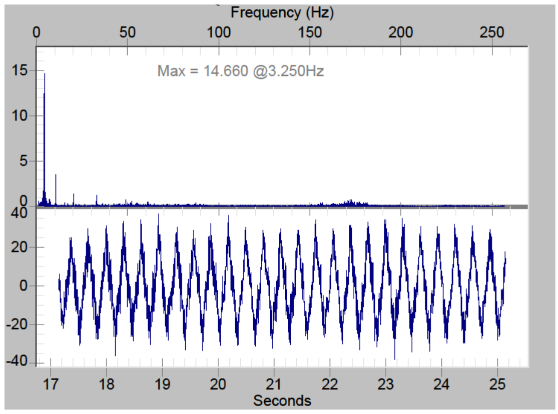


Figure 3 (left) - Time measurement record

Figure 4 (right) – Corresponding FFT frequency spectrum

- The vertical (bounce) vibrations are transmitted to the car through the suspension rope system which can be explained using the spring-mass model shown in Figure 5 where K_e represents the effective stiffness coefficient of the suspension ropes, M is the mass of the lift car assembly, *s(t)* represents the motion excitation at the traction sheave end due to excentricity or out-of-roundness error and *x(t)* is the response / displacement of the car assembly.

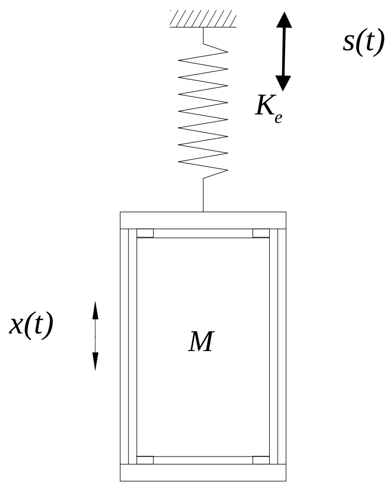


Figure 5 - Spring-mass model

The natural (resonance) frequency of the car-suspension system can be calculated using the following equation

$$\omega = \sqrt{\frac{K_e}{M}} \ \frac{\text{rad}}{s} \ \left(f = \frac{\omega}{2\pi} \text{Hz} \right) \tag{3}$$

The response can then be determined by solving the following equation [5]

$$\ddot{x} + 2\zeta\omega\dot{x} + \omega^2 x = s_{\max}\sqrt{\omega^4 + 4(\zeta\omega\Omega)^2}\,\sin(\Omega t + \theta_0) \tag{4}$$

where the overdots denote the time derivavtive, $s_{\max}$ is the maximum displacement due to the excitation at the sheave, Ω represents the frequency of the pulley, ζ is the damping ratio and r represents the frequency ratio . The maximum displacement of the car is then determined as [9]

$$x_{\max} = s_{\max}\sqrt{\frac{1+4\zeta^2 r^2}{\left(1-r^2\right)^2+4\zeta^2 r^2}} \tag{5}$$

so that the corresponding acceleration amplitude is given as

$$a_{\max} = s_{\max}\Omega^2\sqrt{\frac{1+4\zeta^2 r^2}{\left(1-r^2\right)^2+4\zeta^2 r^2}} \tag{6}$$

The natural frequency changes during the lift travel and was determined from the braking tests as 3.125 Hz at the bottom landing and 4 Hz at the top landing, respectively (please see Figure 6 and 7).

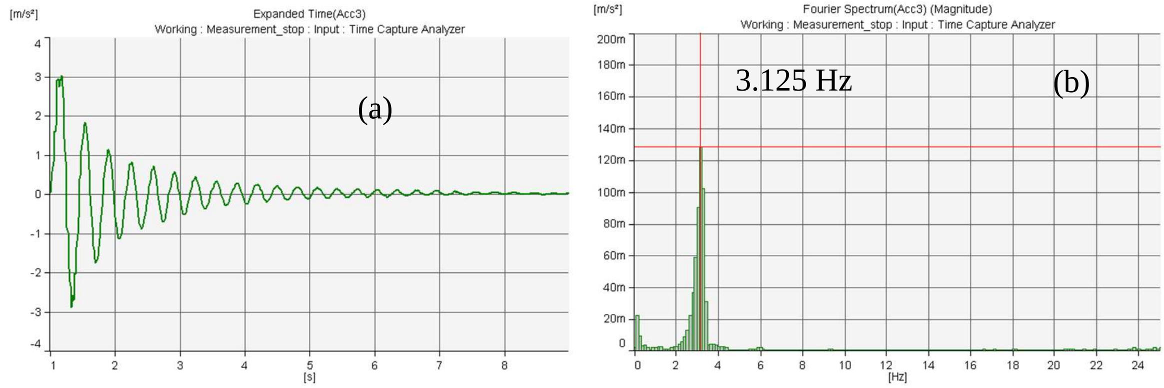


Figure 6 - Vibrations measured at the car sling after the brake was applied when approaching the bottom landing (a) time response; (b) Fourier frequency spectrum.

- It is evident that the range of resonance frequencies is close to the rotational frequencies of the diverter pulleys.

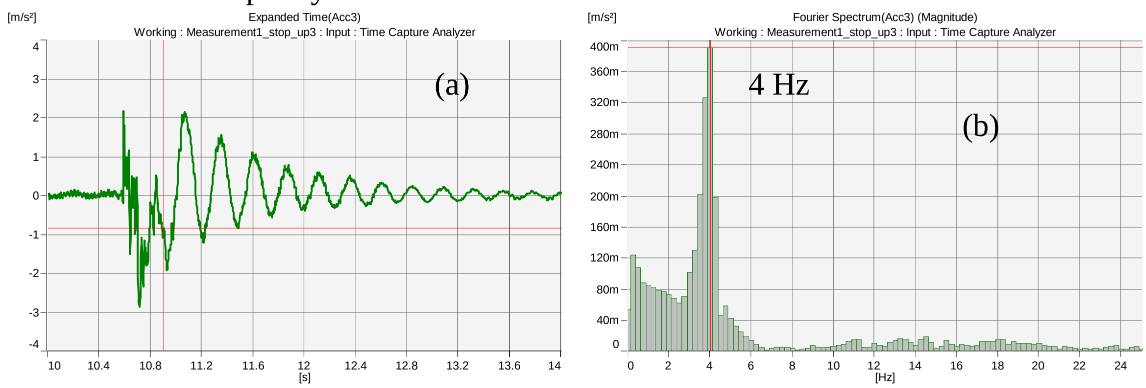


Figure 7 - Vibrations measured at the car sling after the brake was applied when approaching the top landing (a) time response; (b) Fourier frequency spectrum.

In these conditions, if the empty car mass is 15,800 kg and the rated load is 9,100 kg, the suspension stiffness coefficient, with the car approaching the bottom landing is about K_e = 10.545 MN/m, the natural frequency calculated according to equation (3) is 3.275 Hz. Assuming that the out-roundness error results in the maximum displacement $s_{\max}$ = 0.1 mm, with a small damping ratio of 1%, the maximum displacements of the fully loaded car calculated from equation (5) may reach 2.5 mm and the corresponding acceleration determined from equation (6) will be over 100 milli-g.

- The dynamic interactions between the pulleys, suspension and lift car are responsible for compromising ride quality of the system.

6 IMPROVE NOISE AND VIBRATION PERFORMANCE

The following three basic principles can be applied to mitigate the effects of / reduce noise emission and vibration in mechanical systems:

1. Prevention. To reduce the strength of the source.
2. De-coupling. To interrupt the noise/vibration path.
3. Damping. To absorp the energy of noise/vibration.

However in lift systems, due to their unique design and principles of operation, not all available measures can be applied when it comes to an issue of noise and vibration mitigation.

CONCLUSION

The assessment of the influence of noise and vibration in a PTS is based on the subjective passenger perception. Therefore there is limited evidence of how this influence can be quantified.
However, the causes of noise and vibration and their effects (reponses) can be quantified. If the excitation forces are identified the responses are determined through the application of experimental techniques and/or calculated using analytical techniques and/ or computer simulation.Relevant mitigation measures to reduce their effect can then be applied.
In regards to the key dynamic parameters that influence a PTS it can be concluded:

- PTS ride quality can be be assessed by the introduction of certain thresholds, such as the maximum acceleration, jerk and/ or noise levels. However, common limits of these values have not been agreed, as they strongly relate to market segments or country-specific acceptance levels.
- Noise and vibration can cause multiple, possibly severe damage in human physiological sub-systems. However, human response to noise and vibration is as diverse as humankind is and in most cases uncritical in PTS. However, in some cases excessive vibration might lead to failure of the design components and compromise passenger safety.
- PTS ride quality is affected by various sources of excitation that are related to elements such as rails, rail joints, roller guides, imperfect rotating components or ropes.
- The most critical phenomenom is resonance (forced vibration caused by an excitation originating from an external source), as this often leads to in instability of the vibrating system.
- Active and passive measures can be applied to mitigate the effects of resonance, noise and vibration.

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BIOGRAPHICAL DETAILS

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Lifts Without Ropes: How Many Shafts and Cars Are Needed?

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Keywords: Ropeless lifts, multi car, magnetic linear propulsion, handling capacity, quality of service, simulation, safety distance

Abstract. A new generation of lifts currently under development applies magnetic linear propulsion and does not need ropes. Shafts are shared, and lifts move in two or more dimensions. Taller and more densely populated buildings will be accommodated by adding more cars but not necessarily more shafts. Engineers planning lift installations need new ways to assess the handling capacity and quality of service provided by ropeless elevators. In this paper some traffic design principles are established by applying simple cycle time calculations. For example, shuttle lift applications are considered and compared with current roped solutions. Improving on cycle time calculations requires the development of dispatching strategies, the modelling of safety distance requirements and traffic simulation models; an overview of progress in these areas will be presented.

1 INTRODUCTION

The number of roped lifts in known lift systems is limited to one or two cars in one shaft as the suspension ropes of the lower car need to be diverted around the upper car [1]. Putting more than two cars in one shaft is limited because of the space needed by the ropes. Furthermore, traffic handling efficiency is limited by putting more than two cars in one shaft as it becomes more difficult for all cabins to serve the main entrance floors. Using a shaft for both up and down travel means that the cars need to wait until all of the cars need to reverse their direction of travel which is a constraint to improving performance. Having multiple cars running in at least two shafts circulating with one shaft being used for travelling in the up direction and the other shaft for travelling in the down direction enables improvements in performance and efficient shaft usage. An early example is the paternoster, which was the first realisation of a circulating lift system [2]. The continuous slowly circulating chain of open cabins, with no cabin or shaft doors, has limitations in travelling time, safety and transportation of handicapped passengers. Assuming a cabin to cabin distance of 3 metres, a velocity of about 0.3 m/s [3] and two passengers per cabin the handling capacity (HC5) of a paternoster is about 60 passengers/5 minutes.

For new and safe circulating multi car lift systems (MCLS), linear motors installed in the shaft lifting multi individual and independent cars are one of the main enabling technologies. The concept and idea of a circulating multi car lift system with independent moving cars is not new in the lift industry [4].

Simple traffic calculations of a circulating lift system were published based on technical assumptions as there were unanswered technical and economic questions [5]. Technical challenges using lifts without ropes/counterweights and opportunities in building efficiency for circulating lift systems were discussed [6]. Advanced two dimensional traffic systems that include horizontal passenger movement were also analysed [7, 8].

In 2014 a multi car system currently under development was unveiled [9]. Different technical innovations and solutions solve technical challenges to realise a circulating MCLS [10]. Linear motors propel multiple independent moving cars in multiple shafts. Light weight cabin designs for eight passengers enable an economical system. A certified safety system including safety brakes ensures that there is no collision. A backpack solution guides cars and enables exchanger units to move cars between shafts horizontally.

Traffic analysis of the described realistic system based on simple cycle time calculations is examined in this paper, and constraints of the cycle time are described.

2 TRAFFIC CONCEPT

With intercity trains and urban transportation different horizontal transportation systems exist and are linked together as a horizontal transportation concept. Compared to the horizontal transportation, a circulating multi car lift system needs to fit into a vertical traffic concept of a tall building.
A circulating MCLS is used as shuttle lifts between ground and sky lobbies within a vertical traffic concept [10]. Exchanger units are installed in the ground lobbies and in the upper sky lobbies. Figure 1 shows examples of how a circulating multi car lift system can be included in a vertical transportation concept. Different MCLS (S1) serve the sky lobbies of different building zones (zone 1 and zone 2). The local transportation within the building zone can be provided by traditional lift systems e.g. machine room less systems (L1 b) or by systems with two independent cars in one shaft (L1 a). The latter solution enables direct inter zone traffic. MCLS with double ground lobbies and double sky lobbies (S2) enable simultaneous loading of two cabins in a shaft. Local groups can be realized with double deck elevator systems (L2 b) or with more flexible systems with two independent cars in one shaft (L2 a). Horizontal transportation of passengers is also possible, but not considered in this paper.

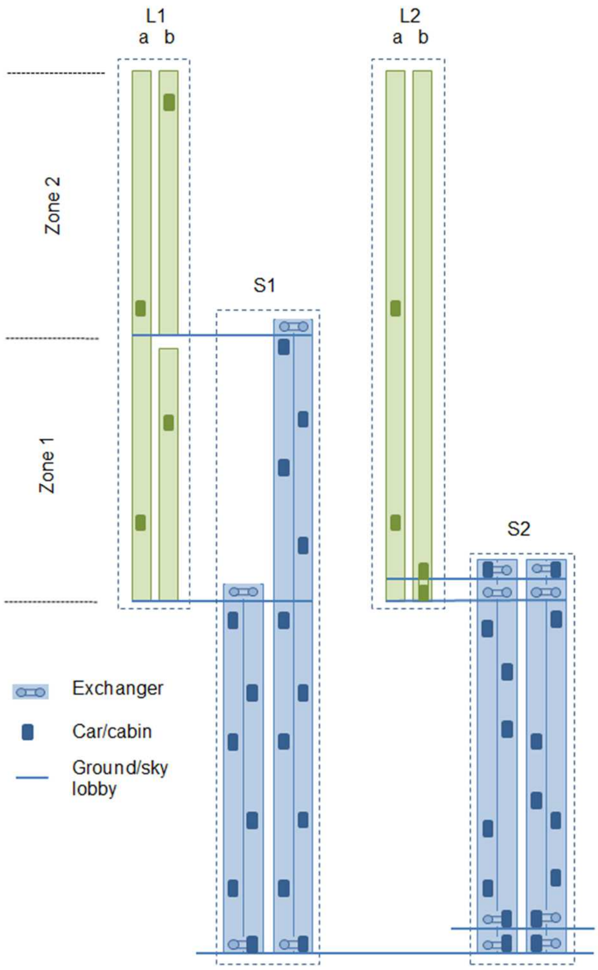

Figure 1: circulating multi car lift systems in a vertical transportation concept (examples)

3 MINIMUM POSSIBLE CYCLE TIME

The number of passengers arriving at a specific lobby that can be transported by the MCLS within a specific time can be calculated by the number of departing full cabins. The time between two subsequent cars is the cycle time.

3.1 Cycle time

The cycle time in a MCLS is the time between the departure or arrival of two subsequent cars. It also can be defined as the time between two subsequent cars passing a specific position in the shaft travelling at the same speed and in the same direction.

Figure 2 shows the vertical positions over time of two subsequent cars $D_{VCar1}(t)$ and $D_{VCar2}(t)$. Both cars are travelling in the up direction in the first shaft, are changing shafts at the top floor at 100m, and are travelling in down direction in a second shaft. While car 1 has already changed to the down direction shaft, car 2 is arriving at 100m in the up direction shaft. At the bottom floor the cars are changing shafts again. Both cars are stopping in each direction at an intermediate floor at the 50m level. The time between car 1 and car 2 is the cycle time. For a better overview the position of additional cars travelling in the MCLS is not shown. As the minimum possible cycle time is limited by the minimum distance during a complete round trip of the cars, critical situations need to be considered in detail. It is obvious that only one car can be at a specific position at the same time. If cars are travelling they are changing position continuously and make the position available for the next car. If cars are standing only one car can be at that position for the time the car is located at that position. To find the minimum possible cycle time over a complete round trip the stops of the cars need to be analysed in detail.

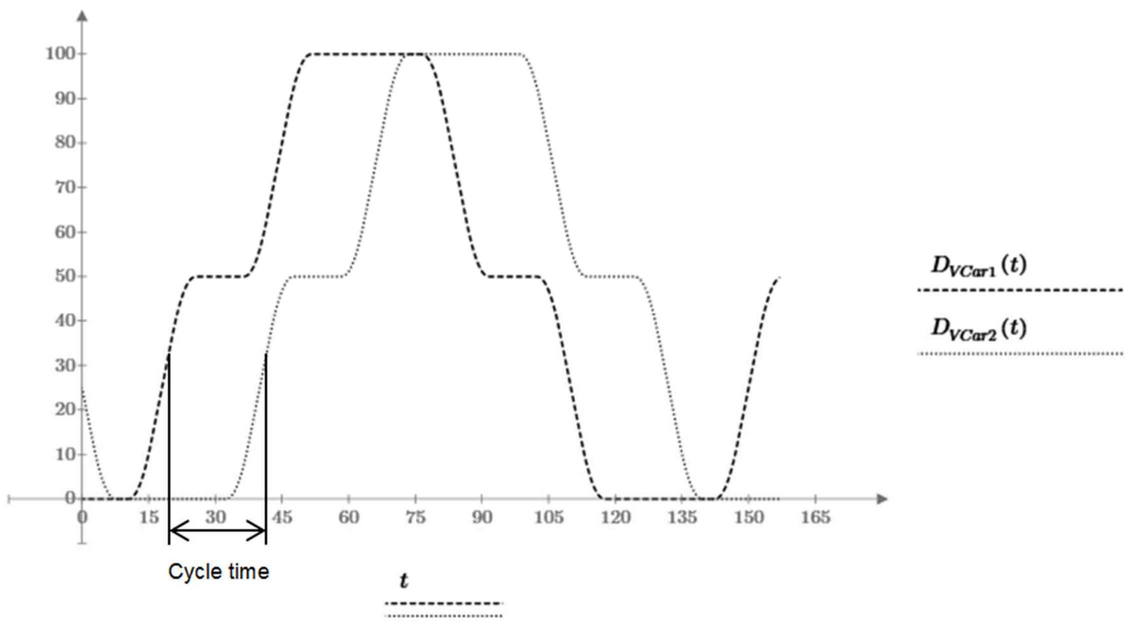

Figure 2: Vertical position of two subsequent cars

3.2 Safety distance constraints

To define the minimum possible cycle time between cars in a MCLS safety distance constraints need to be considered. There must be a minimum distance between cars at any time during normal operation. The control system responsible for an optimised handling capacity in 5 minutes (HC5) and quality of service needs to consider this minimum distance. A certified safety system triggers an emergency stop of the cars in case of violated safety distances. In addition, by enabling a controlled stop of the cars the control system monitors positions and movements of the cars and decelerates cars in unexpected situations without triggering the emergency stop. The controlled stopping of cars includes the same or higher jerk and deceleration rates than normal operation rates.

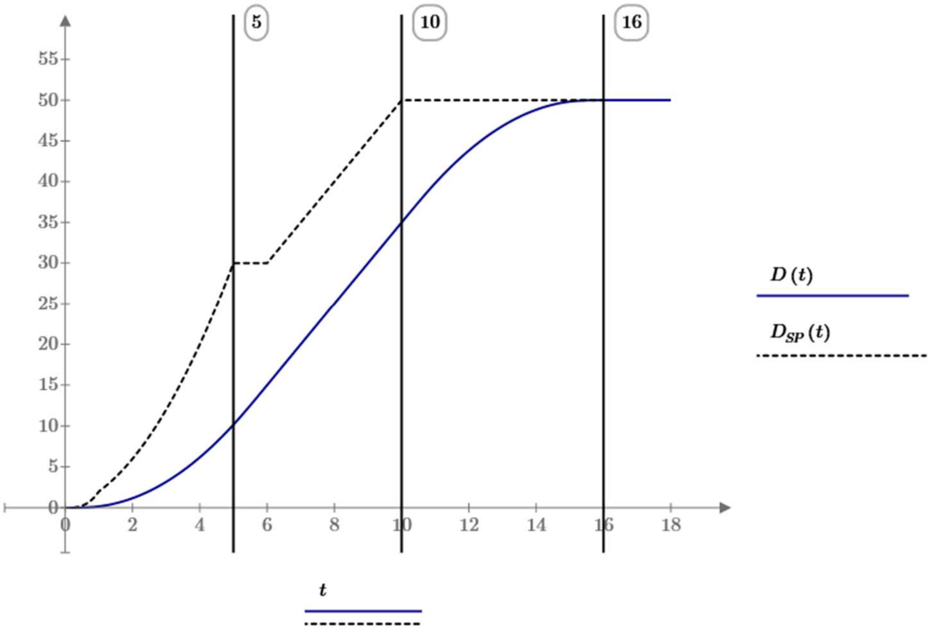

Figure 3: position (D(t)) and stopping point (D_{SP}(t)) of a car

A stopping distance and a stopping point of the controlled deceleration can be calculated at any time [11]. In case of violating any minimum distances between cars, the cars can be stopped by executing controlled deceleration. Figure 3 shows the position of a car over time (D(t)) and the stopping point (D_{SP}(t)) after a spontaneous controlled deceleration with rated deceleration values. If the lift is in the deceleration process to the 50m level (10s-16s) the spontaneous controlled deceleration cannot stop the car earlier if the rated values for deceleration and jerk are used. The stopping point is also constant if a spontaneous deceleration is started during the end of the acceleration process (5s-6s) while the acceleration is reduced by a negative jerk. The controlled deceleration can also be operated with higher values for deceleration and jerk. To calculate a safe position of another car, a minimum distance which includes the car height needs to be added to the stopping position.

3.3 Exchanger

To analyse the stop at an exchanger unit the design of the exchanger unit and the process of exchanging cars between shafts needs to be considered. The analysis is based on a backpack solution including the linear motor and car guidance [10]. The shaft elements are able to rotate by 90°. Cars can move horizontally. Passengers can load and unload during the rotation process since the cabin is held in an upright position. Figure 4 shows a simple example of the functionality of the exchanger unit.

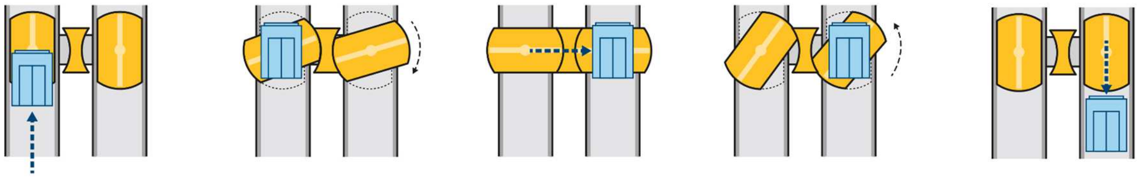

Figure 4: Exchanger functionality

3.4 Calculation of the minimum possible cycle time

As the bottle neck of the minimum possible cycle time (t_{Cy}) is when cars are stopping, these are the situations analysed. This includes the stops at the exchanger units and intermediate stops where both cars are stopping successively.

Cycle time at an exchanger landing: The minimum cycle time at an exchanger landing (t_{CyEx}) with passengers loading and unloading can be calculated with equation (1).

The passenger transfer during the standing time (t_{Stand}) of the cabin can be done in parallel to the exchanger preparation time t_{Ex} (rotation of the shaft element) for the following horizontal or vertical movement.

$$t_{CyEx} = t_{Arr} + \max(t_{Stand}, t_{Ex}) + t_{Dep} + t_{Ex} \tag{1}$$

After the time a previous/front car has departed from the exchanger unit (t_{Dep}), the next car arrival time (t_{Arr}) is the time that it takes a car to arrive after the time the exchanger unit has been prepared for the next car (t_{Ex}). A long car arrival time (t_{Arr}) for the next car may enable the parallel preparation of the exchanger after the previous/front car has departed the exchanger landing.

The standing time (t_{Stand}) is calculated with equation (2) and includes passenger transfer times (t_p), average number of passengers in the car (P) and door times (door open time: t_o, door dwell: t_{dwell}, door closing time: t_c).

$$t_{Stand} = t_o + P\, t_p + t_{dwell} + t_c \tag{2}$$

Cycle time at an intermediate floor (both stopping): The minimum cycle time at an intermediate floor with two subsequent cars stopping at the same floor (t_{CyF2}) can be calculated with equation (3). The time between departure of the front car 1 and the arrival of the following car 2 (start to stop time t_{s2s}) depends on the stopping distances and minimum distances between cars and is shown in figure 5. The safe position for car 1 related to car 2 is shown with $D_{2SfP}(t)$ and depends on the position, stopping point of a controlled deceleration with rated values of car 2 and an additional minimum distance between car 2 and car 1. The safe position must not touch the position of car 1.

$$t_{CyF2} = t_{Stand} + t_{s2s} \tag{3}$$

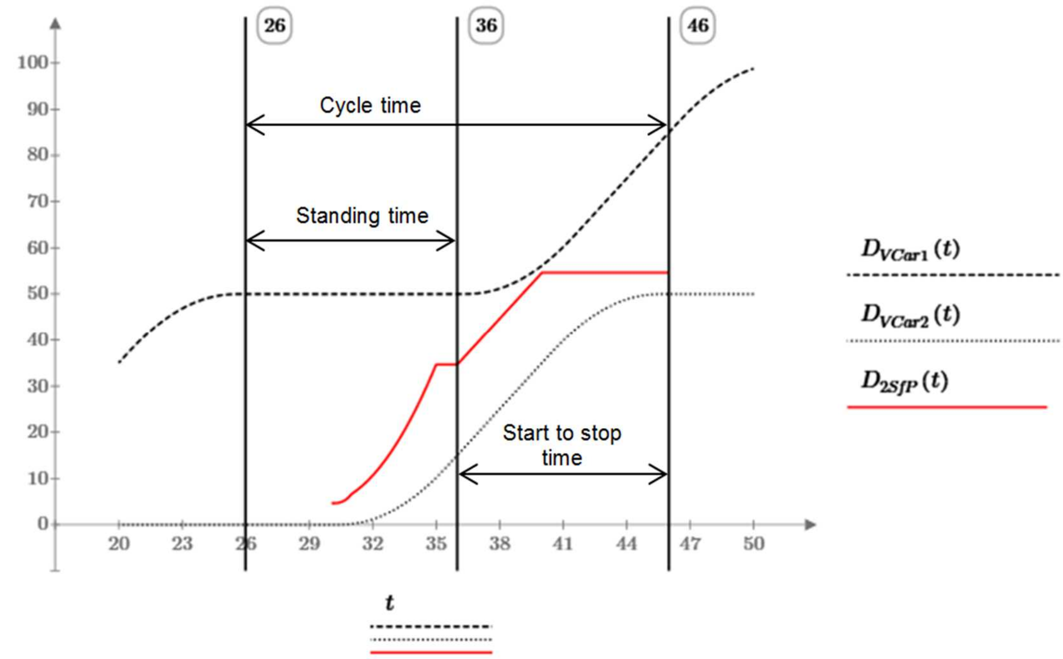

Figure 5: Cycle time at an intermediate floor

The situation with the longest minimum cycle time is the minimum possible cycle time of the MCLS and is defined with equation (4).

$$t_{Cy} = \max(t_{CyEx}, t_{CyF2}) \tag{4}$$

4 HANDLING CAPACITY

To use a circulating multi car system in a vertical traffic concept, it is necessary to know the handling capacity in 5 minutes (HC5). As the lift system is different to traditional lift systems, the known equations need to be adapted to the new system.

4.1 General

The handling capacity for incoming passengers can be calculated with the simple equation for conventional lifts using the interval (INT) and number of passengers per cabin (P) (see equation (5)) [12]. This is also true for a circulating MCLS.

$$UPPHC = \frac{300s*P}{INT} \tag{5}$$

The interval (INT) of a group of circulating MCLS is defined by the average cycle time (t_{Cy}) and the number of MCLSs (N_S) (see equation (6)).

$$INT = \frac{t_{Cy}}{N_S} \tag{6}$$

The handling capacity for incoming passengers in an up direction is independent from any down traffic or traffic between upper floors (e.g. sky lobbies). Additional down traffic will affect the RTT of a cabin because of passenger transfer times and door times of existing or additional stops. If the RTT of the cabins change/increase then the number of cabins or the speed of the cabins needs to be adapted accordingly in order to keep the average cycle time between subsequent cars to a constant value.

4.2 Cabin size

Increasing the cabin size will increase the handling capacity, especially in shuttle applications. However, in shuttle applications the HC5 is not a linear function of the cabin size. Doubling the cabin size does not double the HC5 as passenger transfer times and cycle times increase.

4.3 Double entrance

As handling capacity is limited by the passenger loading and unloading time, double entrance lobbies (two lobbies above each other) enables simultaneous loading of two cabins which increases the handling capacity. For a circulating MCLS each entrance level may have an exchanger unit enabling a parallel exchanging of two cars (see Figure 1 – S2). The cycle time is now measured between two pairs of cars (see figure 6), therefore double the number of passengers can be transported per cycle time. The cycle time will increase slightly since the arrival time and the departure time of two cars at a double lobby/floor is longer compared to a single car stopping at a single floor.

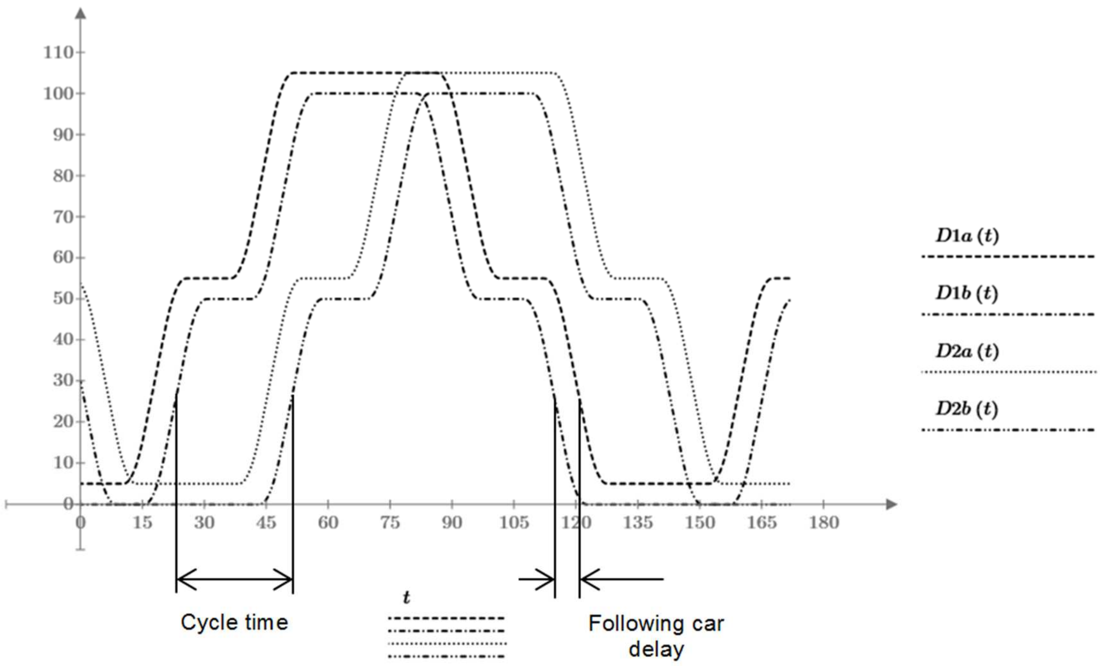

Figure 6: Cycle time between two pairs of cars

5 NUMBER OF CABINS

The number of cabins (N_C) in a circulating MCLS depends on the round trip time (RTT) and the cycle time (t_{Cy}). It can be calculated with equation (7).

$$N_C = \frac{RTT}{t_{Cy}} \tag{7}$$

This is also illustrated with figure 7. It shows a complete round trip of a car (D1(t)). The round trip time is divided by the cycle time and shows every position of the car after a period of the cycle time. These positions equal the current position of the other cars in the MCLS at time t=0, which is shown with the two shafts of a MCLS in figure 7. With double entrance configurations and pairs of cars the number of cars is doubled.

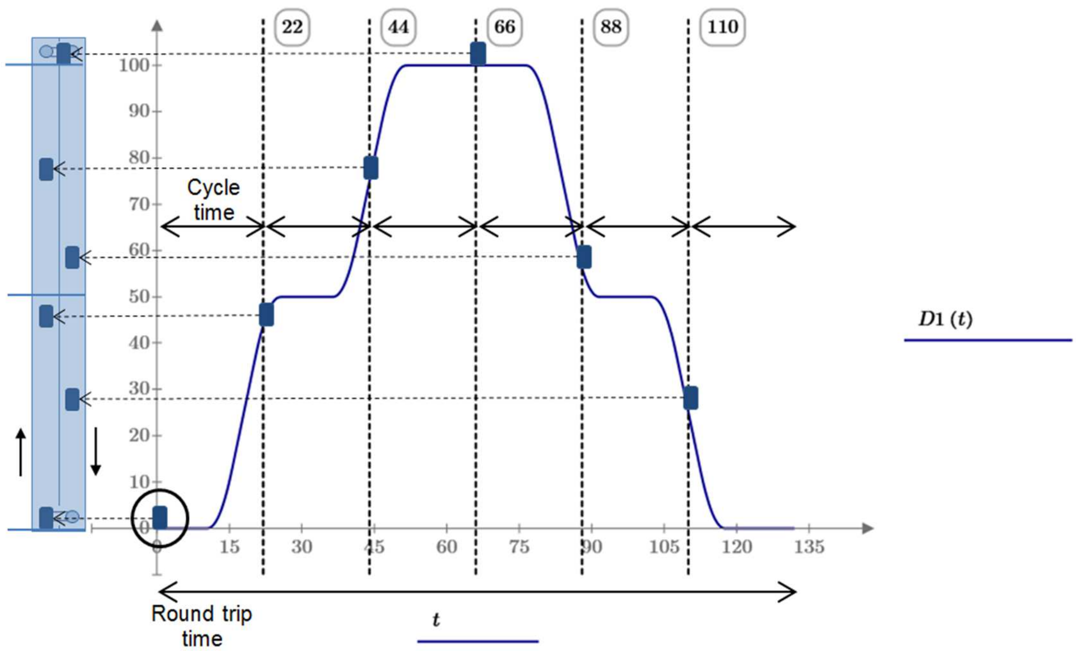

Figure 7: Cycle time, RTT and number of cabins

It is only possible to put an integer number of cars into the system. In case of an unchanged round trip time (RTT) and rounding down the number of cars/the result of equation (7), the real average cycle time (t_{CyR}) will be higher than the minimum possible cycle time (see equation 8). To achieve the same handling capacity the round trip time (RTT) needs to be reduced, e.g. by increasing the speed of the cars.

$$t_{CyR} = \frac{RTT}{N_C} \tag{8}$$

In case of rounding up the number of cabins/the result of equation (7) the average minimum possible cycle time cannot be reduced because it is limited to a minimum. The RTT needs to be increased according to equation (9) to avoid traffic jams, e.g. by reducing the speed of the cars.

$$RTT = N_C * t_{Cy} \tag{9}$$

6 QUALITY OF SERVICE

As the major measure of quality of service is waiting time, the waiting time derived from the cycle time and interval may be the main measure [12]. However, travelling times and the number of stops also need to be considered. In multi car applications additional delays may be included as quality measures [13].

The maximum HC5 for conventional rope elevators is achieved in a two stop shuttle application. The RTT is kept to a minimum. Using RTT calculations the quality of service, interval and waiting time can be optimised.

For a circulating MCLS the HC5 is independent from the number of stops. In addition, the waiting time - e.g. in the main entrance - can be kept to a minimum, but additional delays during the journey will affect quality of service. In applications where all cabins have the same stops these additional delays can be reduced to a minimum or completely avoided through synchronisation of the cars. This can be compared with an underground train for urban transportation. Every train of a specific line has the same stops with a similar stop time. If one train cannot pass another train additional delays can be avoided during normal operation of the system.

Allowing individual stops for each car limits the options to avoid these delays without sacrificing HC5 as cars cannot pass each other. More sophisticated controls allocating passengers to cars can help improve the situation. This requires advanced passenger guidance, good indication and passenger awareness that cars loaded from the same landing door travel to different destination floors. This is unexpected by most lift passengers and could be confusing; it may be an option in the future.

Therefore the shuttle application with one or multiple sky lobbies is preferred as it ensures good quality of service with maximum possible handling capacity.

7 COMPARISON OF SHUTTLE LIFT SYSTEMS

Consider a MCLS when compared to traditional double deck lift systems in a shuttle lift application. Figure 8 shows the compared configurations. The comparison is based on the cycle time calculations for the MCLS described in this paper and RTT calculations for the double deck system. Different travel heights will be compared: 100m, 200m, 300m, 400m, 500m and 600m. Table 1 shows the parameters of both systems. The traffic split is 80% incoming and 20% outgoing passengers equally distributed to both lobbies. Figure 9 shows the chosen velocity and number of cabins and the HC5 and interval depending on travel height.

Table 1: parameters of both systems

	Double Deck	MCLS
Space shafts + waiting area	36 m² + 18 m²	24 m² + 12 m²
Passenger/car	2x16	8
Number of cabins	2x4	variable
Velocity	variable	variable

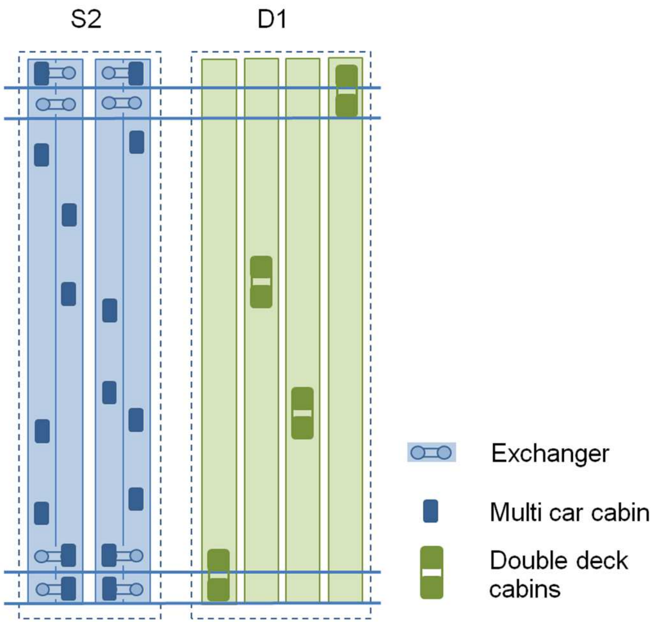

Figure 8: Comparison of a group of circulating multi car systems with a double deck group

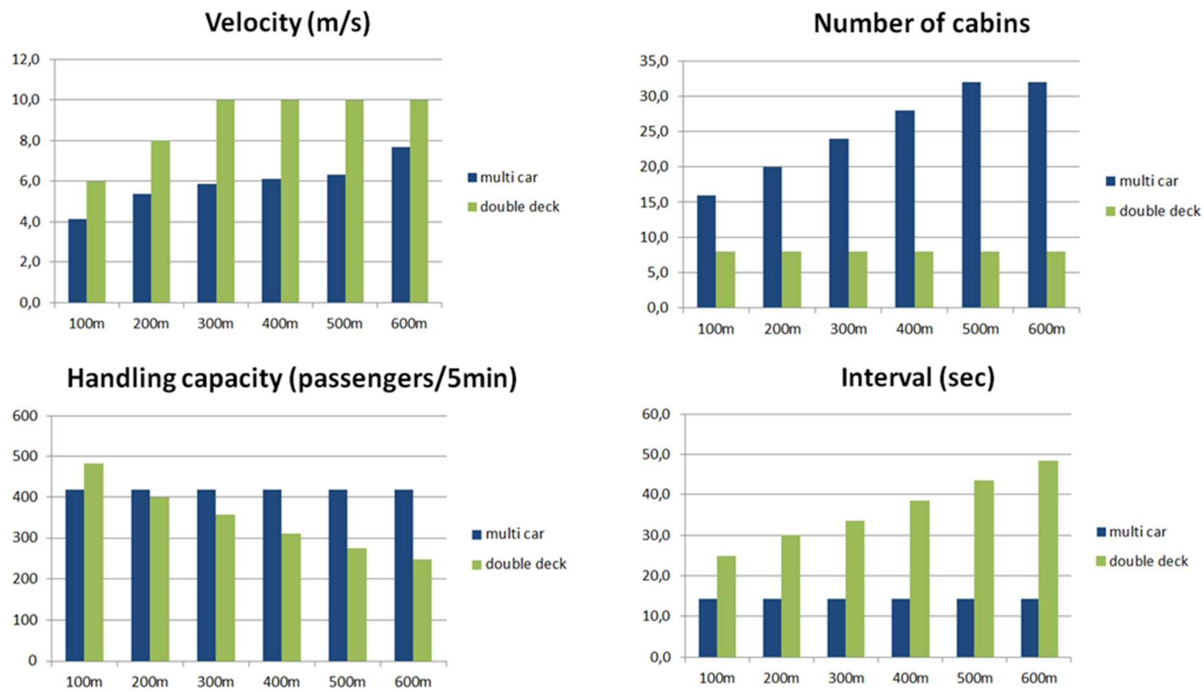

Figure 9: Comparison multi car vs. double deck depending on travel height: handling capacity, velocity, number of cabins and interval

The handling capacity of the multi car system is constant, independent from the travel height. Starting with a travel height of about 200m, it is going to be higher than the compared double deck system. With increasing travel height, the benefit of the circulating MCLS can be seen. To keep the handling capacity constant at the MCLS for every travel height the number of cabins required needs to be adapted for the MCLS without additional shafts. Without adding any shafts the number of cabins for the four double deck shafts is constant.

With increasing travel height the rated velocity is increased for both systems. The velocity of the MCLS is lower than the velocity of the double deck.

The average waiting time (AWT) and average transit time (ATT) of both systems is compared in figure 10. The relationship between interval and waiting time is complex [14]. For simplicity, in these results the average waiting time of roundtrip time calculations is taken as 50% of the interval.

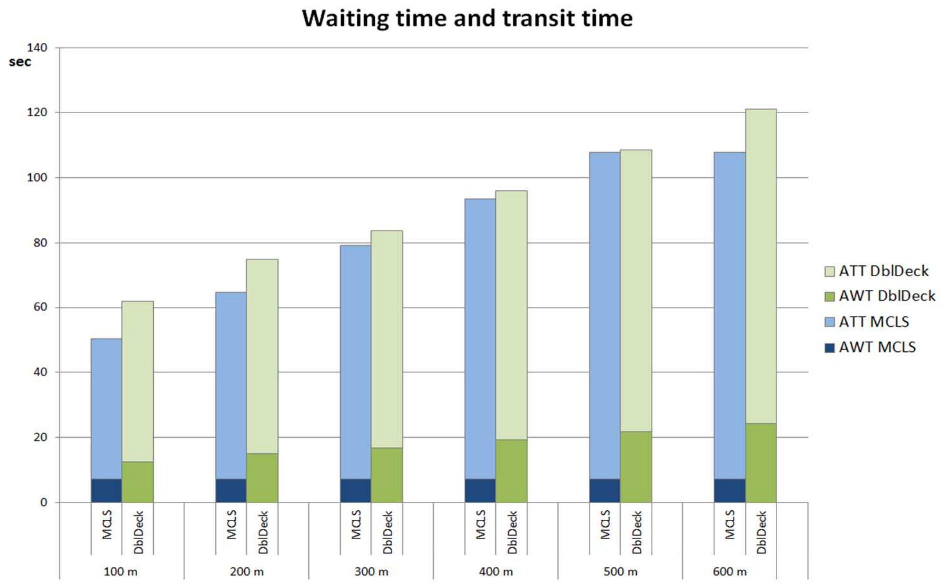

Figure 10: Comparison multi car vs. double deck depending on travel height: average waiting time (AWT) and average transit time (ATT)

Since the interval of the multi car is constant, the average waiting time is constant. Although the chosen velocity of the multi car is less than the double deck, the time to destination of the MCLS provides better values. This is caused by lower average waiting times and shorter passenger loading/unloading times.

8 CONCLUSION

Handling capacity for a circulating MCLS is based on the minimum possible cycle time of the system. The minimum possible cycle time of a circulating MCLS is discussed and defined in this paper. If the average RTT of a MCLS increases, the number of cars has to be adapted in order to keep the minimum possible cycle time and a constant handling capacity. To achieve the minimum possible cycle time without traffic jams the velocity is also adapted. Safety distances and stopping distances needs to be calculated and considered in order to calculate reasonable values for the minimum possible cycle time.

Based on a cycle time and RTT calculations a circulating MCLS and a double deck system are compared with different travelling heights in a shuttle application. The MCLS provides constant values for handling capacity and average waiting time with increasing travelling heights by adding more cars to the system. Also short cycle time enables short average waiting times.

These values need to be proven by simulation. Advanced control algorithms may also enable additional MCLS applications.

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BIOGRAPHICAL DETAILS

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Selling Lifts in the Late 19^{th} and Early 20th Century

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Keywords: History, Lift Manufacturers, Catalogs.

Abstract. Among the most interesting artifacts associated with the history of lifts are manufacturers' catalogs. The audiences for these documents included architects, building owners, engineers, and other lift manufacturers. These catalogs typically included detailed descriptions of lift types and individual components, which were accompanied by illustrations and accounts of specific installations. The catalogs also often described normative use patterns, which allows a unique glimpse into the world of late 19^{th} and early 20^{th} Century lift operation. Finally, the advertised critical virtues of lift system were similar to contemporary products: they were described as safe, efficient, and economical. The catalogs examined for this paper include those published by Brady & Thornborough, R. Waygood & Company, Archibald Smith & Stevens, William Wadsworth & Sons, Ltd., and H. Breakell & Co. (Blackburn) Ltd.

1 INTRODUCTION

The typical lift catalog in the late 19^{th} and early 20^{th} century included text that highlighted the technical virtues and qualities of a company's products, illustrated various lifts and lift components or accessories, and contained testimonials from satisfied customers. Catalogs were also often published with the specific goal of educating the reader on topics such as lift safety, technology, application, and use. The goal was to lead the reader to the inevitable conclusion that the manufacturer offered the safest and most technologically innovative lift on the market, which was ideally suited to the reader's needs.

The catalog author faced a distinct challenge in that he was writing for several different audiences: engineers, architects, and building owners. In addition to these target audiences, the authors of lift catalogs also, occasionally, aimed their rhetoric at their industry rivals. Although rivals were rarely mentioned by name, the phrases and language employed often allowed readers familiar with the lift industry to perceive these subtle commercial attacks. The following examples illustrate all of the topics referenced above and also reflect the diversity of lift catalogs published during this period.

2 BRADY & THORNBOROUGH

Brady & Thornborough of Manchester was a typical representative of an important type of 19^{th} century lift manufacturer. The company primarily advertised itself as "Manufacturers of Patent Revolving Shutters in Wood, Iron or Steel" [1]. However, in their advertisements this designation was often followed by – in much smaller type – a listing of their secondary line of products, which included "Improved Self-Acting Sun Blinds, Hoists and Lifts & Patent Swivel Partitions" [1]. The capacity of a general manufacturing firm to build lifts was predicated on the perceived mechanical simplicity of systems used in small commercial and light-industrial buildings.

Brady & Thornborough's 1887 catalog devoted two of its twenty-three pages to hoists and lifts. These products included hand-powered lifts, dinner lifts (dumbwaiters), and goods and passenger lifts. The latter could be powered by a gas or steam engine or by line shafting. The catalog's advertising copy is intriguing because the term *elevator* was used to describe their two primary lift systems: one was referred to as a "self-sustaining elevator" while the other was identified as a "goods & passenger elevator" (Fig. 1). The former was essentially a hand-powered platform lift that could be fitted with a "power gear" driven by line shafting. The goods & passenger lift utilized a belt-driven winding drum machine and featured an enclosed car. Although the catalog copy referenced safety devices, the text implied that these were not standard features: "Safety apparatus is fitted to the cages, when required, on the most approved principle" [1]. This statement raises several questions about the use of safeties, such as: why would they only be installed *when required*? The use of the phrase "on the most approved principle" was also commonly employed when a manufacturer wanted to avoid having to identify a specific technical solution to a difficult problem.

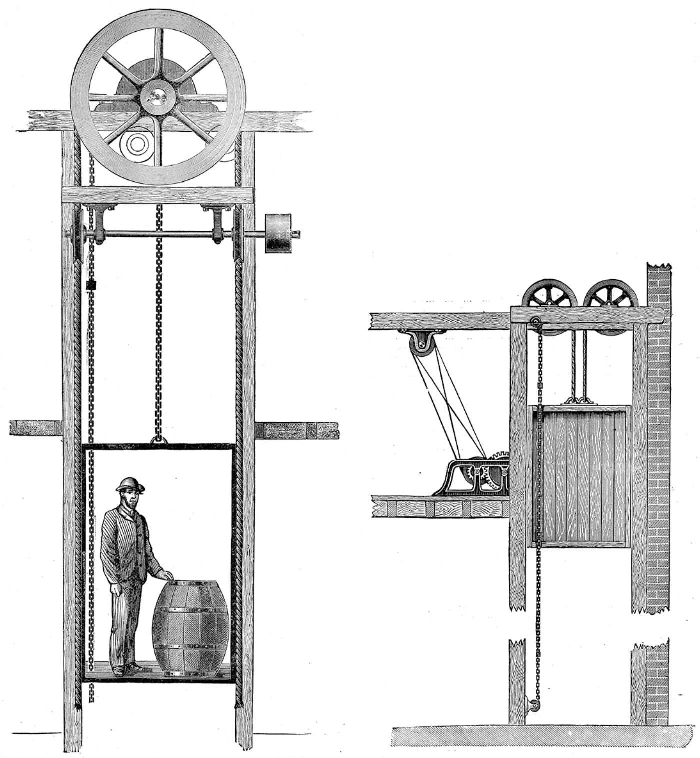

Figure 1. Brady & Thornborough's Self-sustaining Lift (left); Goods & Passenger Lift (right)

3 R. WAYGOOD & COMPANY

R. Waygood & Co.'s 1889 catalog left no doubt about the importance of lift safety and the specific means with which it was ensured. By the late 1880s Waygood was one of the country's leading lift manufacturers and they described themselves as "hydraulic engineers" who specialized in high and low pressure "hydraulic lifts and elevators" [2]. They also manufactured "all kinds of lifts and hoists for passengers, merchandise or food," which were "worked by hand power, gas, or steam" [2]. The firm could readily provide "designs and estimates for fitting up lifts in clubs, restaurants, offices, hotels, mansions, factories, public and private buildings" [2]. Their catalog's title, graphic presentation and content, reflected their commercial success and specialization. The cover title was *Hydraulic passenger Lifts: A Guide to Intending Purchasers*. The secondary, interior title was, in typical 19th century fashion, longer and even more descriptive: "Hydraulic Passenger Lifts: A comparison of the distinguishing characteristics of direct-acting and suspended lifts and of high-pressure and low-pressure systems for the guidance of those interested in the adoption of high-class work" [2].

The catalog opens with a statement about the current perception of lifts: “As the prejudice which at one time existed against Lifts (or Elevators are they are called in America,) has given place to an almost universal appreciation of their utility they are being more generally used, and … no important edifice is considered complete by Proprietor, Architect, or Tenant without one” [2]. The reference to America and elevators is intriguing and may have hinted at an interest in expanding the company’s presence across the Atlantic. In 1889 Waygood had offices in London, Liverpool, and Birmingham, agents who represented them in Amsterdam, and a full branch office in Melbourne, Australia. Thus, the prospect of a branch office in America may have also been under consideration (in the 1890s Robert Carey of Waygood pursued two U.S. patents for hydraulic lifts).

Although the catalog provides descriptions and illustrations of three different hydraulic lifts – their Patent Hydraulic Balanced Direct-Acting Lift, Patent High-Pressure Suspended Lift, and Low-Pressure Suspended Passenger Lift – the catalog’s goal was to convince readers that “Waygood’s Patent Hydraulic Balanced Direct-Acting Lift” was the “best class of lift” available (Fig. 2). The lift employed a “companion cylinder” or accumulator that provided the required water pressure to elevate the ram and car. Although they marketed “suspended lifts,” they claimed that their direct-acting lift was “inherently safer than those which depend upon the support of chains or ropes” [2]. The direct-acting lift also had an aesthetic advantage: “In point of appearance a Direct-acting Lift balanced by hydraulic pressure commands a very marked preference, especially if the Lift is to be fixed in a handsome staircase; as this arrangement avoids the overhead beams, sheaves, and ropes or chains, which constitute a disfigurement and obstruct the light” [2].

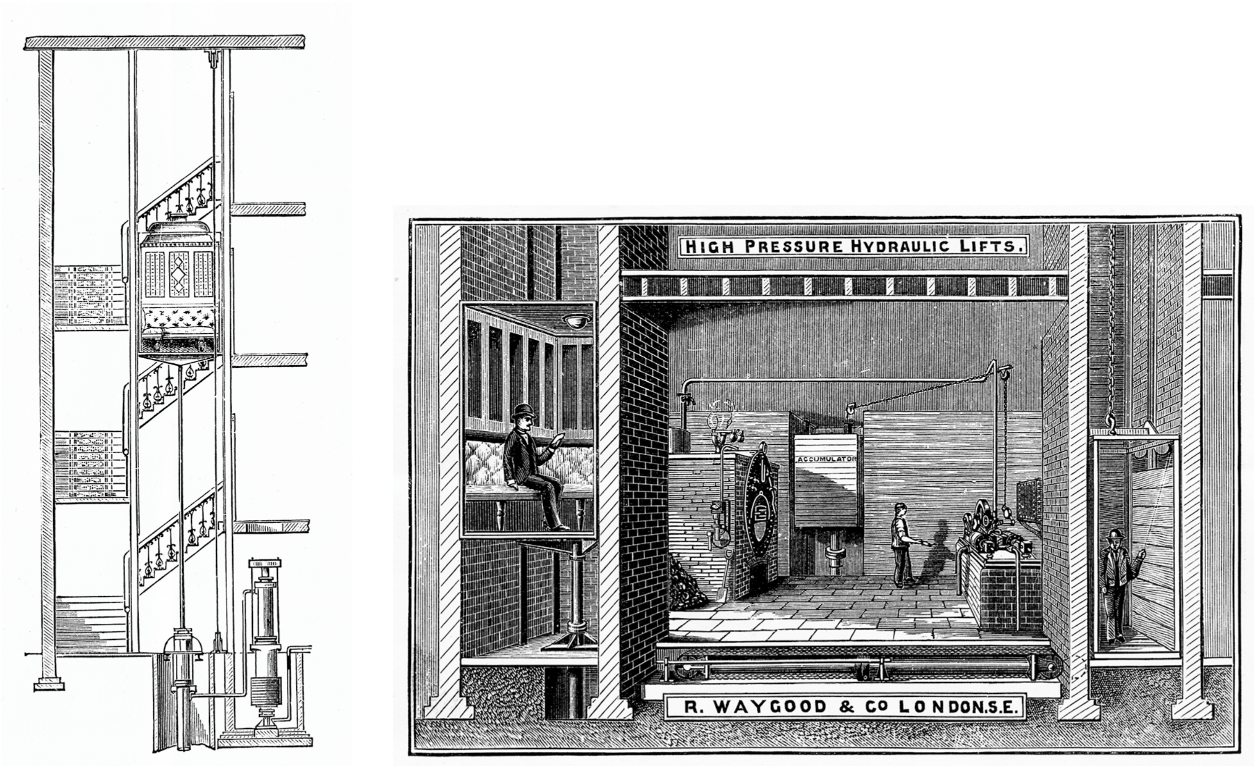

Figure 2. Waygood’s Patent Hydraulic Balanced Direct-Acting Lift (left); Waygood’s High-pressure Hydraulic Plant (right)

In addition to illustrations of the three types of hydraulic lifts. The catalog includes a drawing of a “high-pressure hydraulic plant” that provided power to a direct-acting lift on one side and a suspended lift on the other (Fig. 2). A close reading of the image reveals the presence of a boiler on the left, a massive accumulator in the center, a small steam engine and pump (with an associated array valves and controls) on the right, and the horizontal hydraulic cylinder of the suspended lift located under the floor. Addition details include the well-dressed gentleman seated on the bench in the passenger car, and the standing passenger on the right who appears to holding the lift's shipper or control rope. This relatively complete depiction of a lift mechanical room is somewhat unusual and offers a rare glimpse into this aspect of early lift history.

4 ARCHIBALD SMITH & STEVENS

The title of Archibald Smith & Stevens 1905 catalog – *Notes on Electric Lifts* – emphasized the publication's educational focus. This was, in fact, the third edition of this catalog and the rationale behind its publication was clearly stated in the introduction: "In placing before you a third edition of our notes on this subject, we have taken the opportunity of bringing it up to date, and it thus becomes more than ever a Record of Results obtained in practice. The careful purchaser will place more reliance upon a sober statement of results achieved, than upon a glowing series of promises as to future performance, and we therefore submit the following notes chiefly as a statement of accomplished facts. Where deductions are drawn it should be remembered that they are based on a continually growing volume of facts, and it is gratifying to find that every statement put forward in earlier editions is fully confirmed by the additional data now available" [3]. This introduction, titled "A Record of Actual Results," represents a well-crafted advertising strategy in its precise use of words: *careful purchaser*, *results* and *practice* versus *promises*, and *accomplished facts* [3]. It compliments the potential client on their intelligence for making a decision based on facts and established a calm, confident narrative tone that was sustained throughout the catalog.

It must be remembered that, in 1905, the electric lift was a relatively new development and it faced strong competition from hydraulic lift systems, which dominated the marketplace. This context doubtless determined the focus and content of the catalog's first section: "What type of Lift shall I adopt?" This section was devoted to a detailed comparison of electric and hydraulic lifts with the goal of answering the question found in the title. The catalog's author noted: "This question confronts the Architect and the Property Owner, who, in the babel of conflicting claims, are sorely puzzled as to what they may accept as reliable. The object of these notes is to offer some assistance towards the elucidation of the problem, in the shape of a brief statement of facts culled from experience" [3]. While the "brief statement of facts" included thorough descriptions of the merits of both hydraulic and electric lifts, Archibald Smith & Stevens' primary argument was summarized in two tables.

The first table provided comparative cost data for three electric lifts, five hydraulic suspended high-pressure lifts, one hydraulic suspended low-pressure lift, and one hydraulic ram lift (Fig. 3).

Type of Lift.	Load.	Source of Power.	Travel in Feet.	Cost of Average Round Trip Up & Down in Pence.	Number of Trips per penny.	Remarks.
Electric	7 cwt.	Birmingham Corporation ...	50	·072	13·6	Observed. Conditions ordinary. Current at 2½d. Test covered 40 round trips with full load.
Hyd. Suspended H.P. ...	7 cwt.	Manchester Corporation ...	50	·29	3·45	Calculated from Published Scale.
Hyd. Suspended L.P. ...	7 cwt.	Town Supply	50	·445	2·2	Calculated at 6d. per 1000 Gallons. Pressure, 50 lbs.
Electric	9 cwt.	Private Supply	50	·066	15	Observed. Conditions ordinary. Current at 2½d.
Hyd. Suspended H.P. ...	9 cwt.	London Hyd. Power Co. ...	50	·237	4·22	Calculated from Published Scale.
Electric	9 cwt.	Glasgow Corporation ...	50	·066	16·4	Observed. Current 2½d.
Hyd. Suspended H.P. ...	9 cwt.	Glasgow Corporation ...	50	·212	4·7	Calculated from Published Scale.
Hyd. Suspended H.P. ...	12 cwt.	London Hyd. Power Co. ...	50	·287	3·48	Observed.
Hyd. Suspended H.P. ...	9 cwt.	London Hyd. Power Co. ...	50	·235	4·25	Observed.
Hydraulic Ram. H.P. ..	12 cwt.	London Hyd. Power Co. ...	50	·344	2·9	Observed.

Figure 3. Table 1. Comparative Cost of Working Hydraulic and Electric Lifts, Archibald Smith & Stevens, *Notes on Electric Lifts* (1905)

The table includes information on load, power source, travel distance, average round trip cost, and number of trips per penny. The efficiency and economy of the new technology was evident by the fact that the three electric lifts made an average 15 trips per penny while the seven hydraulic lifts made an average 3.6 trips per penny. The table also includes a column titled "remarks," which indicates how the cost data was determined: in six cases the lift was "observed" and in four cases the information was "calculated from published scale" [3]. Although the term "observed" is undefined, if it is assumed to mean both the literal observation of a machine in action and the accurate measurement of its power consumption, then the data contained in the table supports Archibald Smith & Stevens' statement of using facts and actual results to assert their claim of greater efficiency. The second table provided annual operational cost figures for the company's various electric lift types with the detailed cost figures given in pounds, shillings and pence. The average annual electric lift cost was £8 5s. 4d., while the average annual cost of operating a hydraulic lift was £15 11s. These tables, and their associated text, allowed Archibald Smith & Stevens to proclaim: "The only conclusion possible is that the Electric Lift is relatively a most economical machine as regards power" [3]. The statement's wording is a perfect example of a *mostly* definitive statement that is carefully modified by the word "relatively."

The remainder of the catalog addressed a variety of topics including repairs, types of current, machine drives (direct coupled or belt and counter shaft), and controls (hand-rope, electric switch or push button). The catalog noted that, when the company "first commenced the manufacture of electric machines" they were "doubtful" regarding the annual repair costs associated with this new technology [3]. However, after "a few years of practical working" they realized that the annual repair cost was "almost negligible" and that a "well designed electric lift" required "less repair than any other form of lift" [3]. A survey of repair work they had done on their machines revealed that the annual cost to their customers was £2 19s. The other technical features are described with the same clear, straightforward prose employed throughout the catalog. In addition to this precise prose, the catalog also contained thirteen black-and-white photographs: eleven that depict various lift machines and two that depict passenger machines with cars (Fig. 4).

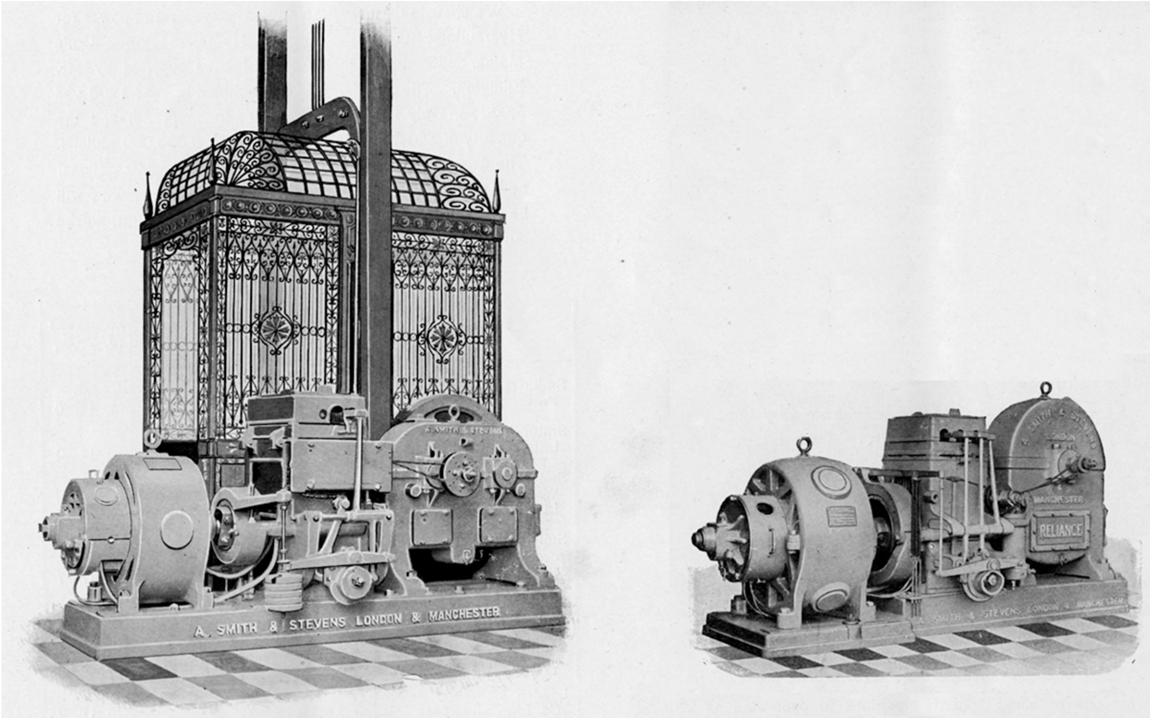

Figure 4. Archibald Smith & Stevens' Passenger Lift with Art Ironwork Cage and Four-pole Motor with Balanced Gearing (left); Ten cwt. Passenger Gear, 1902 Pattern (right).

The catalog's final section had a question for a title: "What are the essentials of a good electric lift?" Archibald Smith & Stevens' answer to this question was predictable: "Our best answer to this question is obviously a description of the machine which we have gradually perfected during several years of manufacturing experience, combined with close observation of results" [3]. While this statement reinforced the integrated themes of practical experience and a results-based-design strategy, the general description of their electric lifts that followed was aimed at their competitors: "Our electric lift is not a miscellaneous collection of unrelated parts separately designed for various purposes, and gathered together from all quarters, but is a carefully considered and harmonious arrangement, designed specially for the purpose in view, every detail being in perfect relationship to its fellows, and specially adapted to the peculiar requirements of lift service" [3]. It was common practice in the early 20th century for electric lift manufacturers to build the winding drum, safeties and mechanical components and then purchase the electric motor, controller and other electrical components from companies that specialized in their production. Only the leading companies had the resources to manufacture an entire electric lift system. Archibald Smith & Stevens also sought to set themselves apart from their perceived leading industry rivals. They described their electric lift as "the first, and we believe, so far, the only entirely British-made machine on the market" [3]. This statement was likely aimed at Otis who had established the American Elevator Company in London in 1885, which had become the Otis elevator Company, Ltd. (London) in 1900.

5 WILLIAM WADSWORTH & SONS, LTD.

Whereas Archibald Smith & Stevens quietly claimed to build the “only entirely British-made machine on the market,” William Wadsworth and Sons, in their circa 1920 catalog proudly proclaimed (in bold type face) that their electric lifts were “British Built Throughout” [4]. In fact, this phrase appeared throughout their catalog, which was titled *Wadsworths Lifts, Transporters, Hoisters*. The 168-page catalog was not, however, evenly divided between these three topics. Information on electric lifts filled 120 pages, with 36 pages devoted to transporters (self-landing and delivering hoists) and 12 pages addressed hoisters (job cranes, friction hoists, hand lifts, etc.). The catalog’s graphic design also reflected this content division: each page had a decorative border that featured the company’s name, hoisting sheaves, lift machines, and a declarative phrase. In the section on passenger and goods lifts Wadsworth announced that they were “Electric Lift Specialists” and in the sections on transporters and hoisters they were simply “Engineers” [4]. Other more subtle differences in the border design included different engines, gearing, and the presence of a car versus a lorry (Figs. 5 & 6).

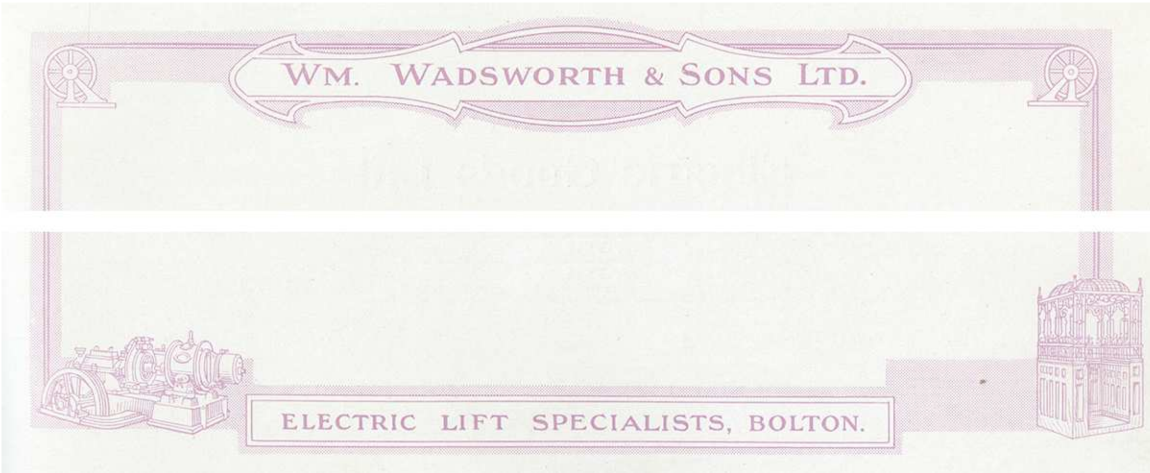

Figure 5. Header and Footer Design, *Wadsworths: Lifts, Transporters, Hoisters* (c. 1920).

Wadsworth’s catalog copy embraced several of the themes employed by Archibald Smith & Stevens, however, the landscape of the lift industry had clearly shifted during the 15 or so years between the two publications. Wadsworth claimed that electric lifts were now “superseding the earlier types of hydraulic and belt-driven lifts” [4]. While the gradual ascendance of the electric lift in the marketplace was perceived as sign of modernity, older technologies and/or operating systems were still present in significant ways. The presence of a 24-page section on belt-driven goods lifts served as a reminder that one of the first means of powering lifts – the belt drive – remained a common feature in British factories. According to Wadsworth: “In works where mechanical power is available, or the cost of an Electric Lift is prohibitive, a Belt-driven Lift is a safe and efficient

Figure 6. Header and Footer Design, *Wadsworths: Lifts, Transporters, Hoisters* (c. 1920).

machine" [4]. These lifts were also often controlled by shipper or hand ropes, the first means of lift control that was introduced in the early 1800s. However, while one goal of the catalog was to introduce the potential client to the full range of lifts manufactured by Wadsworth – which included older systems – the clear focus was on the modern electric lift. Thus, in addition to hand rope controllers, the catalog included detailed descriptions of car switch, semi-automatic push button, and automatic push button control systems.

Wadsworth also emphasized that the company was dedicated to lift manufacturing and they echoed, on a catalog page titled *A Caution*, Archibald Smith & Stevens' warning about *certain types* of rivals: "The *Bete Noir* of a Lift-maker or User are the firms who play at being Lift-Engineers. They purchase various parts from different sources – a gear box from this firm, a controller from that firm, and so on. They assemble the parts together and then style themselves *Lift-makers*" [4]. Wadsworth urged readers not to be "misled by such firms, otherwise your experience may be sad and expensive" [4]. They also reported that their electric lift motor was "specially built" to their specifications by a "first-class firm," noting that this was "the only portion" of their lifts sub-let to another manufacturer, with all other parts manufactured "under expert supervision" in their works [4]. They also stated that each lift was subjected to a "severe *running* test" prior to leaving the factory. Wadsworth summed up its approach by noting that, while their lifts were not the lowest price in the first cost, they represented the "highest quality at a reasonably low price," reminding readers that "the cost of a good lift is soon forgotten, but the quality is well remembered" [4].

A common feature of many lift catalogs was information required when ordering lifts or seeking estimates. Wadsworth recommended that clients seeking estimates provide the following information: "maximum load, height of travel and number of landings, speed, size of car or well-hole, class of lift required (whether for passengers or goods, or for both), current supply available (if alternating, also phase and periodicity), and method of control" [4]. The catalog also included a series of plans intended to help readers determine the car size and shaft dimensions. The drawings provided, and their accompanying text, addressed various counter weight, guide rail and engine locations and illustrated the versatility of lift design: for example, cars could have one, two or three doors. General information included proper placement of the shaft bonding timbers, the height required above the car (depending on machine location), pit depth, car area per passenger (three square feet was recommended) and basic shaft dimensions. The latter were interesting in that all dimensions were given from the interior of the shaft wall to the interior of the car (Fig. 7).

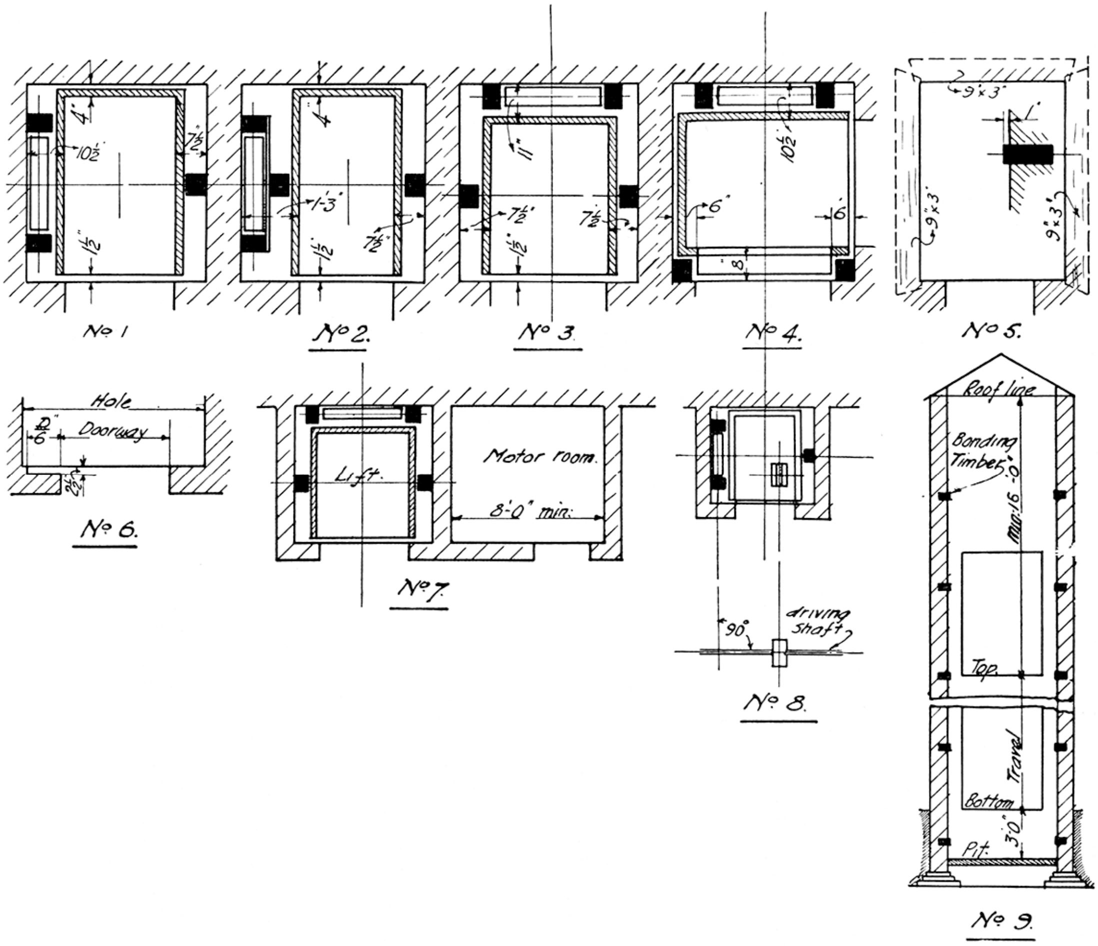

Figure 7. Lifts Plans and Section: "How to determine the size of car and dimensions of lift well," *Wadsworths: Lifts, Transporters, Hoisters* (c. 1920).

In addition to manufacturing lifts Wadsworth also provided an inspection service. The company stated that they had "inaugurated, some time ago, a system of inspection, which has made such rapid strides during the past two or three years, giving such excellent results, proving economical, and saving our customers much trouble and annoyance, that we are now enabled to keep a regular staff of practical engineers for carrying out such inspections" [4]. Wadsworth recommended that their *practical engineers* inspect lifts "three or more times per annum" [4]. After each inspection the client received a report on the lift's condition and the repair work required (if any). The costs associated with this service depended on the type of lift machine and the number of inspections per year. The prospective of inspecting a lift *three or more times each year* may reflect – in spite of its increased commercial popularity – concerns associated with the relative newness of the electric lift and unknowns about its operation over long periods of time.

The Wadsworth catalog's 175 illustrations feature an extraordinary collection of color and black-and-white photographs of lift machines, components, and cars (Figs. 8-10). The various components illustrated include gates, limit switches, automatic floor setters, direction limit switches, controllers, speed governors, slack cable switches, automatic screw cut-off switches, safety catches, and lift enclosures. The machine types illustrated include direct-connected electric passenger and goods lifts as well as belt-driven goods lifts. Although the information associated with each image varied, it permits a glimpse into the commercial and industrial settings of these lifts. Passenger lifts were depicted in hotels, infirmaries, offices, public buildings, and an art gallery and a jeweler. Goods lifts were depicted in a variety of factories, works and warehouses including a boot factory, furniture works, soap works, rubber works, cloth warehouse, and railway stations. Other specialized lifts, such as automobile lifts, were also illustrated. The images of belt-driven goods lifts and transporters are also of particular interest in their depiction of early 20th century industrial buildings.

Figure 8. Electric Passenger Lift (left); Passenger Lift Car E7. *Wadsworths: Lifts, Transporters, Hoisters* (c. 1920).

Figure 9. Passenger Lift in Offices (left); Belt-driven Goods lift (right). *Wadsworths: Lifts, Transporters, Hoisters* (c. 1920).

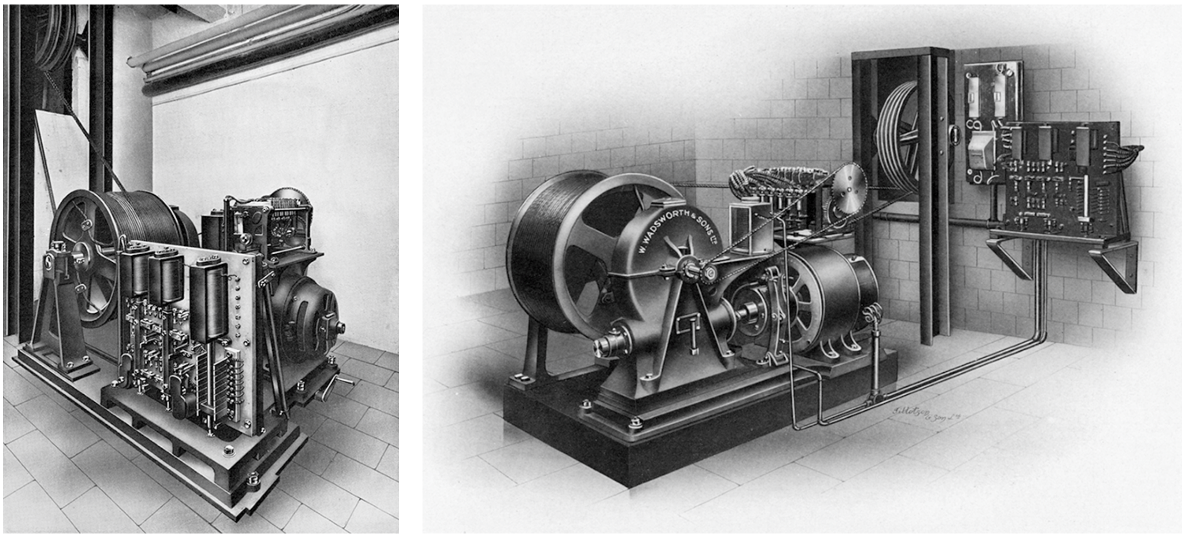

Figure 10. Electric Passenger Lift Winding Drum (left); Electric Goods Lift (right). ***Wadsworths: Lifts, Transporters, Hoisters* (c. 1920).**

6 CONCLUSION

Although the collection of catalogs examined for this paper is limited in number, their relative age, size, scope and focus represent a reasonably comprehensive cross section of the most common catalog types published during this period. Brady & Thornborough's comprehensive catalog featured their full range of products, with lifts given the same emphasis as self-acting sun blinds. While Waygood sought to educate prospective "intending purchasers" on the virtues of their lifts, Archibald Smith & Stevens saw themselves as educating about and advocating for the newest lift technology. Wadsworth's massive catalog represented the range of electric lift types manufactured in the early 20th century, illustrating the sustained presence of older technology alongside the latest innovations. Finally, the language associated with selling lifts reflects the culture that produced it and, in many ways, resonates with contemporary advertising copy that seeks to convince potential customers to buy one lift over another.

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BIOGRAPHICAL DETAILS

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Knowledge Transfer Partnership Project as an Example of Best Practices for Innovation in the UK Lift Industry

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Keywords: Knowledge Transfer Partnership, Innovation, Lift, Project Management, Design, Composites, Technology.

Abstract. This paper outlines the process, and provides an insight into the best practices that were implemented throughout the course of a Knowledge Transfer Partnership (KTP) project undertaken to develop an innovative Machine Room Less (MRL) lift system. The particular attention on Knowledge Transfer Partnerships, project management, composite materials, design process and new technology allows for evaluation of the effectiveness of the KTP scheme.

1 INTRODUCTION

Global economy and unrestricted access to products and markets forces companies in developed countries to have a continuous improvement and innovation strategy in place. This is even more important for Small and Medium Enterprises (SME's) as the ability to relocate their manufacturing operations to save labour costs is limited by a number of factors. The active strategy of Innovate UK, a leading innovation organisation that works for and with the businesses allows for a significant boost of available resources and funding [1].

2 KTP PROJECT OVERVIEW

2.1 Knowledge Transfer Partnership

Knowledge Transfer is commonly defined as: "*the exchange of information through networks where knowledge transfer is about transferring good ideas, research results and skills from universities and other research organisations, to business and the wider community to enable innovative new products and services to be developed" [2].*

Knowledge Transfer Partnerships is a programme in the United Kingdom helping businesses to improve their competitiveness and productivity using knowledge, technology and skills [3]. A KTP aims to meet a core strategic need and to recognise novel solutions to help that business grow. The rationale behind KTP projects is that the successful commercial exploitation of new ideas will require knowledge, skills, technology and adaptability in order to implement it. A number of selected case studies accessible on the KTP portal would increase understanding of the programme impact on UK economy [4]. The desired outcome of a KTP project is to embed new capability into the company, improve efficiencies, optimize business performance, define arising business opportunities and to bring new technology to the market.

It is proven that "*businesses acquire new knowledge and expertise which is related to tangible outcomes on a large scale. For every £1 million of government spend the average benefits to the company amounted to a £4.25 million annual increase in profit before tax, £3.25 million investment* *in plant and machinery with 112 new jobs created and 214 company staff trained as a direct result of the project. [5].*

2.2 Project Stakeholders

Project stakeholders include the company partner, the knowledge-base partner, KTP adviser, KTP sponsors and the associate. The company that can undertake a KTP Project is usually a UK based business (but in some cases it can also be a not-for-profit organization) regardless of size. The knowledge-base partner is a UK based higher education institution (HEI) which can be a public or privately funded university, college or research organization. The expertise of a knowledge- base partner would normally be aligned with the particular project. A KTP adviser is a mentor appointed to provide unbiased views on the project's progress and to provide solutions to any potential problems that could arise. KTP sponsors include Innovate UK and the company. The associate that is appointed to work on the project is a recently qualified graduate from a UK based educational institution. The associate is normally employed by the knowledge-base partner but is working at the company premises. Project progress and future actions were reviewed by the main stakeholders during Local Management Committee (LMC) meetings on a periodic basis. In the case of this project, the project team included three supervisors with both academic and professional qualifications, who were visiting the company on a regular basis and were able to advise on any related matter.

2.3 Project Benefits and Deliverables

In any project deliverables and products are the vehicle to acquire the benefits. For a company partner the benefits would include new knowledge and capability, enhanced performance and profitability. Although it is not always possible during a KTP project to deliver a commercial product, as the knowledge developed in academic institutions may need extensive or intensive adaptation to particular business applications, the real know-how obtained by the companies during the project allows for innovative change in businesses. This is quantitatively shown by statistical figures of annual increase in profit before tax and new jobs created [2]. In case of the knowledge–base partner, the acquired benefits would include enhanced knowledge, academic publications, research and teaching materials. The structure of the project would allow the associate to gain new skills related to technology, communication, management and organisation, and to increase competences by formal and informal training. A proportion of the project budget is reserved for the associate's personal development, allowing for career progress and increased employability. In this particular case, the associate working on the project had an opportunity to attend two week-long training sessions in project and business management. This training was critical to effective project management and understanding of project constrains. Additionally, the development budget allowed the associate to determine and attend a professional training in composite materials and relevant trade shows in line with project demands.

2.4 Project Proposal

It is an essential element of a KTP project that clear project objectives are communicated to all parties prior to commencement of any work. In case of any KTP Project the objectives need to be defined during the project funding application. These objectives were further clarified when the company and knowledge-base partner representatives agreed on the objectives which were written down in an initial project plan. At the grant application stage the original aim was defined as *to research, design, implement and embed an in-house mechanical design capacity to manufacture an innovative new range of energy efficient, green lifts*. This plan was drafted prior to the appointment of a KTP associate, therefore it was a base point for any possible developments in the future. This allowed preparation of a project proposal, where all known modern technologies, materials and solutions were outlined and analysed. Technologies were divided into energy storage, energy saving, energy regeneration, and energy generation. Most innovative and prospective options which were associated with highest risk were evaluated using a Strengths – Weaknesses – Opportunities and Threats (SWOT) analysis. This allowed for a constructive discussion by all parties in the project team.

2.5 Project Planning

The duration of this particular KTP Project was 18 months. Although the standardized PRINCE2 methodology in project management [6] could be implemented, it was found to be excessively bureaucratic and time consuming therefore a simplified methodology based on a Gantt chart was used during this project. Workload was initially divided into separate subsystems allowing for drafting an initial Gantt chart. This initial Gantt chart was reviewed and all necessary amendments were made where appropriate.

2.6 Project Management

Every project is unique, with different sponsor and stakeholder conditions, different goals and external factors. The successful delivery of a project requires all participants to work together as a team. Effective teamwork is based on both good informal and structured communications.

In the case of this KTP Project the communication means included: Local Management Committee meetings held every quarter, project team meetings held every month, weekly meetings and ad-hoc meetings with Company Supervisor, proposal submission (innovative technology or business opportunities as a result of research, meeting or visit to a relevant trade show), project presentations during LMC, meetings with Knowledge Base Partner using virtual meeting tools, email communication, preparation of agendas and meeting minutes, review of Gantt charts and project plans. Fig. 1 shows project drivers which are common for all projects that are undertaken by practicing engineers. It is evident that the risk of project failure must be minimized by ensuring the scope and quality of a project is achieved within specified timescales without exceeding a specific budget.

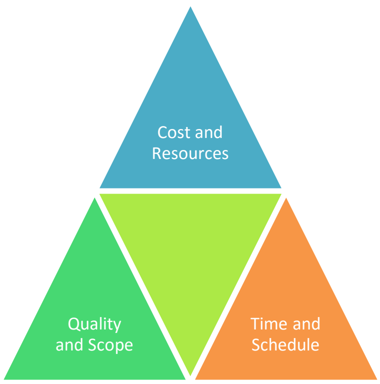

Fig. 1: Project Drivers

Project drivers were discussed by the Project Stakeholders during the early stages of the development allowing for a drafting of a comprehensive project plan based on KTP project proposal. During the project it has become apparent to the company that a large investment would be necessary to manufacture a new lift range. As a result the company decided to discuss partnership with established manufacturers of a standard range of components.

3 CASE STUDY

The case study to design a new, innovative Machine Room Less lift (MRL) includes use of a number of engineering techniques in order to optimise the design and installation process and reduce overall energy consumption throughout the product lifecycle of the proposed lift system.

Specification of a new lift system include: new, composite modular lift cabin, new drive with optimised selection of modern, coated rope suspension and Permanent Magnet Synchronous Motor (PMSM), Remote monitoring solution, and Energy monitoring capability (Fig.4). Although many of the technologies were previously successfully implemented in a lift system, the use of modern technology workflow in design, such as three dimensional Computer Aided Design (3D CAD) software, motion analysis, and Finite Element Analysis (FEA) including Composite Material Modelling constitutes a novel approach to a lift design. Apart from the main design, project work has also included the initial design of a new, adjustable counterweight system, studies on energy savings, energy monitoring devices, embedding load weighing device into remote monitoring and into a lift control system in order to determine lift energy consumption, improvements in functionality of a software based control system (standby and sleep modes), development of energy certification tool for all lifts, and research of laser alignment systems in lift installation.

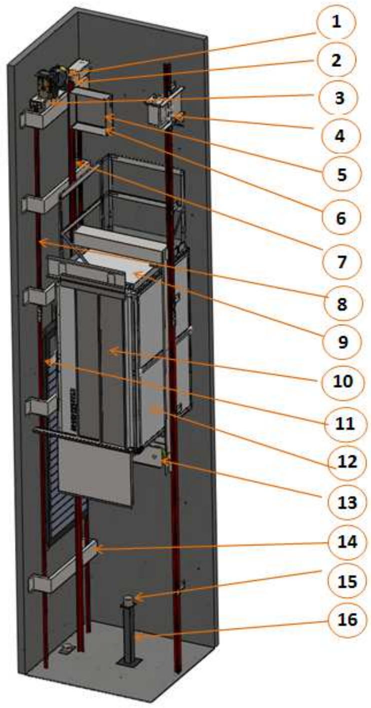

Fig. 2: 3D CAD model of a new lift system

The main benefits of the chosen methodology include reduced cost and time in product development. Additionally, 3D CAD along with motion analysis was used extensively to evaluate and visualize concepts, obtain feedback from stakeholders, communicate with customers and suppliers, and create General Arrangement drawings and manufacture drawings. Finite Element Analysis allowed determination of reaction forces in critical areas of the design. This significantly reduced the cost and time required to develop a product.

Advanced Composite Materials (ACMs) have broad, proven applications in aircraft, aerospace and sports equipment sectors [7]. Application of this technology in the lift industry is still marginal, as the financial benefits related to the cost of development are not as significant as in the previously mentioned sectors. The Knowledge Transfer Partnership scheme allowed us to minimize the cost of development with the help of the Knowledge-base partner. During the initial research a number of composite materials were evaluated, including fibre reinforced polymers (FRP) and glass reinforced polymers (GRP), and composite laminates with a number of core materials. The selected solution was a best option compromise between structural performance, mass and cost.

Mechanical performance of the structural components (including composite components) was evaluated using Finite Element Analysis (Fig. 5). Different operational scenarios were evaluated using Failure Mode Effect Analysis (FMEA) [8] and to limit the time of development the simulation work was concentrated only on worst case scenario loads. Results were confirmed using analytical calculations developed for composite panels (Fig. 6.).

Fig. 3: Finite Element Analysis – plot of deflection of lift cabin and Composite Panel Calculations

Fig. 4: Prototype of a Cabin Floor under static load test

The FEA simulations allowed the most critical components in the design to be determined. This allowed the cost of development to be minimized, as it was only required to test the components in question. Tests performed by the cooperating company allowed the evaluation of material strength and the options made possible by using adhesive in the design. It has also allowed the full component build of the lift floor to be progressed. The work was carried out in a well-known strategy loop: Plan – Do – Check – Act. The development was also optimized for cost during the development and during Design for Manufacture stages.

A prototype of the floor was manufactured in the company using standard manufacturing procedures such as drilling, cutting, grinding, and adhesive joining. Welding, plasma cutting and waterjet cutting of structural members was done by cooperating subcontractors. Manufacturing procedures were documented in appropriate manuals associated with manufacturing drawings, required Risk Assessments and COSHH forms [9]. To ensure that the company benefits from the project design and manufacturing, a training package for manufacturing operatives was developed.

The lift system could be optionally equipped with a remote monitoring system which allows for determination of an efficient service schedule, thus reducing the costs to the maintenance company and the customer. In this case, the company had a remote monitoring system available which can also support a voice alarm transmission (iCOM), using GSM, for transferring data and voice utilising modern interface allowing for easy implementation into any architecture.

The system has modular design, allowing it to connect to other modules such as a continuous load monitoring module, temperature monitoring and even condition monitoring modules, which could monitor vibration in lift components that could indicate wear.

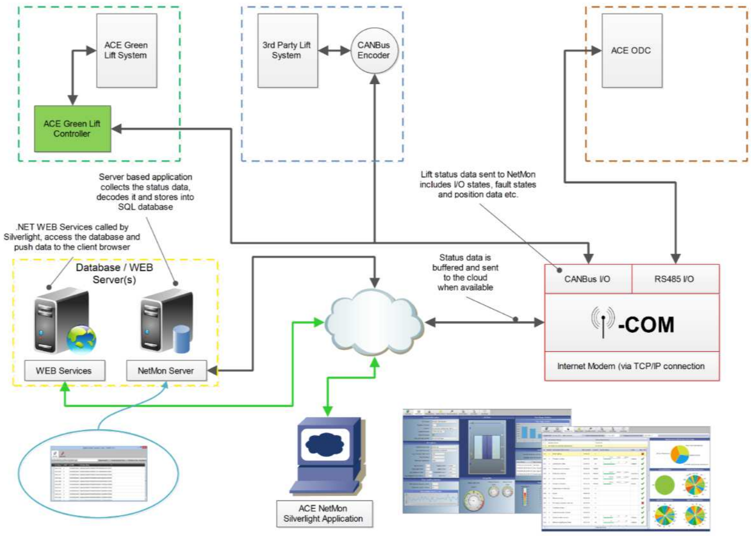

Fig. 5: Remote monitoring solution

The energy efficiency of any lift system could be benchmarked using interactive tools developed during the course of this project.

Although the full scale field tests of a new design were not feasible due to difficulties and associated cost, it is perceived that the energy efficiency and carbon footprint of a new design would be improved in many areas. Use of 3D CAD in design greatly reduces errors in the manufacturing (time and material waste) as the component can be evaluated in 3D prior to manufacture. A composite cabin has a potential of reduced mass, which would allow the use of a counterweight system of smaller weight, thus reducing both costs of materials, system footprint and installation time and effort. A composite cabin designed and built in the UK would also reduce the project footprint as the lead time can be shortened with an additional benefit of much better customer experience and flexibility in the design. A modern control system, with monitoring capability and energy saving modes would be beneficial in delivering greater benefits in energy consumption.

4 CONCLUSIONS

Development of the project was associated with many challenges and risks. It was possible to minimize the risks and turn challenges into opportunities by effective teamwork of the project team.

The technology of a design process of a new lift range and manufacture of a new composite cabin was successfully researched and embedded into the company. In a design process all required components were appropriately selected, ensuring energy efficiency and suitability for application in a new range of lifts. All required calculations and tools allowed us to design and specify the mechanical side of a complete lift system.

The energy efficiency was addressed in many areas of the project, including:

- the initial design of a new, adjustable counterweight system and studies showing possible savings achieved by using the new system,
- using energy monitoring devices on a standard range of lifts to determine real values of energy consumption in a lift system,
- embedding a load weighing device into remote monitoring and into a new range of control systems in order to determine lift energy consumption,
- improvements in functionality of a software based control system (standby and sleep modes),
- development of energy certification tool for all lifts,
- research of laser alignment systems in lift installation.

Business performance was discussed in many cases throughout the project duration; examples include optimisation of the manufacture and design of a standard lift control system (decreasing the cost and size of components) and use of energy certification tool in sales and marketing. During the project the Associate has also contributed to the company operations, gaining knowledge and helping in design, planning and project management activities on a number of occasions.

The Associate has acquired a wide range of knowledge related to the lift sector. In many areas the project was successful and allowed us to embed new capability into the company, to fill knowledge gaps, improve the design process, improve new project development, improve quality and efficiencies, propose solutions to optimize business performance, propose new business opportunities and to bring new technologies to the market. The knowledge-base partner has acquired understanding related to the lift market, real life implications, constrains and problems in the small enterprise and knowledge of all activities within the project which would allow for further innovations in the field of vertical transportation.

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Optimisation of the Running Speed of Escalators on the London Underground

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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.

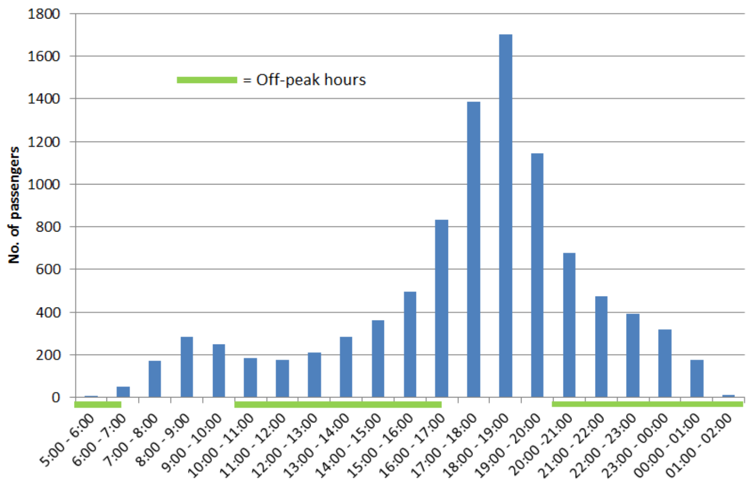

Figure 1: Passenger count data for Gants Hill from platforms to ticket hall

[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

Energy Consumption Model

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

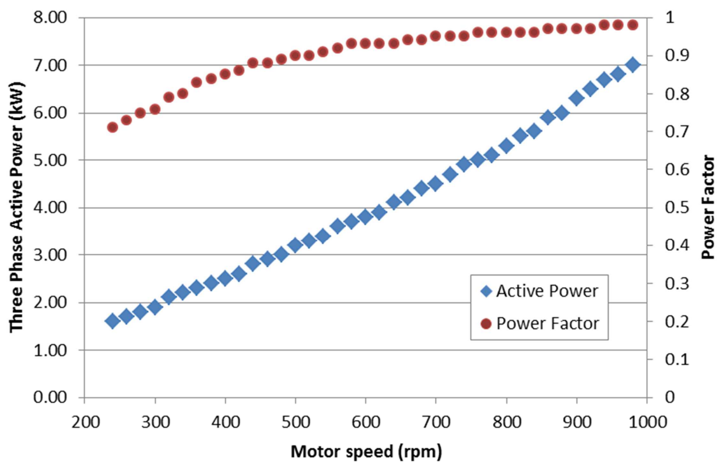

Figure 2: Empirical measurements of three phase active power (kW) and power factor vs motor speed for Gants Hill escalator 2

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

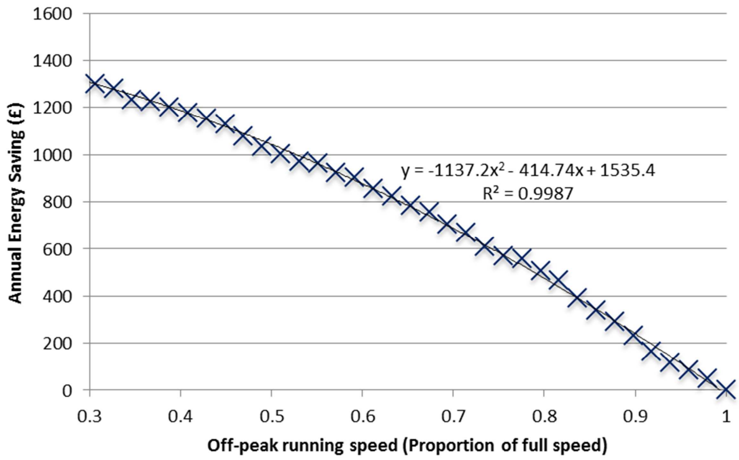

Figure 3: Predicted annual energy cost savings due to off-peak speed reduction modelled from empirical power measurements

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.

Passenger Delay Model

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.

<u>Combined Model</u>

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.

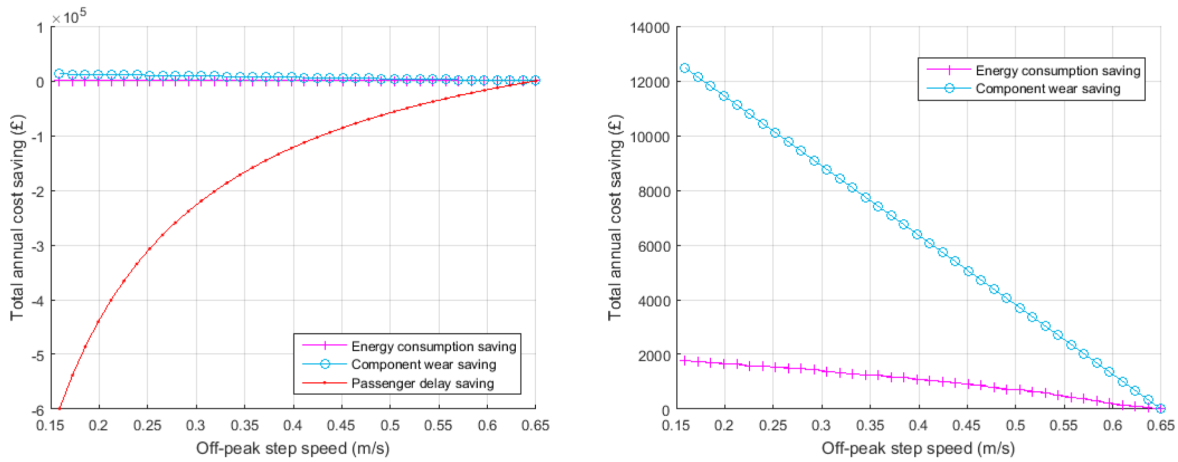

Figure 4: Predicted annual savings for Gants Hill escalator 2 a) All three outputs b) Energy and component wear only

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.

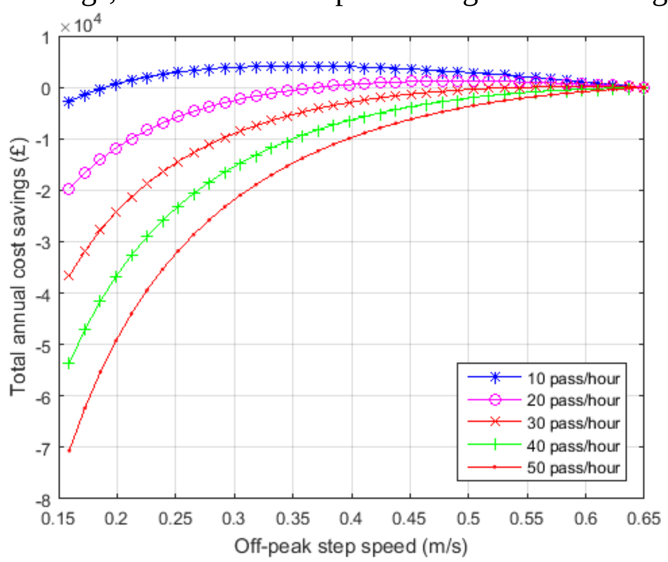

Figure 5: Predicted total annual cost savings due to energy, component wear and delays for pre-programmed off-peak speed reduction with up to 50 passengers per hour

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.

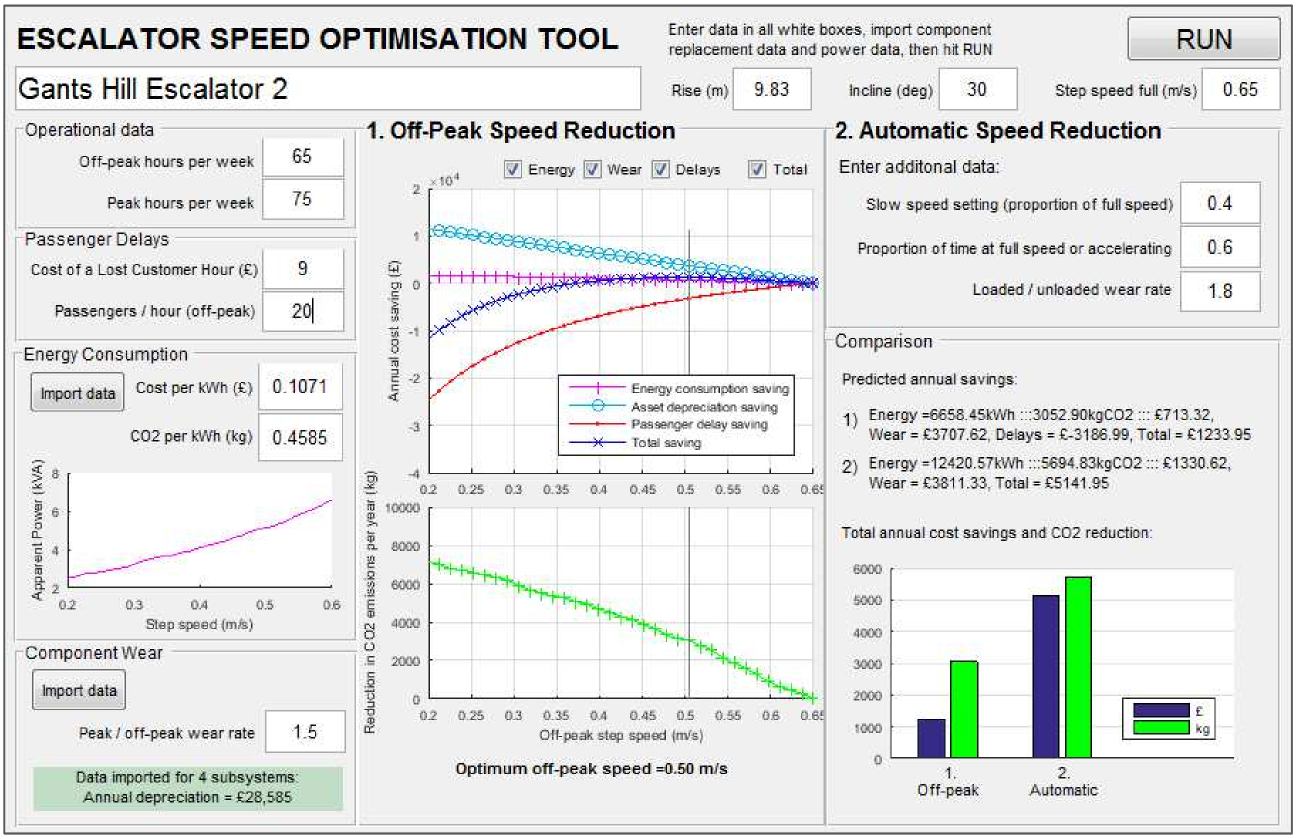

Figure 6: Optimisation tool user interface

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.

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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.

Modelling and Computer Simulation of Aerodynamic Interactions in High-Rise Lift Systems

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Keywords: High-Speed Lifts, Multibody Dynamics, Computational Fluid Dynamics, Computer Simulation.

Abstract. The aerodynamic effects that occur when a high-speed lift travels through the hoistway involve a range of diverse phenomena that lead to excessive vibrations of the sling-car assembly and noise inside the hoistway and the car. Noise and vibration may then be transmitted to the building structure. Thus, a good understanding and prediction of aerodynamic phenomena occurring in high-speed lift installations is essential to design a system which satisfies ever more demanding ride quality criteria. This paper discusses the fluid-structure interactions taking place in high-rise applications and presents the results of a study to develop a computational model to predict the aerodynamic interactions in high-speed lift systems using Multibody Dynamics (MBD) and Computational Fluid Dynamics (CFD) techniques. The model is implemented in a high-performance computer simulation and 3D visualisation platform. It is demonstrated that the model can be deployed as a tool for aerodynamic design and optimization of high-rise lift systems.

1 INTRODUCTION

The operation of lift systems is affected by vibrations and associated vibro-acoustic noise. This affects ride quality and results in a high level of dynamic stresses in elevator components.

The underlying causes of vibration in a lift system are varied, including poorly aligned guide rail joints, eccentric pulleys and sheaves, systematic resonance in the electronic control system, and gear and motor generated vibrations [1]. In high-rise applications lifts are subject to extreme loading conditions. High-rise buildings sway at low frequencies and large amplitudes due to adverse wind conditions and the load resulting from the building sway excites the elevator system. This results in large vibratory motions of elevator ropes. The taller a building, the higher the rated speeds of elevator systems are needed. The vibrations are increased as the speed increases. Torque ripple generated in the motor causes vertical vibrations of the car. At high speeds guide rail deformations induce large lateral vibrations of the car. Furthermore large aerodynamic loadings due to the airflow around the car result in excessive noise and flow-induced vibrations of the car structure.

A good understanding and prediction of vibration phenomena occurring in lift installations is essential for developing vibration suppression and control strategies in order to design a system which satisfies ever more demanding ride quality criteria. Therefore it is of benefit to apply computer simulation techniques to address vibration problems in high-speed high-rise lift (HRHSL) systems.

2 MULTIBODY SYSTEM AND FLUID-STRUCTURE INTERCATIONS MODEL

Vibration sources affecting the dynamic behaviour of a car in a HRHSL system include the excitations applied due to air flow interactions (FSI), imperfections of the guiding systems and the influence of dynamics of suspension and compensating ropes (MBD), see Figure 1.

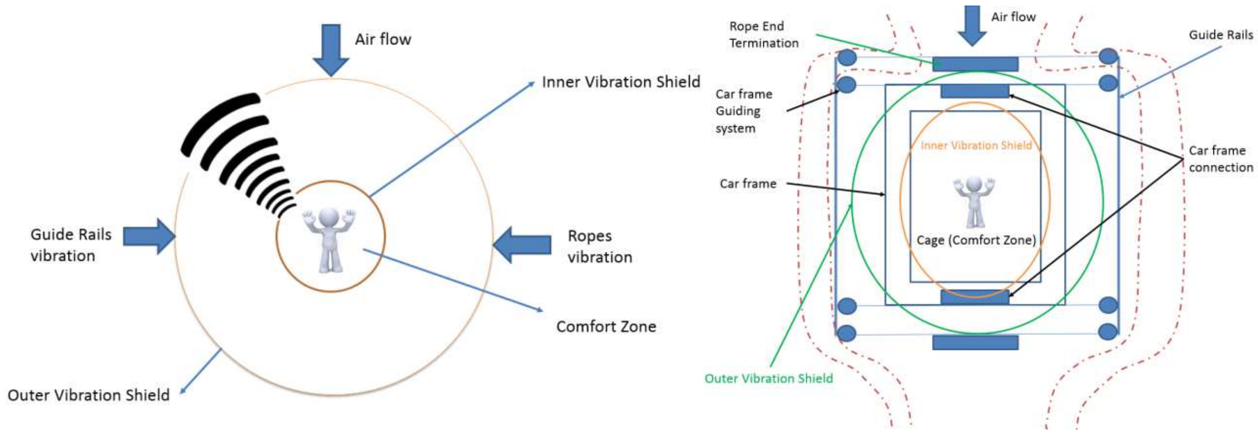


Figure 1 Vibration and Noise Excitation Sources

2.1 Air flow-induced vibrations and noise

The aerodynamic phenomena affect the performance of HRHSLs. At high speeds the air flow around the car – frame assembly induces excessive vibrations and noise. During the lift travel large air pressure differences between the front and rear of the car are being generated [2]. Furthermore, the effects due to multiple cars running in the same shaft cannot be neglected. Funai et al. [3] conducted a computer simulation case study into these effects when two cars run parallel to and pass each other in a hoistway. The results indicate that the dominant frequency of air pressure fluctuations in the former case is around 3.7 Hz being close to the out-of-phase mode of the car – frame vibration mode. On the other hand, the dominant frequency of air pressure fluctuations in the latter case was 2.2 Hz.

A study to characterize the most important vibro-acoustic energy sources and identify the dominant paths of broadband (100 – 500 Hz) acoustic energy transmission to the car interior in HRHSL installations has been carried out by Coffen et al. [4]. It has been identified that lift cars are subject to structure-borne as well as to air-borne noise. Structure-borne noise is caused mainly by the vibration induced by the car roller guides – guide rail interaction and by the hoist rope – rope hitch interface. This structure-borne vibro-acoustic energy is transmitted to the car interior through the car frame structure (and in particular by the uprights).

The air-borne noise is generated by aerodynamic effects during the car travel. It includes shaft noise entering the car through the ventilation openings and the door seals. The wind (flow)-induced vibrations of the car exterior panels generate noise that is transmitted to the car interior.

Finite element modelling, modal analysis and statistical energy analysis (SEA) are used as noise prediction techniques. The latter technique have yielded accurate results and facilitated the identification of the dominant sources and paths of vibro-acoustic energy in the lift car assembly [4]. Namely, it has been concluded that at higher speeds (over 9 m/s) the dominant path was air-borne noise radiating through the acoustic leaks and non-resonant energy transmission. The secondary path was identified as structure-borne noise arising from the car floor. However, at lower velocities (5 m/s) the contributions to interior car noise were the same for both paths.

2.2 Modelling Methodology

A HRHSL installation can be considered as a multi-body system (MBS) with discrete and continuous (distributed-parameter) components. The diagram presented in Figure 2 illustrates the modelling process of the MBS. The components of known geometry, mass, stiffness and damping characteristics are subjected to constraints applied at their boundaries and their responses exhibit non-stationary, nonlinear coupled modes of motion.

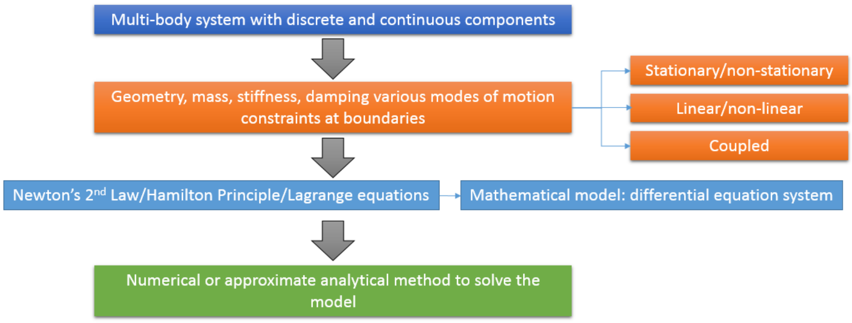


Figure 2 MBS modelling process.

In order to derive the differential equations of motion (the mathematical model) of such a system Newton's 2nd law or Hamilton principle/ Lagrange's Equations techniques can be applied [5]. The use of Hamilton principle/ Lagrange equations facilitates the derivation of equations of motion in terms of generalized coordinates, without the need of free body diagrams. The structure model can then be stated as

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right)-\frac{\partial T}{\partial q_i}+\frac{\partial V}{\partial q_i}+\frac{\partial \Re}{\partial \dot{q}_i}=Q_i^{nc}, \quad i=1,2,\ldots,n \tag{1}$$

where q_i is the generalized coordinate, $\dot{q}_i=\partial q_i/\partial t$ represent the generalized velocity, $T(\mathbf{q},\dot{\mathbf{q}})$ is the total kinetic energy of the system, $V(\mathbf{q})$ is the total potential energy of the system, $\Re(\dot{\mathbf{q}})$ denotes Rayleigh dissipation function and Q_i^{nc} is the non-conservative generalized force corresponding to the generalized coordinate q_i.

In general, the equations of motion (1) are of a non-stationary and nonlinear nature and their closed-form analytical solutions are not available. But they can be treated by approximate analytical methods (such as perturbation analysis). However, the most convenient approach is to use direct numerical integration (numerical simulation) techniques.

The fluid model is expressed in terms of Navier–Stokes (N-S) equations that represent the conservation of momentum formulated as

$$\rho\left(\frac{\partial \mathbf{V}}{\partial t}+\mathbf{V}\cdot\nabla\mathbf{V}\right)=-\nabla p+\rho\mathbf{g}+\mu\nabla^2\mathbf{V}+\mathbf{F} \tag{2}$$

where $\mathbf{V}$ is the fluid velocity, **p** is the fluid pressure, ρ denotes the fluid density, μ is the fluid dynamic viscosity and **F** represents external foces applied to the fluid.

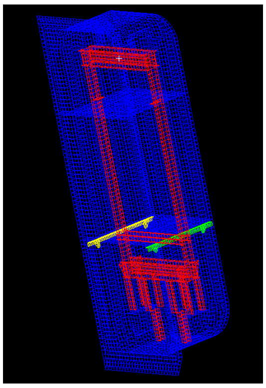
The N-S equations are solved together with the continuity equation representing the conservation of mass given as

$$\frac{\partial \rho}{\partial t}+\nabla\cdot(\rho\mathbf{V})=0 \tag{3}$$

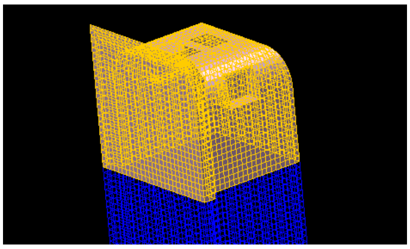
3 COMPUTER SIMULATION TESTS AND RESULTS

The fluid flow is coupled to the structure and the solution scheme is based on Lagrangian formulation for the structure and Arbitrary Lagrangian-Eulerian (ALE) formulation [6] for the fluid regions.

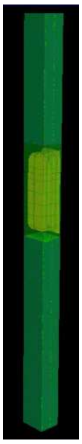
A 3D CAD assembly model of an elevator courtesy of Thyssenkrupp Elevator has been used, see Figure 3, to combine the finite element (FE) analysis on the shroud structure, multibody dynamics (MBD) and computational fluid dynamics (CFD) of the car-sling system.

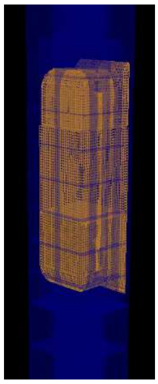


MBD of the car-sling system



FE analysis on the shroud





CFD Elevator Shaft

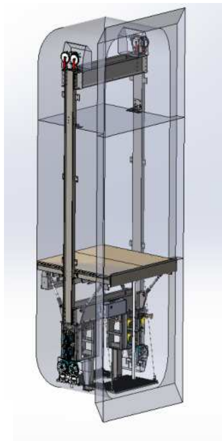


Figure 3 3D CAD assembly model of an elevator courtesy of Thyssenkrupp Elevator

This study was conducted using the base model (in 3D) with an elevator car of mass P = 1000 kg (including the shroud) which is supported by a platform mounted within a sling on elastomeric isolation pads of combined stiffness coefficient k_p = 29 kN/m. The car frame mass is M = 400 kg and the car – frame assembly is suspended on 4 steel wire ropes in 1:1 configuration. The ropes are of modulus of elasticity $E = 0.85 \times 105$ N/mm2, mass per unit length m_r = 0.66 kg/m, metallic (effective) area A_{eff} = 69 mm2 (see Table 1). The car is traveling in the hoistway of dimensions 2.5m x 3m (used for creating a meshed shaft model) over the time interval of 30.2 seconds (the materials for car and shroud have been assumed as steel and isotropic aluminum, respectively) with the car travelling at the maximum speed of 10 m/s.

Table 1 Fundamental parameters of the system

Parameter	Value	Unit
Car	1000	kg
Frame	400	kg
m_r	0.66	kg/m
E	85000	N/mm^2
A_{eff}	69	mm^2
Stiffness of cable spring	7.82	kN/m
Stiffness of spring	29	kN/m
Damping coefficient	20	kNs/m

The air properties are considers as density of 1.14 kg/m3, specific heat ratio of 1.401 at 20 0C with gas constant (R) of 287 J/ (kg.K). The coupling has been considered only for shaft, top/bottom shroud and around car as a velocity, pressure and density parameters with both side flow (in and out).

The computer simulation tests are executed in Dytran [7]. Dytran involves a fluid solver based on the Finite Volume Method (FVM) in which Eulerian mesh is used, as well as a structure solver based on the Finite Element Method (FEM) in which Lagrangian mesh is used. Two interactions could be applied by using Dytran, structure-structure interaction which is based on contact algorithms, and fluid-structure interaction which is based on coupling algorithms. This software has been used to analyse the complex non-linear behaviour of lift structures interacting with air/fluid-flow. Eulerian and Lagrangian meshes can be utilized in the same analysis as well as coupled together allowing the solution of FSI problems (MSC. software Corporation, 2013).

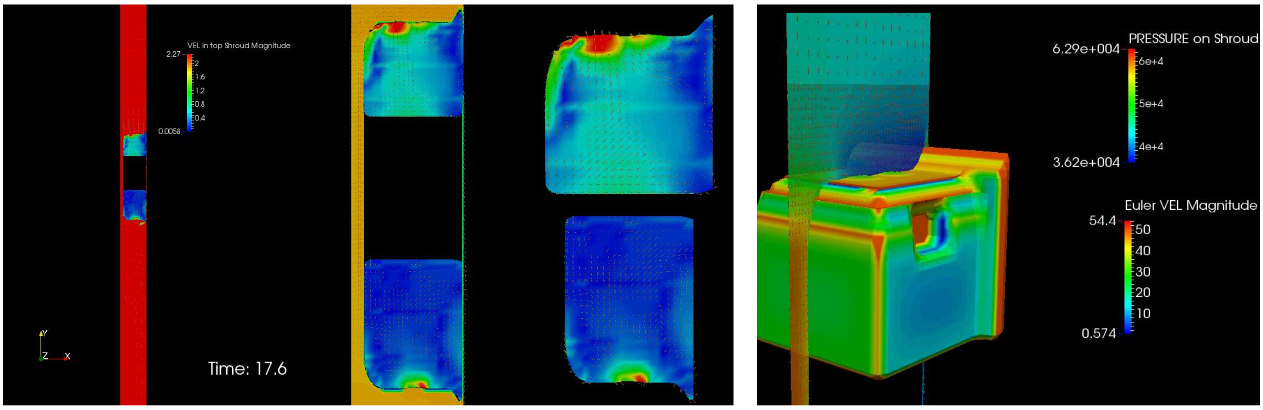


Figure 4 Air flow velocity and pressure profile around the shroud and around the car

Figure 4 shows that the velocity magnitued at the the inside of the shroud can reach the maximum of 2.27m/s, with the car travelling at the constant speed of 10 m/s the pressure acting upon the shroud, with its maximum of 62.9 kPa, together with the velocity profile around the top part of the shroud, the maximum is 54.4 m/s. With same scale factor there are areas at the bottom of the shroud that reach the same maximum velocity.

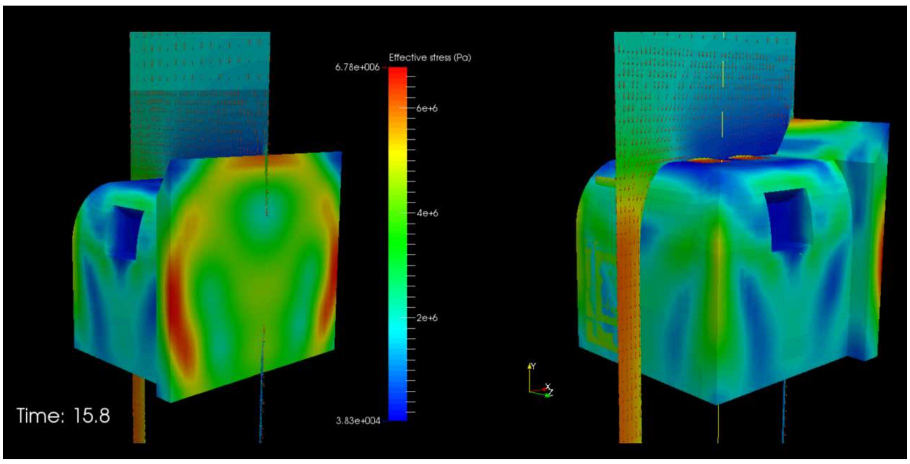


Figure 5 Effective stress in the shroud

Figure 5 is representing the effective stress (EFFST) defined by equation (2), showing the effective stress on the shroud which can reach 6.78 MPa, for the front and back of top shroud, respectively, where σ_x, σ_y and σ_z denote the normal stress components and τ_{xy}, τ_{yz} and τ_{zx} are the shear stress components in the X, Y and Z directions, respectively.

$$\bar{\sigma} = \sqrt{\frac{1}{2}\left[\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + (\sigma_z - \sigma_x)^2\right] + 3(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)} \tag{2}$$

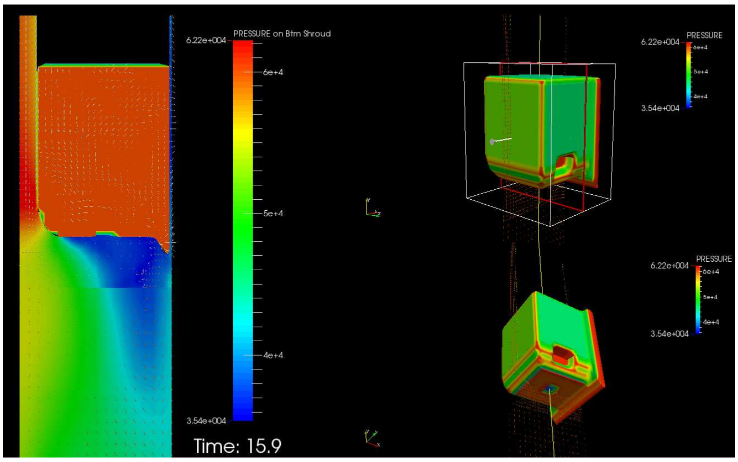


Figure 6 Pressure effect around car and inside of bottom shroud

Figures 6 show the pressure distribution at the bottom part of the shroud with the maximum value of 62.9 kPa, together with the velocity profile which can reach 2.27 m/s.

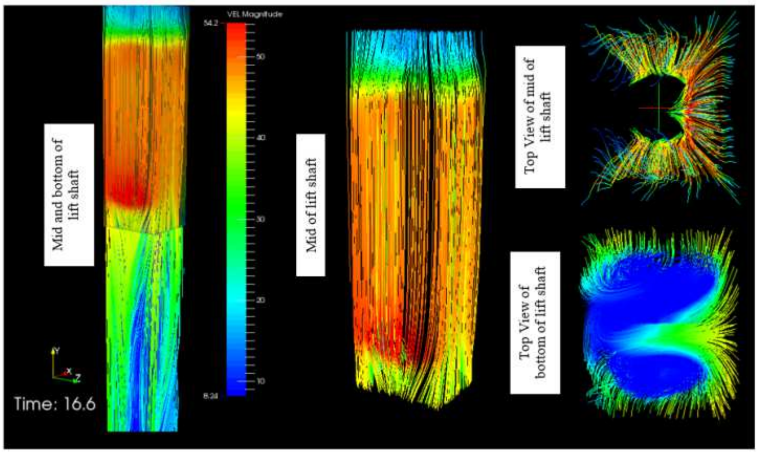


Figure 7 Velocity streamline profile in the elevator shaft

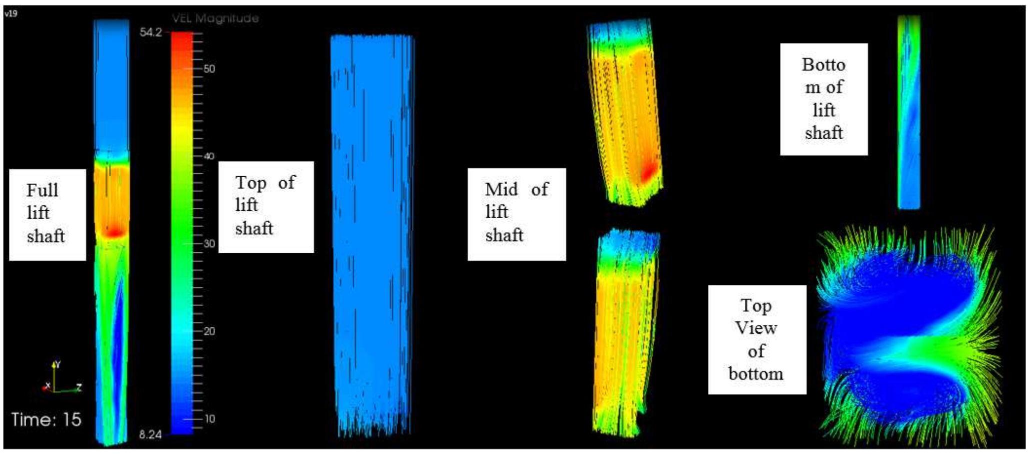


Figure 8 Velocity streamline profile in the elevator shaft

Figures 7 and 8, present Streamlines, which are instantaneously tangent to the velocity vector of the flow for the mid and bottom of the elevator shaft.

4 CONCLUSIONS

This research describes the use of integrated multidisciplinary analysis for modelling and simulation of the dynamic interactions in high-speed elevator systems using a high-performance computer simulation platform. An explicit nonlinear Computational Fluid Dynamics (CFD) solution is used to predict the fluid-structure interactions (FSI). The CFD solution is combined with Multibody Dynamics (MBD) simulation and Finite Element (FE) analysis to determine the dynamic responses and resulting loads due to the complex FSI arising in the system. As a result, this research developed a computer simulation software platform combining the MBD, FE and CFD techniques for the prediction of vibration responses arising in high-speed high-rise elevator (HRHSE) systems.

Further work would be required to optimize further the software platform and hardware configuration in order to reduce simulation time, to test the model performance and to fully integrate all possible excitation sources into the models. Experimental tests should then be carried out to validate the model and simulation results in the next stage.

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Methodology to Identify Noise and Vibrations Problems for Ride Quality Improvements

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Keywords: Ride Quality, Vibro-acoustic analysis, Operational Modal Analysis (OMA), Operational Deflection Shapes (ODS), Structural and airborne transmission.

Abstract. Comfort is an important issue in the lift industry. This paper shows a methodology used to perform the vibro-acoustic characterisation of lift installations to provide data regarding the functional behaviour and to propose changes in the installations to improve the ride quality in car and to reduce the noise levels in the car. To achieve these objectives, different vibro-acoustic analysis techniques are applied to identify the main frequencies of noise and vibration that could lead to an increase in noise and vibration inside the car. The different techniques applied are FFT analysis, 1/3 octave analysis, vibration transmission by FRF analysis, Operational Modal Analysis and Operational Deflection Shapes. With this analysis, it is possible to determine the components that must be modified in order to improve the design and functionality, with the objective of either reducing the source or minimising transmission paths (airborne or structural), or removing any resonance that may increase vibration and noise inside the car.

1 INTRODUCTION

Improving Ride Quality is an important objective of lift manufacturers. The perception of the ride quality by users is based on noise levels, vibration levels and performance inside the car. The perception of lifts by users as "noisy", "vibrating floor" or "sharp starts or stops" can make the brand image worse.

The main causes of the absence of comfort inside lift cars can be produced by noise and vibration sources such as machines (drive), hydraulic pumps, door operators, electrical control cabinets, sliding systems in car and counterweights. However, other causes may also produce an absence of comfort such as resonances of components and insufficient isolation between the sources and the receptor. The passengers inside the car receive noise by airborne and structural transmission, vibration by structural transmission from the sources and a bad kinematic performance of the elevator (jerk, accelerations, vibrations…) [1].

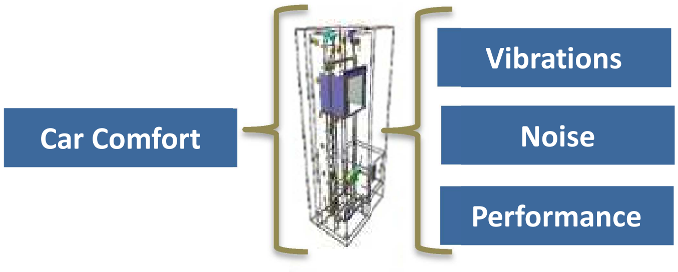


Figure 1 Causes that influence comfort in the lift car

The main vibro-acoustic problems that may appear inside a lift car are:

- High Noise Level (Leq) inside the car: this can be due to high noise of the machine, high noise of guide shoes (friction) and high airborne noise transmissibility. Some possible solutions to these situations are to improve the machine sound insulation, the sliding system performance, and the car sound insulation.

- High noise levels at frequency peaks inside the car can be due to resonances of lift components (car panel, car frame, machine frame…) and/or high structural vibration transmissibility from frame to car. Some possible solutions in these cases are “to shift” the resonances and to improve the vibration isolation between the car frame and the car.
- High vibration levels in the car floor can be due to high machine vibration (unbalanced rotating mass, bearing faults, electromagnetic phenomena…), and bad performance (wrong control, car floor resonance, high structural vibration transmissibility). Some possible solutions in these cases are to improve the machine behaviour, to improve the drive control, to “shift” the resonance and to improve the vibration isolation between the car frame and the car.

For these reasons, we present methodologies to identify noise and vibration problems in lifts using measurement equipment, noise and vibration sensors, acquisition hardware and software for dynamic signals analysis.

2 IDENTIFICATION OF NOISE AND VIBRATION PROBLEMS

It is possible to apply different techniques to analyse noise and vibration data depending on the targeted result accuracy required according to the problem severity.

The “Vibro-Acoustic characterisation of lift” methodology is used to evaluate the behaviour of the lift and to find possible solutions based on vibro-acoustic and dynamic measurements to improve the ride quality. This methodology does not permit the obtaining of quantitative results of the different sources’ contributions (vibration and noise) to the receptor (lift car user), but it does permit learning about which lift components should be modified to improve the ride quality. However, it is not possible to estimate the improvement without measurements. Different data analysis techniques are applied in this methodology, such as Fast Fourier Transform (FFT), Sound Equivalent Level (Leq), 1/3 Octave band analysis, Frequency Response Functions (FRF), Operational Modal Analysis (OMA) [2], and Operational Deflection Shapes (ODS) [3]. Based on the results of the different techniques and applying correlations between the results, it is possible to gain insights to make improvements in the lift.

The source contributions to noise inside the lift car methodology consists of applying techniques in order to identify and quantify noise and vibration sources using frequency response and coherence functions [4]. The Multiple Coherence Technique and the Output Power Allocation technique are applied in this methodology.

The Panel Contributions to noise level inside the lift car methodology consists of estimating the contributions of some areas to the acoustic pressure at a chosen point in a lift car based on the vibration panel (velocity). This methodology can be used to evaluate panels with their different vibro-acoustic properties (damping, reverberation….)

Explanations of the different methodologies and applications to real installations are shown in the following points.

2.1 “Vibro-Acoustic characterisation on lift” methodology

The vibro-acoustic measurements that are necessary to perform on the lift are basically: Ride Quality (Comfort), Noise at different points, Vibration in machine area, Vibration in car panels and the car frame, and Modal Tests of components. The ultimate objective is to find out correlations between the different results. These measurements are taken with at least two load conditions inside the car during downwards and upwards trips. In some cases, it is necessary to modify the nominal speed of the lift to analyse differences of results in frequency through changes in frequency problems.

The *ride quality* measurements are made in the centre of the car floor. The acquisition will be made by means of specific equipment according to ISO 18738-1 “Measurement of ride quality — Part 1: Lifts (elevators)”. The ride quality of the lift can be obtained through these measurements, and it is also possible to evaluate the behaviour of the lift during trips with different load conditions. The lift behaviour could indicate that the lift cannot achieve the nominal speed due to problems with the inverter parameters, insufficient machine power, error in the load balance, high friction force to sliding between the guide shoes and guide rails. It is also possible to apply the vibration narrow band spectra (FFT) analysis to the vibration time signal to detect the vibration frequency peaks in the range 0-80Hz that contribute more to ride quality.

	Performance (Q = 0 kg)		Performance (Q = 100 kg)	
	Upward	Downward	Upward	Downward
Amax (m/s^2)	0.56	0.55	0.57	0.56
A95 (m/s^2)	0.53	0.52	0.53	0.53
Dmax (m/s^2)	0.57	0.58	0.56	0.57
D95 (m/s^2)	0.54	0.53	0.53	0.53
Vmax (m/s)	0.86	0.85	0.86	0.84
V95 (m/s)	0.85	0.84	0.85	0.84
Distance (m)	15.40	15.40	15.40	15.40
Jerk max (m/s^3)	0.95	1.05	0.97	0.95
	Noise (Q= 0 kg)		Noise (Q= 100 kg)	
	Upward	Downward	Upward	Downward
Leq (dBA)	58.0	55.0	58.6	57.6
	Vibration (mg) (Q= 0 kg)		Vibration (mg) (Q= 100 kg)	
	Upward	Downward	Upward	Downward
X-A95 (mili-g's)	2.00	3.00	2.00	3.00
Y-A95 (mili-g's)	4.00	4.00	4.50	6.50
Z-A95 (mili-g's)	20.00	16.50	13.50	14.00

Table 1 Ride Quality values

Figure 2 Speed curve of lift

In this case, the ride quality values obtained (acceleration, jerk and vibration values (A-95)) could be considered as acceptable (table 1), but the noise level was considered high. In lift performance (Figure 2) it can be seen that there is a problem in achieving the nominal speed during downward trips without load. This could be due to the machine not having enough electrical power, an error in the load balance or high friction due to sliding between guide shoes and guide rails.

Different measurement points are selected, including points close to machine shaft bearings, machine frame isolator and guide supports. The analysis of these measurement results will give insights to discover vibration problems. The *vibration measurements in the machine* area are carried out by means of accelerometers placed on the machine in radial directions, both vertical and horizontal (see figure 3). These measurements permit the obtaining of rotational frequencies, the power supply frequency and its harmonics, as well as the machine vibration peaks. These measurements allow us to obtain the vibration severity of the machine based on its vibration spectra. The vibration severity is calculated in velocity units (mm/s) at a range from 1Hz to 1000Hz, because gearless machines have low rotational speed. The machine vibration frequencies measured are compared with the technical data label of the machine to verify that the inverter parameters are correct. The technical data of the machine can be seen in table 2.

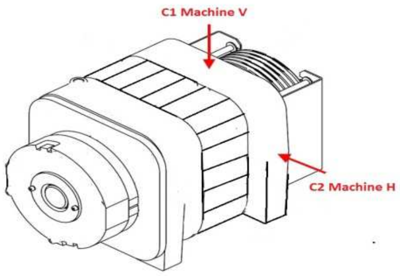


Figure 3 Accelerometers on Machine

Technical data	
Rotation speed (n_M)	**239 min^{-1}**
Power supply freq (F_N)	31,9 Hz
Pulley diameter	160mm
Roping	2:1

Table 2 Machine Characteristics

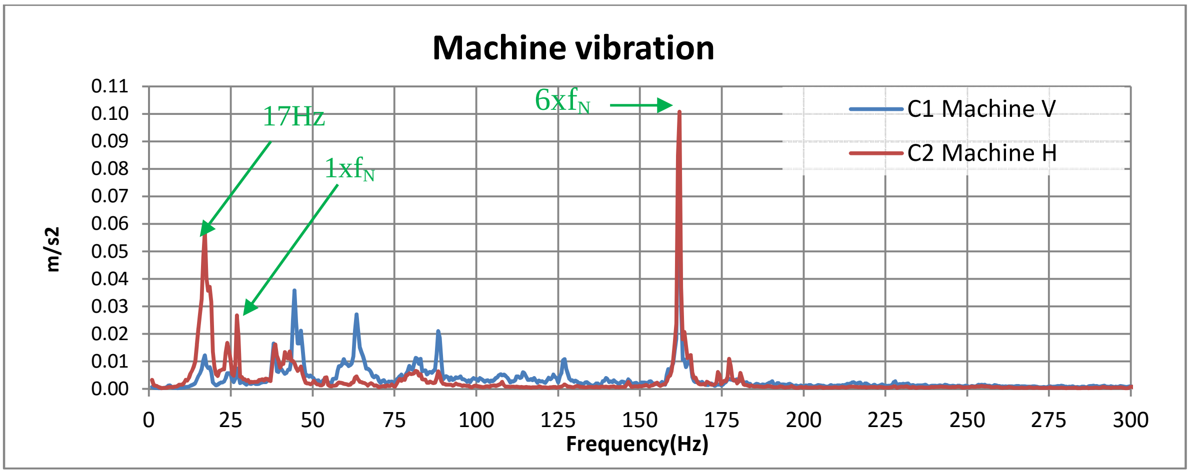


Figure 4 Machine vibration spectra

The machine data show that the nominal speed is 1m/s, but previous performance measurements show that the nominal speed is 0.85m/s, therefore for speed V= 0.85m/s the following frequencies are calculated:

$$f_N = 0.85 \text{ x } 31.9\text{Hz} = 27.1\text{Hz} \quad \Rightarrow \quad 6 \text{ x } f_N = 162.5\text{Hz}$$

The vibration spectra show a peak at 27.1Hz, which is $1xf_N$ (power supply frequency), with higher amplitude in horizontal direction and a peak at 162 Hz, which is $6xf_N$ (6^{th} harmonic of power supply), with similar amplitudes in vertical and horizontal directions. A peak at 17Hz also appears in the horizontal direction in the spectra, which could be caused by a pitch of the machine in a horizontal direction or a resonance of the frame structure. The vibration severity is higher in the horizontal direction (1.3mm/s) due to the possible pitch around the machine axial axis above the isolators at low frequency.

The vibration transmissibility through the machine frame isolators can be obtained by means of accelerometers placed on the machine and accelerometers placed on the machine frame. The vibration transmissibility is calculated at the range 0-200Hz (Figure 5), but the transmissibility is analysed only at the main vibration peaks of the machine in a vertical direction because the higher vibration values on the machine frame are related with the main vibration peaks of the machine. The vibration transmissibility is defined as the ratio of the vibration amplitude on the machine frame and the vibration amplitude on the machine plate (FRF – Frequency Response Function). Figure 5 shows that the isolators are not working correctly at around 150Hz.

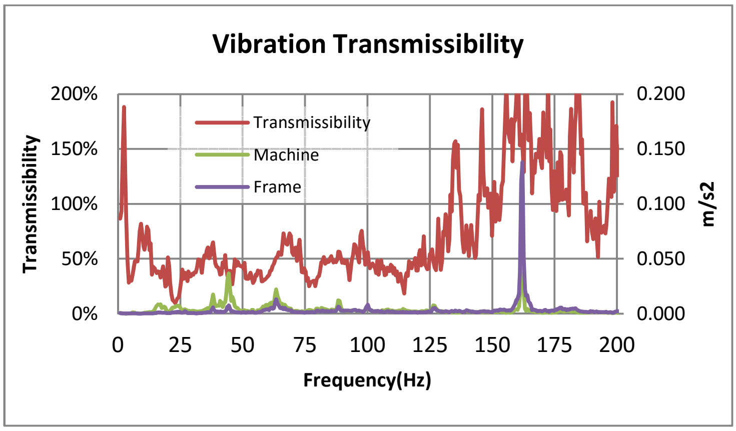


Figure 5 Vibration transmissibility through isolator

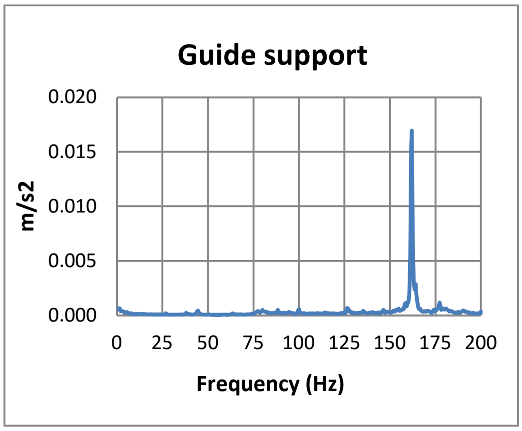


Figure 6 Guide support vibration

Furthermore, the vibration on the guide supports (figure 6) near the machine frame is measured by an accelerometer in a horizontal direction, because, depending on the hoistway structure (metallic, cement), the structure vibration could produce a high noise level inside the hoistway and therefore increase the noise level inside the lift car.

The *noise measurements* are taken inside the lift car and in the hoistway, near the machine and above the roof car. These measurements permit the obtaining of the noise equivalent level (L_{eq}), the noise evolution during the trips, the noise spectra at 1/3 octave band, and the contribution of the machine frequencies and converter frequencies by means of FFT analysis in spectra 1/3 octave band. The noise levels allow us to estimate whether the noise transmission is mainly airborne or structural through the hoistway to the car.

The noise equivalent levels inside the lift car are lower than the levels in the hoistway (Table 3). The main contribution to L_{eq} inside the car corresponds to the 160Hz band (Figure 7). In the noise spectra in the hoistway, the 160Hz band is not predominant, and there are other bands that have a similar contribution to the L_{eq} (Table 3).

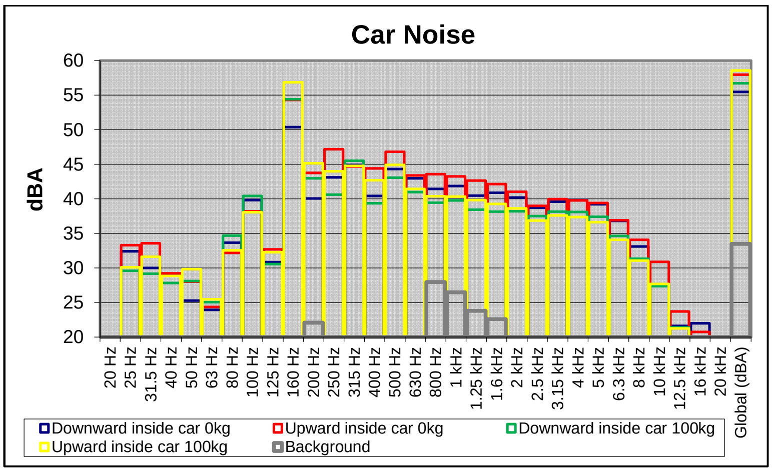


Figure 7 1/3 Octave band noise in Car

	Noise Equivalent Level (dBA)			
	Downward 0kg	Upward 0kg	Downward 100kg	Upward 100kg
Machine	61,4	63,0	61,8	62,8
Above Roof	60,7	62,0	62,2	62,4
Inside Car	55,5	58,0	56,7	58,6
	Noise Level at 160Hz (dBA)			
	Downward 0kg	Upward 0kg	Downward 100kg	Upward 100kg
Machine	50,4	48,1	48,9	48,0
Above Roof	48,6	51,6	51,0	52,4
Inside Car	50,4	54,3	54,4	56,9

Table 3 L_{eq} and L_{A_160Hz} in Car (dBA)

The noise FFT spectra inside the car show that the predominant peak appears at 162Hz (6^{th} harmonic of F_N) and this peak is the main contributor at the 1/3 octave band of 160Hz (Figure 8). The noise transmission from the hoistway to the car is obtained by deducting the levels above the car roof from the levels inside the car. Positive values (levels inside the car are higher than levels in the hoistway) denote that structure-borne has a higher contribution than airborne (Figure 9). The results show that at 160Hz the noise inside the car is mainly structure-borne. This band contains the 6^{th} harmonic of power supply frequency. The noise level values at 1/3 octave band of 160Hz near the machine, above the roof and inside the car are shown in Table 3.

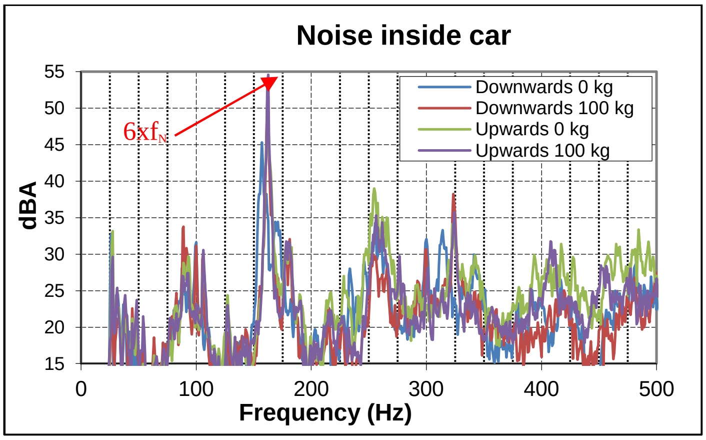


Figure 8 FFT spectra noise in Car

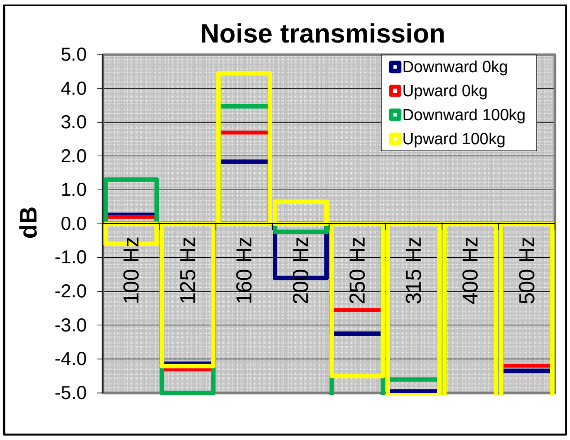


Figure 9 Noise transmission

The *vibration transmissibility through the load cells* between car floor and car frame is obtained by means of accelerometers placed on joint points of load cells. The vibration transmissibility (FRF – Frequency Response Function) is calculated at the main vibration peaks on car floor related to the machine vibration frequencies. The vibration transmissibility at 162Hz can be seen in table 4.

162 Hz	Vibration transmissibility through load cells			
	Load Cell 1	Load Cell 2	Load Cell 3	Load Cell 4
Downwards 0 kg	38%	42%	85%	84%
Downwards 100 kg	32%	31%	81%	81%
Upwards 0 kg	27%	34%	59%	71%
Upwards 100 kg	22%	22%	52%	56%

Table 4 Vibration transmission through Load Cells

The *vibration measurements on the car panels* (lateral, roof and floor) are carried out with the purpose of determining whether there is any car panel that vibrates with a higher amplitude, causing structural noise transmission towards the car passengers. Accelerometers are placed at the centre of the main panels: Lateral panel, keyboard panel, roof panel and floor panel. The FFT spectra (Figure 10) show that the main vibration peaks appear at 27Hz and 162 Hz ($1xF_N$ and $6xF_N$), especially in the roof panel. Therefore the roof vibration could be increasing the noise inside the car.

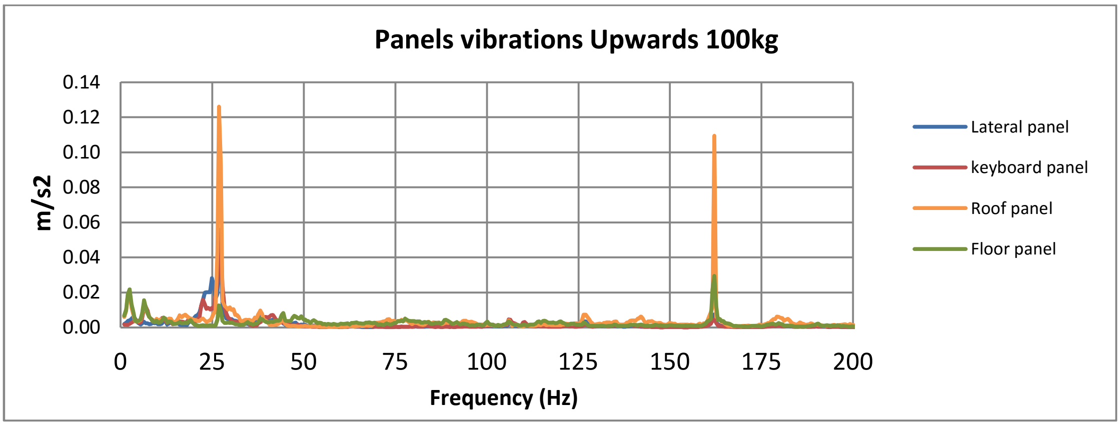


Figure 10 FFT spectra vibrations of panels

The *Operational Modal Analysis (OMA)* and the *Operational Deflection Shapes (ODS)* are the techniques that help understand what the vibration shape is like and to get ideas on how to reduce it. In this case it is applied to some components and panels because, based on the different vibration measurements in the lift, it was found that the machine frame and car roof have a higher vibration amplitude at 162Hz. Therefore, the machine frame and roof panel were selected to obtain their mode shapes (2-200Hz) and to check if there is any mode near to harmonics of the power supply frequency that may increase its vibration. The roof has a mode at 166Hz (Figure 11); this mode shape is near 162Hz, therefore this mode may be self-excited by the 6th harmonic of the power supply frequency (162 Hz). The machine frame has the 5th mode shape at 164.2 Hz (Figure 12), therefore this mode may also be self-excited by the 6th harmonic of the power supply frequency, thus increasing the vibration and noise levels in the lift car. The mode shape at 164.2 Hz can be seen in the figure below. The shapes are similar to the *Operational Deflection Shapes (ODS)* obtained during normal operation.

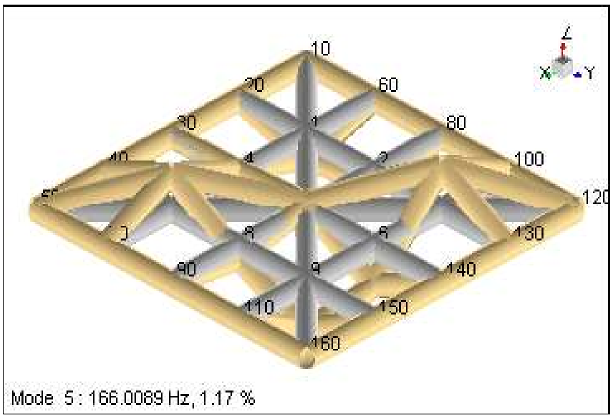


Figure 11 Mode Shape of roof at 166Hz

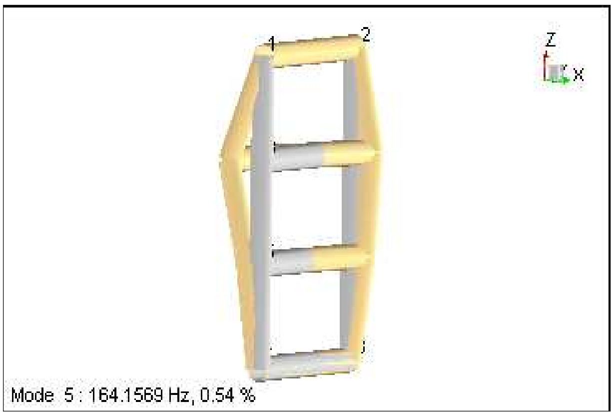


Figure 12 Mode Shape of Machine- frame at 164 Hz

Based on the previous analysis, the actions proposed to improve the performance, ride quality, and to decrease the noise and vibrations would be:

- Review the correct load in the counterweight.
- Reduce the friction force between the guide shoes and guide rails.

- Review the machine, trying to minimise the harmonic peaks of the power supply frequency that could affect comfort in the car.
- New design of machine frame (change the modes at 166Hz by design).
- New design of the isolators on the machine frame to work better at the 6th harmonic of the power supply frequency. The problem is the high vibration level of the machine frame even though the isolators are well designed.
- Minimise the noise levels of the source of excitation (machine) to decrease the noise level inside the hoistway and minimise the airborne noise inside the car.
- Increase the damping of the roof panel or change its stiffness to decrease its ability to generate noise by vibrations. For instance, adding rubber sheets to the roof.
- Minimise the structure-borne noise inside the car by improving the isolation of the load cell between the car frame and floor frame.
- Improve the isolation between the machine and the guide support to decrease the noise transmission to the adjacent room.

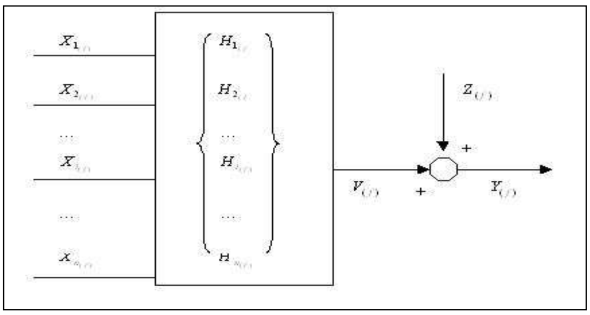
2.2 "Sources contributions to noise inside lift car" methodology

This methodology consists of applying techniques to identify and quantify noise and vibration sources, using frequency response and coherence functions in lifts.

The procedure consists of:

- Selecting the receptor and sources of vibration and noise.
- Obtaining the global contribution of the sources selected to the noise inside the car by means of "*Multiple Coherence*" (A function in a frequency domain expressing relationship, causality or dependence.)
- Obtaining the contribution of each source to the noise level inside the car by calculating the Transfer Matrix (H) between each source and the receptor. "*Output Power Allocation*" technique.

The multiple coherence provides a measurement of the dependency between a set of *n inputs (X1...Xn)* and *one output (Y)*, independent of the correlations among the inputs.



$$Y_{(f)} = \sum_{i=1}^{n} H_{i(f)} \cdot X_{i(f)} + Z_{(f)} = V_{(f)} + Z_{(f)}$$

$$G_{yy} = \{H\}^{t} \cdot [G_{xx}] \cdot \{H\}^{*} + G_{zz} = G_{vv} + G_{zz}$$

$$\gamma_m^2 = \frac{G_{vv}}{G_{yy}}$$

Figure 13. Multiple Input – Single output model

In the previous equations, $Y_{(f)}$ is the Fourier transform of the output $y_{(t)}$, $X_{i(f)}$ is the Fourier transform of the input $x_{i(t)}$, $H_{i(f)}$ is the Frequency Response Function between the input $x_{i(t)}$ and the output $y_{(t)}$, $Z_{(f)}$ is uncorrelated noise at the output, and $V_{(f)}$ is the output fraction, related to all inputs. Then the equation is transformed to a spectral matrix, G_{yy} is the output power spectrum, $[G_{xx}]$ is the input spectral matrix, G_{zz} is the output noise power and G_{vv} is the coherent output power and γ^2_m is the multiple coherence function.

The "*Output Power Allocation*" identifies the frequency response functions of the transmission (H). Each contribution is defined as the input (X) multiplied by the effect of the transmission path (H). The output can thus be written as a sum of contributions (amplitude and phase) from each input.

$$H_{(f)} = {}^{Y_{(f)}}\!/\!{}_{X_{(f)}} = \frac{Y_{(f)} \cdot X^{*}_{(f)}}{X_{(f)} \cdot X^{*}_{(f)}} = {}^{G_{xy}}\!/\!{}_{G_{xx}} \qquad \boxed{\{G_{xy}\} = [G_{xx}] \cdot \{H\}} \qquad \begin{pmatrix} G_{11} & G_{12} & G_{13} & \dots & G_{118} \\ G_{21} & G_{22} & G_{23} & \dots & G_{218} \\ \dots\dots & \dots\dots & \dots\dots & \dots & \dots\dots \\ G_{181} & G_{182} & G_{183} & \dots & G_{1818} \end{pmatrix} \times \begin{pmatrix} H_1 \\ H_2 \\ \dots\dots \\ H_{18} \end{pmatrix} = \begin{pmatrix} G_{1y} \\ G_{2y} \\ \dots\dots \\ G_{18y} \end{pmatrix}$$

The interpretation method is algebraic. The individual contribution and the combining effect are quantified by a triangular scalar matrix. This technique is computationally complicated; the algorithm program and visualisation is implemented in Matlab for each frequency. The visualisation shows the contribution of the different inputs (blue colour) to the output spectrum (red colour). The contribution of the sources at different frequencies can be seen in different diagrams of figure 14. These visualizations permit us to identify the sources which provide the main contributions to the output.

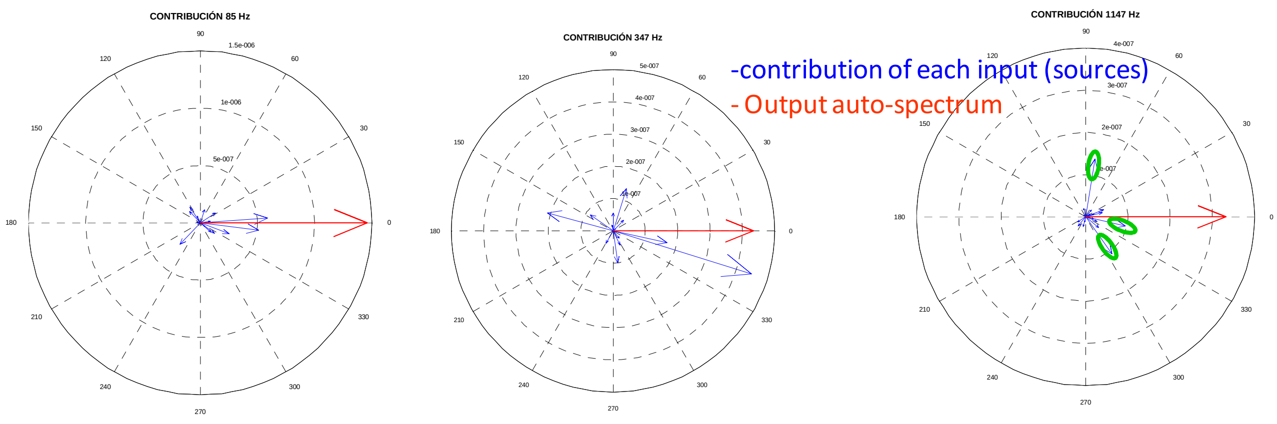


Figure 14 Visualisation of contributions

2.3 "Panel Contributions to noise level inside lift car" methodology

This methodology is based on considering that the car panels are a series of sources with their sound power. The sound power of sources is obtained by means of acceleration measurements at the different points of car panels. The pressure inside the car will be computed with the sound power sources.

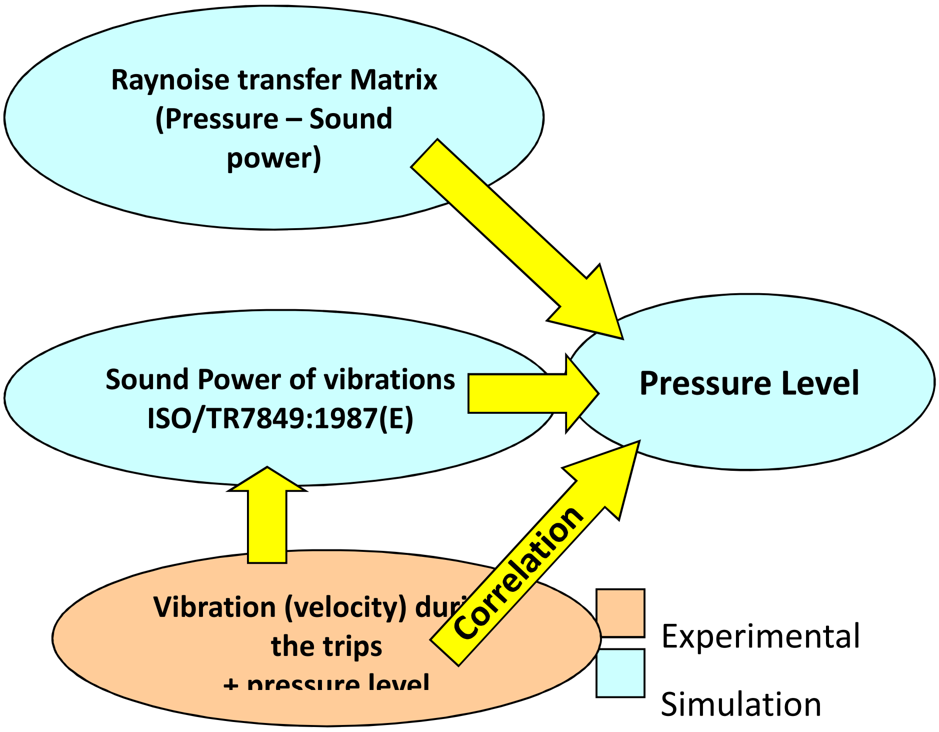


Figure 15 Methodology summary

The Transfer Matrix is obtained with Raynoise software. This software is based on the Mirror Image Source Method and the Ray Tracing Method.

The acoustic sources of the panels are determined from the acceleration measurements in different points of panels according to standard ISO/TR 7849 [5]. The sound power radiated by a vibrating surface may be determined by:

$$P_s = \rho c \bar{v}^2 S_s \sigma$$

P_s=Sound power
ρc = specific acoustic impedance of the fluid
v^2 = Mean square surface-averaged velocity
S_s = surface area
σ = radiation ratio

Finally, the sound pressure evaluation is calculated, and the model is correlated with the experimental results.

3 CONCLUSIONS

The "Vibro-Acoustic characterisation on lift" methodology enables us discover how much the different sources (vibration and noise) qualitatively affect the receptor, therefore it enables us to know which lift components need to be changed in order to achieve our goal, namely, to improve the ride quality. However, the improvements are estimated roughly.

The "Sources contributions to noise inside lift car" and "Panel Contributions to noise level inside lift car" methodologies permit obtaining quantitative results of the contribution of the sources, but their application and analysis are complex. Thus, the time spent is much greater in comparison with the first methodology.

Therefore, the first methodology is perfect for troubleshooting activities whilst the other two are more advisable for R&D activities.

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BIOGRAPHICAL DETAILS

Raúl Monge

Mechanical Engineer by the University of Zaragoza. His professional career in the Institute has been linked to different R&D areas, above all, solutions to noise and vibration problems in different systems and components (lifts, automotive, construction machinery, railway) with knowledge in applying different techniques, such as system dynamic response (frequency analysis), experimental modal analysis, operational modal analysis, operational deflection shapes. Noise contribution of sources, airborne and structure-borne transmission of sound. Isolation of vibration by means of passive elements and semi-active elements, including the system simulation model

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Floor Warden Control – a New Concept for Evacuation Lifts

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Keywords: evacuation lift, fire, Emergency Response, Floor Warden, innovation.

Abstract. We are introducing the Floor Warden (FW) controlled lift as a new concept for evacuating building occupants with the help of lifts. Existing evacuation lift concepts have the lift controlled either manually, by a member of the Emergency Response Team (ERT) present in the car, or (semi-) automatically supervised by an external third party Building Management System (BMS) and monitoring thus allowing self-evacuation. In the FW concept the lift is also manually controlled by a member of the ERT, but from the floor that will be evacuated, instead of being controlled from inside the car by a dedicated member of ERT. The advantage of this concept is that there is no need to appoint an extra ERT member exclusively for controlling the lift, thus making more efficient use of the ERT organization. On top of that the lift capacity is also used more efficiently, because 100% of the lift capacity is available for occupants that need to be evacuated. Based on this concept, we developed a system that can operate fully independently from external third party building systems, and has its own integrated intercom. It is therefore easy to implement in new or existing buildings. The system that we developed appears to be very simple in use. Details of the concept and its development are discussed in this paper.

1 INTRODUCTION

As a starting point of our development we analysed the current situation with regard to lifts being used for evacuation. The result of this study was published in a previous article [1]. One of the conclusions was that the various concepts that are available are rather complementary to each other, so there will be a market for each of them. However, another conclusion was that there is room for further development, more specifically for the development of a control system allowing a lift to be controlled from the landing of the floor that needs to be evacuated, rather than being controlled from inside the car. In the following sections we will give more comments about the current situation, and then explain our development of the Floor Warden control system.

2 CURRENT SITUATION / STATE OF THE ART

2.1 Literature

A long list of articles has been published about using lifts during fire emergencies. This proves the long existence of interest in this topic. In contrast to this literature the developments in this field seem to go relatively slowly, which can be explained by the concern which exists when it comes to actual application.

The main concern being discussed in literature is that of functioning of the lift being threatened by the results of fire, such as heat, smoke, water, or loss of power. As a result of all the literature one could come to the conclusion that there seems to be a certain common understanding of what would be needed to protect a lift against those threats.

A useful study of the literature in place is published by NIST as "Special Publication 1620" [2]

2.2 Practice

In our previous articles we have already discussed the evacuation lifts being applied as of this moment, especially with respect to ultra high buildings. Examples of such ultra high rise buildings are the Petronas Towers and Burj Khalifa [1,3] where the "Life Boat" principle is applied, as described by Fortune [4]. According to this principle, occupants will first escape to a safe refuge floor, from which shuttle lifts will bring them to the main evacuation exit.

In the UK one will find more examples of lifts being assigned as evacuation lift, as the UK implemented the BS9999 [5] which specifies certain requirements for evacuation lifts.

In other countries, such as the Netherlands, if lifts would be applied for evacuation, the lift would be fitted as a firefighter lift in accordance with EN81-72 [6]. In some high buildings in the Netherlands arrangements are made with the fire brigade, allowing one of the two available firefighter lifts to be used as an evacuation lift. In these cases, members of the building's Emergency Response Team (ERT) are allowed to use the lift for that purpose. Examples of such buildings are Delftse Poort in Rotterdam and Rabobank Headquarters in Utrecht.

2.3 Regulations (codes and standards)

The main regulations that are currently in place for evacuation lifts are BS9999 in the UK, and A17.1 in North America [7].

The BS9999, "Code of practice for fire safety in the design, management and use of buildings" was published by BSI in the UK in 2008. It deals with fire safety of a building in general, but it dedicates one chapter to evacuation of the disabled, and some paragraphs to evacuation of persons in wheelchairs. Annex G of the document specifies recommendations for evacuation lifts and discusses the construction of the environment of the lift, the refuges, the power supply of the lift and the control of the lift. For the control of an evacuation lift 2 persons are needed: one person inside the lift for controlling it, and one on the main floor for coordination and communication.

The American Society of Mechanical Engineers (ASME) published in 2013 the document A17.1, "Safety Code for Elevators and Escalators". It describes Occupant Egress Operation (OEO) which allows occupants that are within the five closest floors to an emergency, to call for the lift and evacuate themselves. This is thus a completely different approach than the BSI approach presented in BS9999, and it aims at contributing to fast evacuation of any occupants from high rise buildings, rather than focusing on disabled persons or persons in wheelchairs.

Other regulations are still under development such as the draft prEN81-76 being developed by CEN with the aim of coming to a harmonized standard based on published technical specification CEN/TS 81-76 [8]. The approach is quite similar to that of BS9999, aiming at evacuation of disabled persons. In 2014 ISO published a Technical Specification ISO/TS 18870 "Requirements for lifts used to assist in building evacuation" in order to get some experience on the market before publishing it as an ISO standard [9].

Around the world building regulations are making more and more reference to using lifts for evacuation either for disabled persons in any building, or in the case of high rise buildings not only for disabled but for any occupants.

2.4 Summary of the current situation / analysis

Summarizing the current situation we could say that lifts are more and more accepted as a means for evacuating occupants from a building. In practice the focus is on high rise buildings where the Life Boat principle is applied, or where one out of two firefighter lifts is available for evacuation. Another focus is on evacuation of disabled persons. There seems good common understanding of the way the functioning of the lift should be protected.

With regard to control systems for evacuation lifts, we feel that there is room for development. At this moment evacuation lifts would be controlled either (semi-) automatically, or manually from inside the car (see Fig. 1, left side). However, in many cases controlling the lift from the landing being evacuated would lead to certain advantages and more effective evacuation.

This is why we developed the Floor Warden control. The advantages of this concept will be discussed in the following parts. From our point of view these various kinds of control are complementary to each other (see Fig. 1, right side). In some cases they could even be combined in a single building.

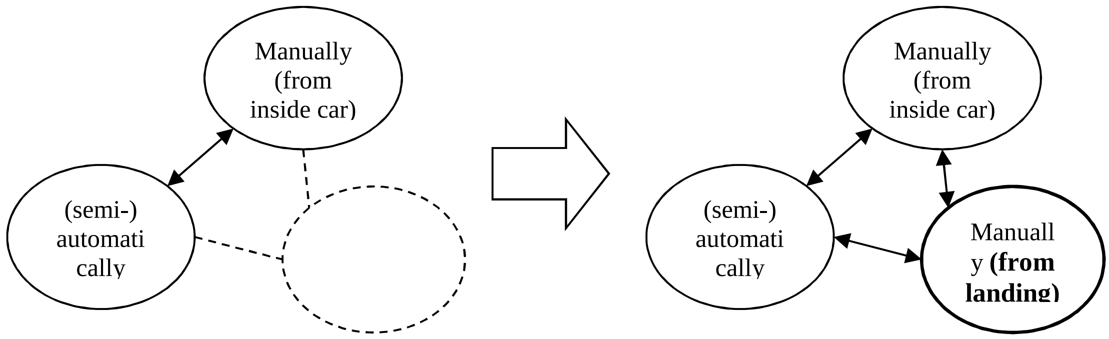


Figure 1 A new concept for the control of evacuation lifts

3 THE FLOOR WARDEN CONCEPT

3.1 Starting point

In our Floor Warden concept, the evacuation lift is not controlled from inside the car (manually, such as in BS9999), and not semi-automatically (as in A17.1), but from the landing that needs to be evacuated. Many buildings will have a kind of Emergency Response Team (ERT) or similar kind of organization. Within such organizations Floor Wardens are often appointed. These Floor Wardens would be the suitable persons to call for control over the lift in need of an emergency. This is why we called our concept the Floor Warden concept, sometimes abbreviated with 'FW'. One of the applications of the FW-control would be for the earlier mentioned Life Boat principle where occupants gather at a refuge floor, and lifts will shuttle between that floor and the main evacuation exit floor. The FW-concept makes it feasible to use this principle not only in very tall buildings but also in smaller buildings, and serving more than only one refuge floor. Indeed, all floors could be served if the number of emergency staff is sufficient.

With the Floor Warden concept we aim to achieve the following benefits (see Table 1):

Table 1 Aimed-for benefits of the Floor Warden concept

Aimed-for benefit	Explanation
Efficient use of ERT organization	There is no need to appoint an extra ERT member exclusively for controlling the lift or coordinating such as in BS9999. So, the staff of the ERT organization can be used more efficiently.
Reduced psychological work load	In the existing concepts the one person in the car has a complex task with large responsibility. This is reduced.
Panic Control	By controlling the lift from the landing, it will be easier to reassure occupants that remain on the landing if the car is full. And in the worst case it will allow the floor warden to keep persons away from the landing doors while closing.

Saving car space	The lift capacity is used more efficiently, because 100% of the floor area is available for occupants that need to be evacuated.
Wide range of applications	Our concept relates to a way of controlling the lift, but it is not restricted to certain application. For example it can be used for small buildings serving each floor for evacuation of disabled persons. But it can also be applied as the control system for Life Boat lifts that are used in tall buildings for evacuating occupants from intermediate refuge floors.
Simple and low threshold system	Independent from a Building Management System (BMS) or alike, such as required for the system described in A17.1. In addition to the above intrinsic advantages of the principle, the principle also allows the creatione of a system that can (when needed) operate independently from external systems such as a BMS. In order to keep this independency we also included a fully integrated intercom system.

In his article “On the development of Occupant Evacuation Elevators” [10] Dr. Albert So discussed some issues that arise with lifts that are controlled from inside the car. The benefits that follow from our FW concept seem to solve several of these issues mentioned by So.

3.2 Floor Warden control – the basic concept

The concept of the Floor Warden (FW) control is very simple, and has some similarity with the Life Boat principle. The basic routine is as follows (see also Fig. 2):

1) A floor warden takes exclusive control over the lift by operating the FW-key-switch with the special FW-key (either triangular key or unique cylinder key).
2) Any coincidental passengers are first delivered at the Main Evacuation Exit Floor (MEEF) before the lift arrives at the assigned floor of the Floor Warden.
3) Building occupants enter the lift under supervision of the Floor Warden.
4) By continuous pressure on one of the hall buttons, the doors will close and the car will shuttle to the MEEF.
   Step 3) and 4) are repeated until the Floor Warden has fully cleared his own floor.
5) When the floor is cleared, the Floor Warden will join the last group of passengers with their journey to the MEEF. He cannot close the doors with continuous pressure on one of the hall buttons, but instead the doors will close automatically just this one occasion when the Floor Warden gave up the priority control by switching back the FW-key-switch to its original position.
6) The lift will now become available for another Floor Warden on another floor.

The similarity with the Life Boat principle is that the lift will shuttle up and down between one floor and the MEEF. What we added to this principle is:

- We described a method of controlling the lift from outside the car, from the landing being evacuated.
- We developed a method to allow several floors to be served by one lift in an organized way with a simple algorithm for deciding the priority and order of serving: first priority goes to the Floor Warden who activates the FW-control for the first time, when 2 Floor Wardens are

waiting, the control system will pick the Floor Warden who asked for priority on the highest landing.

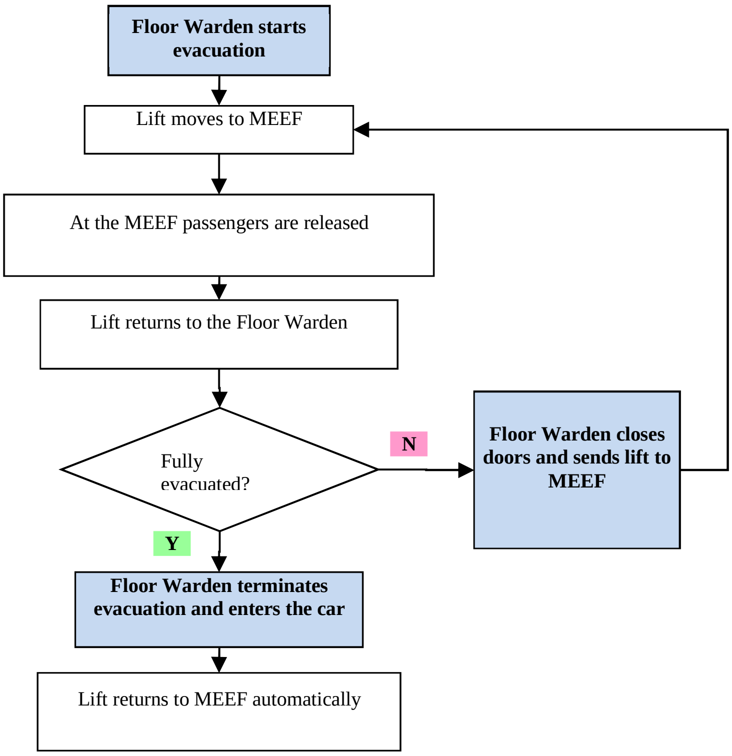


Figure 2 Basic routine of the FW-concept in case of a single Floor Warden

3.3 Applications

The most obvious application of the FW-control is within the Life Boat principle, where one floor in a high rise building is assigned as intermediate refuge floor. One or several lifts will shuttle up and down between this floor and the Main Evacuation Exit Floor (MEEF). The FW-control is particularly suitable for this application (see Fig.3, left example).

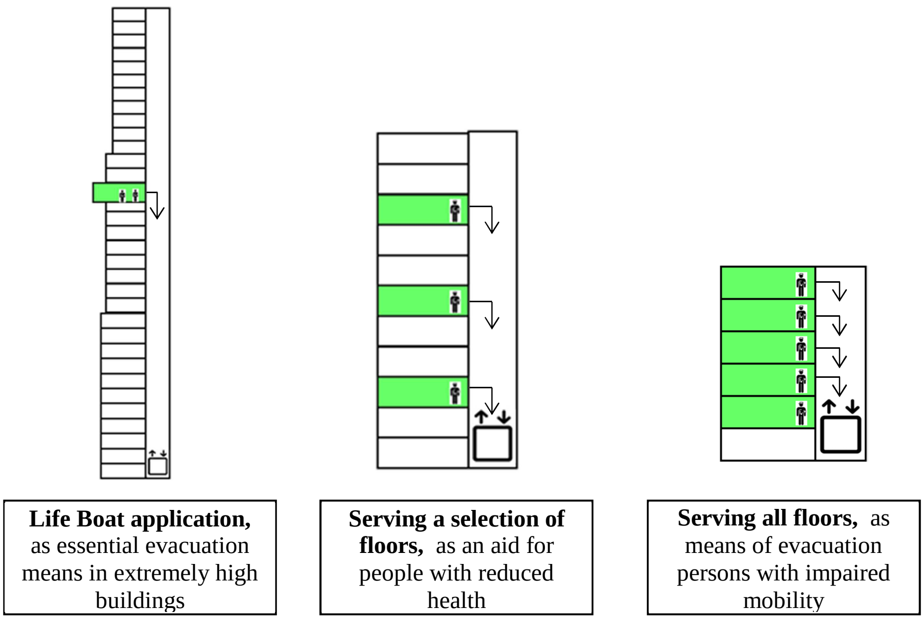


Figure 3 Possible applications of the FW-control system

However, with the system that we developed we aimed to make it applicable for various applications. For this reason we added the possibility to have FW-controls on more than one floor only. As a result it is up to the designer of the building which floors would be dedicated as FW-floors. One option would be to divide buildings into zones, each zone comprising several floors, and each zone to be provided with one collective refuge and FW-floor with FW-controls, as shown in the middle of Fig.3.

The building designer could even decide to install FW-controls on each of the floors. This would especially be the case if the FW-lift is being used as the main measure for evacuating persons with mobility problems or persons in wheelchairs (see Fig.3, right example).

4 DEVELOPMENT OF THE FW-CONTROL

Based on above concept we made a risk assessment, and developed countermeasures and several FW-functions.

4.1 Risk Assessment

As the starting point of our development we made an extensive risk assessment, which was also used to prove the compliance with the Essential Safety Requirements (ESR's) of the Lifts Directive. For this risk assessment we used the format of the risk assessment table as presented in EN-ISO 14798:2013 [11]. Some examples of risks and our countermeasures are presented in Table 2:

Table 2 Risks and countermeasures

Risk	Countermeasure
No fire alarm system in the building, or not functioning	The evacuation, or 'FW-mode' can be initiated by the Floor Warden who is present on the floor where the emergency is by means of FW-key-switch
Floor Warden may forget to give up priority, leaving the lift idle at the floor	1) Continuous pressure on hall button needed to send the lift away. 2) 'Self-evacuation' of Floor Warden only possible by switching the FW-key-switch to normal (giving up priority) 3) Automatic termination of priority after predefined time-out.
Unnecessary time waste at MEEF	1) The door-open time at the MEEF can be adjusted by parameter setting to shortest required time, before returning to the assigned FW-floor (at the MEEF, the door sensor remains active) 2) When rescue staff is present at the MEEF, the doors can be closed manually even before the pre-set time has exceeded.
Other Unnecessary time waste	When present in the building, a fire alarm system can direct the lift to the MEEF allowing coincidental passengers to leave the lift at the MEEF, even before a Floor Warden has initiated FW-control.
Power Failure	1) Power supply shall comply with the same requirements as that of firefighter lifts. 2) A battery pack will allow the lift to bring the passengers to the nearest floor with a protected lobby

4.2 Hall panels with Floor Warden control functions

In our concept, the designer of the building and/or evacuation plan has the freedom to assign one or several floors as 'Floor Warden-floor'. The hall panels on these landings will provide the special Floor Warden controls, either integrated or in a separate Floor Warden panel (see Fig. 4).

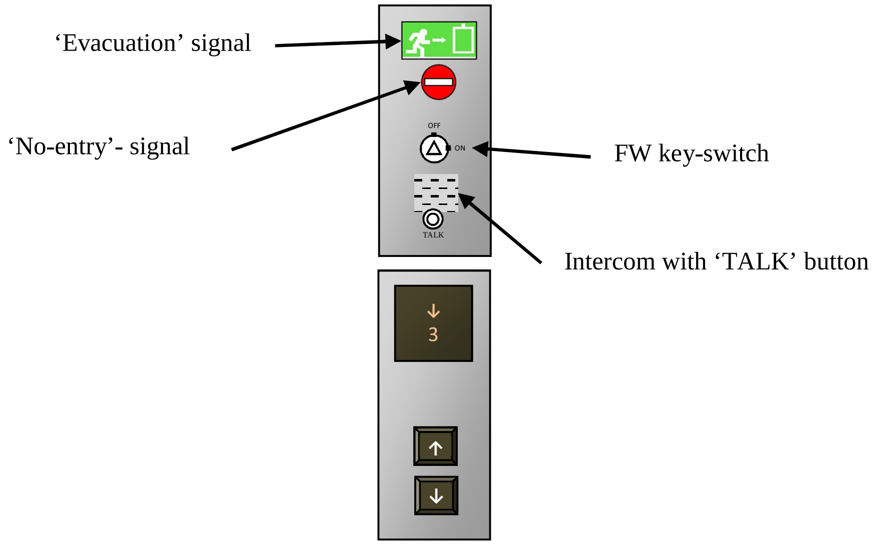


Figure 4 Hall panel with FW-functions

Upon directions of the fire brigade, additional functions can be provided on the main evacuation exit floor, so that the fire brigade can take over the control in a safe manner after their arrival when needed.

4.3 Interaction with building alarm

One of the advantages of our FW-system is that no alarm system is needed to start evacuation with the lift. The system can simply be initiated manually by means of the FW-key switch. However, when an alarm system is present in the building, it may be connected to the FW-system, and direct the lift to the main evacuation exit floor in a similar manner as described in EN81-73 [12]. This would further reduce the time for evacuation, because it will already release any passengers who happen to be traveling with the lift when an emergency is detected by the alarm. This would eliminate such home-return trip, which otherwise would be necessary when the FW-key switch is operated, while passengers are still using the lift.

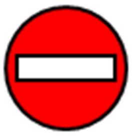
4.4 Monitoring

The FW-control system is equipped with interfaces allowing signals from detection systems monitoring the safe environment of the lift. Some basic monitoring is always provided as a standard. When a dangerous situation is detected, the lift will be put out of service in a safe way, and this will be indicated by the 'No-entry' signal on the FW-panels.

4.5 Signalization

The FW-control system is provided with 2 signals, the 'lift-evacuation' or 'evacuation' signal (internally we would abbreviate this as the EV-signal), and the 'no-entry'- signal. The illuminated status of these signals shows the operational mode of the lift. The meaning of the illuminated signals is explained in Table 3:

Table 3 Signalization & mode of operation

Signal	Operational mode	Remarks
No signal illuminated	Normal service	
Evacuation signal illuminated continuously 	Floor Warden operation	One Floor Warden has operated the FW-key-switch and has control
Blinking 	Waiting queue	One Floor warden has control, a second Floor Warden has also operated the FW-key-switch and is waiting for control
No-entry signal 	No service	Situation 1) the building alarm has terminated normal service, the lift is ready for FW-control Situation 2) FW-control overruled, either by building monitoring, or by fire service.

4.6 Intercom

During FW-mode, an intercom system allows the Floor Wardens to communicate with passengers in the car, and also with each other. Floor Wardens will need to press a 'TALK'-button, to make themselves heard. Passengers do not need to press a button; the microphone in the car is always open when the lift is in FW-mode. The messages will be heard on all intercom stations.

5 EVALUATION

5.1 Review of prototype

Apart from the risk assessment, which was revised several times, we built a prototype and had it reviewed by experts and users with different backgrounds. This helped us to further improve the design of our FW-system. Even after the type certification of our system by the Liftinstituut, a well respected notified body from the Netherlands, we continued with reviewing and further improvement.

5.2 Evaluation of aimed benefits

As a conclusion of this paper we make an evaluation based on the benefits that we aimed for when we started the development. The evaluation of these benefits is listed in Table 4 below.

Table 4 Evaluation of the aimed-for benefits of the Floor Warden concept

Aimed-for benefit	Evaluation
Efficient use of ERT organization	**Achieved**. No need to appoint 2 extra members for controlling the lift as in prEN81-76 or BS 9999 ***Remark:*** Each assigned floor will need at least one Floor Warden. In some cases this may result in a need for extra staff. Some floors may need extra staff for controlling the FW-lift
Reduced psychological work load	**Achieved**. No person has the single responsibility of controlling the lift until evacuation has completed. Floor Wardens have good overview and control over their own floor.
Panic Control	**Achieved**. Floor Warden at the floor can reassure passengers who are waiting, and if needed the Floor Warden can guard off the lift door when closing.
Saving car space	**Achieved**. No need for a Floor Warden to be present in the car. Car capacity fully used for evacuation of occupants ***Remark:*** This benefit only counts when larger groups need to be evacuated.
Wide range of applications	**Achieved**. The FW-system can be applied both in low rise as in extreme high rise, and intermediate rise. It can be applied for evacuation of occupants with mobility problems, serving every floor, or large groups in tall buildings. ***Remark:*** Only applicable in buildings where there is some form of emergency organization ***Remark:*** There is a limitation in the number of floors that should be served by one single lift in order to avoid waiting queues;
Simple and low threshold system	**Achieved**. Intercom is integrated and, if needed, the FW-system can be used as simple standalone system, independent from fire alarms or other third party building systems. Controlling the FW-system appeared to be simple and easily understood.

6 CONCLUSION

We have developed a new control system which can be used effectively for evacuation of occupants from buildings where some kind of emergency organization is present. The FW-control system is controlled from the landing on the floor that needs to be evacuated. This is a new way of controlling, and is a useful supplement to the control systems that already existed. When starting the development we aimed to develop a simple and low threshold system, that is simple to use and with a broad range of applications. The system that we developed seems to meet these goals. We obtained type-certification under the Lifts Directive, and the development is now reaching its final steps.

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BIOGRAPHICAL DETAILS

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Challenges of Low-Voltage Energy Storage for Lifts

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Keywords: Efficiency, energy recovery system, energy storage, energy buffering

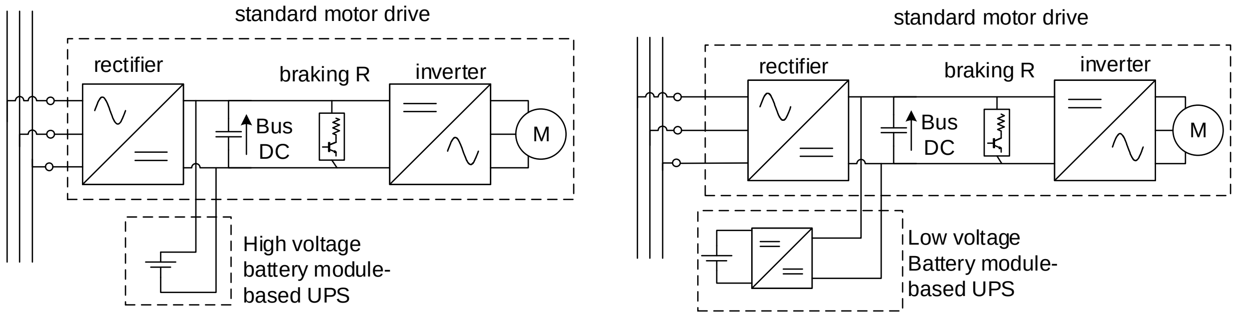
Abstract. Nowadays, the lift industry is moving towards finding new solutions for energy management. Examples of this are energy recovery systems based on local storage in ultracapacitors, battery-powered lifts for peak power consumption mitigation and improved UPS operation, solar and/or wind powered lifts, among others. Most of these new concepts include energy storage systems, so they require batteries and/or ultracapacitors, depending on the energy to be stored and the power cycling profile. As a matter of fact, both batteries and ultracapacitors are low voltage technologies, whereas lift traction systems are based on well-known three-phase industrial AC drives, operating at high voltage levels of around 600V at their DC bus. One of the possible solutions consists of the serialization of a large amount of basic cells until industrial voltage levels are reached. This solution, though apparently simple, is not practical because it is expensive and safety and reliability problems are multiplied. Thus, a practical energy storage system for lift applications should operate at around 48V, which is a safe, commercially standard and cost-effective voltage level.

Some modifications are required if a 48V energy source must be integrated in a lift traction system. There are two possible options. First, (bidirectional) DC-DC converters can be used interconnecting low-voltage 48V to conventional lift traction systems at 600V. Second, the entire traction system can be redesigned so as to operate at 48 V. This work shows the technical challenges of the integration of low-voltage energy storage systems in lift traction systems. Issues related to efficiency, cost, availability of required parts for production, flexibility of use and others are analysed. This way it is possible to identify the key challenges and the best suited solutions in each case.

1 INTRODUCTION

In recent times customers have been demanding products that turn around local energy storage ability and lift manufacturers are providing solutions [1-7]. Standard energy storage devices are primarily based on chemical batteries, and therefore lifts with electrical traction systems are the best suited ones for this type of adaptations. Ultracapacitor technology is relatively new but its advantages in terms of number of cycles and power density make them ideal for applications that require a high number of high power charging and discharging cycles [6],[8]. Next some application examples with batteries and ultracapacitors are shown:

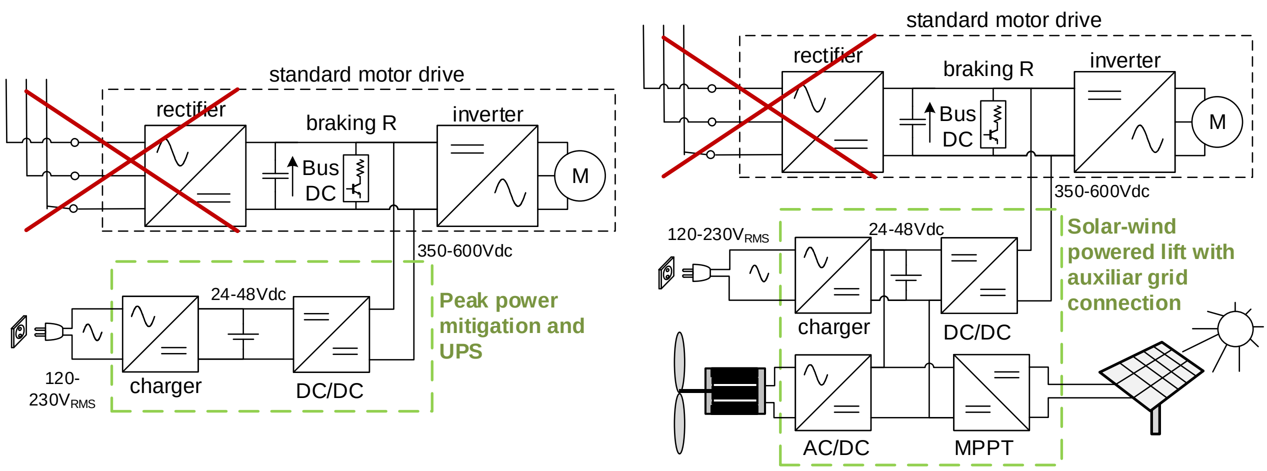
a) Extended UPS (Uninterruptible Power Supply) operation: some customers require to keep the operation of the lift even under long-term line black-outs. Among other solutions, an easy way out is to connect a battery module to the DC bus of the inverter, see Figure 1.a. Typical operating voltages are around 600V so a big amount of batteries must be serialized, which leads to an oversized energy storage capability. Moreover, special safety and battery management circuitry must be included, which makes this solution practical but expensive. In the same way, due to the fast ageing of batteries, operation costs are incremented. Another solution is just to interconnect a set of low voltage batteries with the high voltage DC bus through a DC/DC converter, see Figure 1.b.



a) b)

Figure 1 Different configurations for UPS function: a) with high voltage battery module, b) low voltage battery module plus DC/DC converter

b) Energy buffering and/or peak power mitigation for lifts: electrical consumption by lifts is characterized by cycles of high power peaks during acceleration or deceleration and (typically) half the peak power during steady travel. The peak power determines the installation and operation costs of the connection to the grid. The peak value could be one order of magnitude higher than the average power. This fact is particularly relevant for residential lifts where, due to the low number of travels, the total amount of required energy is very low. Installation and operation costs could be reduced if the lift is fed from a set of batteries that are permanently charged from the grid at a very low peak power rate, see Figure 2.a. Other benefits of this system are extended UPS functionalities and lower line-perturbations. This system can be complemented by an ultracapacitor-based storage system, thus minimizing high power demands from the battery and therefore increasing its life expectancy.



a) b)

Figure 2. a) Energy buffering and/or peak power mitigation system, b) Solar and/or wind powered lift with back-up grid connection

c) Solar and/or wind-powered lift: new trends related to energy efficiency and harvesting have pushed several manufacturers to offer systems that are powered by solar and/or wind energy sources. Typically batteries are used in order to store the generated energy and provide the demanded power to the lift. Both solar and wind powered sources are interfaced through power electronic devices so standard low-voltage battery modules at 48V can be used, see Figure 2.b. If a standard lift inverter must be used, a DC to DC power converter is required in order to connect the low-voltage battery storage system to the high-voltage (600V) DC bus at the inverter. If solar and/or wind energy resources are not enough to keep the elevator working, a back-up low-power grid connection can be added.

d) Energy recovery systems (ERS): lifts with gearless traction systems, high traffic and good levels of mechanical efficiency (around 80%) regenerate a considerable amount of energy that nowadays is lost at the braking resistor or transferred back to the grid. Thanks to ultracapacitor-based energy storage system (see Figure 3) it is possible to store this energy during braking phases and reuse it during demanding traction phases. Additionally, using the same hardware and without supplementary cost, it is possible to cover the peak power mitigation functionality.

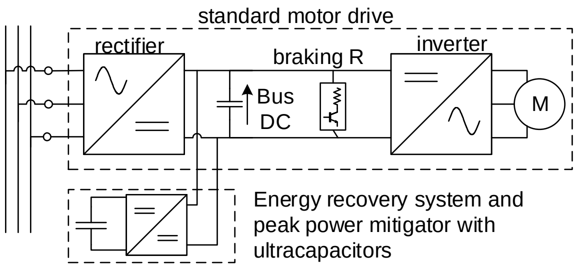


Figure 3 Energy recovery system with peak power mitigation functionality based on ultracapacitors

Previously listed applications require different energy and power ratings but their storage voltage levels and some components are common.

2 ENERGY STORAGE REQUIREMENTS

Basically there are two energy storage scenarios. First we have the long-term large-energy exchange case. This is the situation when extended UPS functionality or solar & wind energy is required and the lift must perform as much as 100 or more trips using its own stored energy. In this case the energy storage sizing is determined by the required energy and therefore the power exchange capability is much larger than the required one. The second case corresponds to short-term low-energy exchange. Energy buffering, peak power mitigation and energy recovery systems (ERS) require the exchange of short-term high power peaks. Thus, the total amount of energy is low and the required peak-power determines the size of the energy storage device. Anyway, some energy buffering applications under high traffic operation require the storage of a large amount of energy and therefore fall within the first scenario.

Figure 4.a shows the energy storage requirements for the above-mentioned cases and different car loads. A small lift (6 persons) 5 floor lift needs around 30Wh for ERS functionality. If a 100 travel autonomy is required on UPS operation mode, a small residential lift will need to store a little less than 2kWh. Figure 4.b shows the peak power exchange for different loads. Both absorbed (discharging) and regenerated (charging) powers are shown. These powers depend on the acceleration and speed profiles as well as on the overall lift efficiency, herein considered to be 80%. In the discharging case, the maximum absorbed power is related to low mechanical efficiencies, whereas when regenerating, the best mechanical efficiencies lead to the maximum charging power.

3 ELECTRICAL ENERGY STORAGE TECHNOLOGIES

Among the possible electrical energy accumulating systems there are only two technologies that offer mature and commercial products: batteries and ultracapacitors. Both of them have been manufactured in large scale quantities for some years and therefore their performance, cost and reliability are optimized and they are somewhat standardized. Batteries are electrochemical devices that operate through chemical reactions, thus it becomes difficult to get an accurate knowledge of their internal state of operation. A battery is a complex device whose behaviour is mainly characterized by empirical models, its charging process is different from the discharging one and it is difficult to identify its state of charge (SOC) and state of health (SOH). Moreover, its ageing process depends on the depth of charging-discharging cycles, current, temperature, and other parameters.

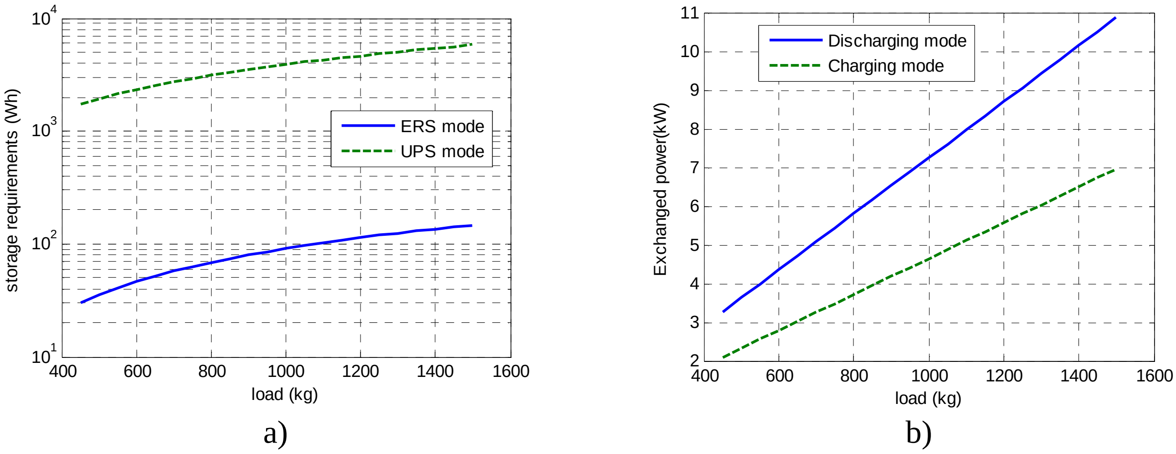


Figure 4. a) Energy storage requirements and b) power requirements for different loads and functionalities

Nowadays there are two main battery technologies in the market: Lead Acid Batteries and Lithium-Ion batteries. Figure 5 shows the main power-energy characteristics of both technologies and Table 1 summarizes the main features. The data in Table 1 is approximate and has been included only for comparative purposes. It is straightforward to identify Li-ion as the best choice in terms of functional features: it offers the best specific energy and power figures and the longest life span. However, on the other hand it requires the inclusion of battery management systems (BMS) and its cost is 10 to 20 times higher than the cost of Lead Acid technology.

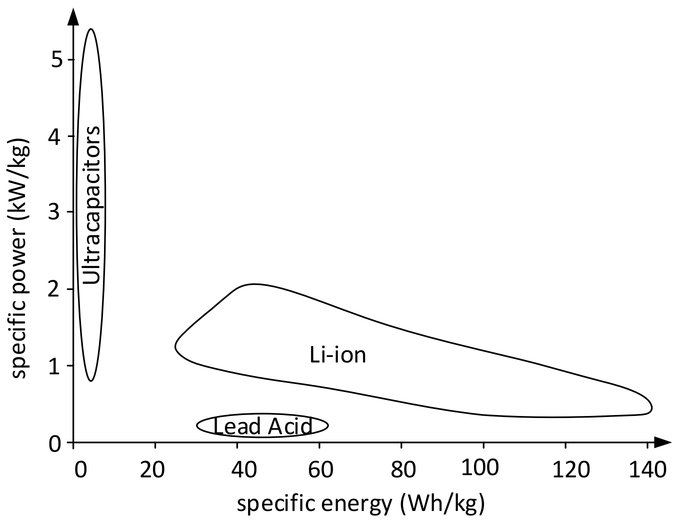


Figure 5. Power-energy properties of batteries and ultracapacitors

Considering the cost, ease of use and the habit gained from many years of successful installations, Lead Acid technology is the preferred choice for non-portable energy storage devices.

Contrary to batteries, ultracapacitor technology is based on pure capacitive phenomena. Thus, an ultracapacitor-based storage unit admits high charging and discharging powers, its state of charge is straightforwardly determined by the well-known equation (1) and it withstands up to 1.000.000 charging-discharging cycles, see Figure 5 and Table. 1. The main drawbacks are its low energy density and its very low nominal voltage, around 2.7V, which leads to the serialization of a big amount of cells and the inclusion of a voltage management system (VMS).

$$W = \frac{1}{2} C V^2 \quad (1)$$

Table 1 Comparative of battery and ultracapacitor technologies

Feature	Lead Acid	LiOn	Ultracapacitor
Number of cycles	300-2000	**>5000**	**>1000000**
Specific power (W/kg)	180	300-2000	**5000**
Specific energy (Wh/kg)	30-60	30-**140**	5
BMS/VMS	**no**	yes (BMS)	yes (VMS)
Cost (€/kWh)	**170**	1200	17000

It can be concluded that for UPS functionality a big amount of energy is required and therefore Lead Acid batteries must be installed, whereas in ERS or power mitigation applications ultracapacitors will be the favoured choice. Hybrid technologies are possible with additional electronics needed to make them truly compatible.

4 MATCHING OF REQUIREMENTS

An appropriate battery or ultracapacitor module for a given application must be selected. The fact is that considering safety issues and available complementary technologies (battery chargers, inverters and so on), 48V has become the highest standard nominal voltage for commercial battery modules and one of the most widely used voltage levels for ultracapacitors. Figure 6 summarizes both the energy and power requirements of Figures 4 and 5. Two storage design examples are also shown in the same figure.

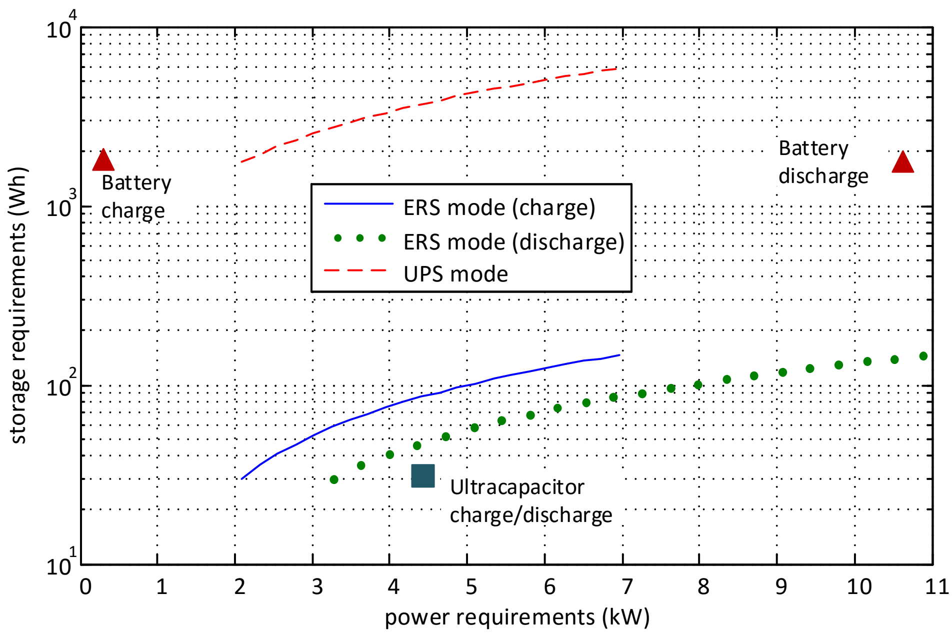


Figure 6. Energy-power diagram of requirements and technologies

First, a battery module has been selected for a small lift UPS functionality. It comprises 4 commercial cells of 12V/40Ah, leading to an overall energy of 1920Wh, with a discharging power of 11kW and a charging power of 400W. The volume is only 22 litres so it can be easily fit in any lift installation. Both the charging and discharging powers are shown by triangles at Figure 6. This battery module will be denoted as the basic battery module (BBM). It is obvious that energy requirement leads to a set of batteries that are clearly oversized in terms of power. In this type of functionality fast charging is not a requisite so the charging power can be significantly lower than the discharging one. Anyway, it has to be pointed out that in order to avoid fast battery ageing, it is recommended to operate far below the nominal power of batteries and assuring low energy discharge cycles. Therefore, the rated discharging power of the battery at Figure 6 cannot be fully exploited and the actual power capability will be closer to the required one.

Next, an ultracapacitor module has been designed for ERS functionality intended for small lifts. It usable energy is 35Wh and offers an equal charging or discharging power of 4.5kW. It takes a volume of no more than 10 litres. This ultracapacitor module will be denoted as the basic ultracapacitor module (BUM) and it is indicated by a square at Figure 6. As can be observed, energy and power requirements are relatively close to that offered by the selected module.

Looking at Figure 6, it is straightforward to determine that using 1 to 3 parallelized BBMs it is possible to cover all the considered UPS requirements and, in the same way, using 1 to 3 BUMs in parallel meets ERS requirements. Therefore, it can be concluded that 48V battery modules and 48V ultracapacitor modules could play the role of basic building blocks covering the considered energy storage needs for lift applications.

5 INTEGRATION OF A 48V SOURCE IN LIFT TRACTION SYSTEMS

The “standard motor drive” block depicted in Figures 1 to 3 represents the common topology used in lift drives. When a given electrical power has to be exchanged a current-voltage pair must be selected, see equation (2)

$$P = VI \tag{2}$$

Considering that the current is responsible for the main part of power losses, a high voltage-low current set of parameters is preferred. Thus, the industry has been adopting standard voltage levels that are related to the power to be exchanged. When dealing with powers from some kW up to several tens of kW, three-phase $400V_{RMS}$ is the electric distribution standard. Electrical lift traction systems are modified versions of well-known industrial drivers, which are fed from a $400V_{RMS}$ three-phase grid and, therefore, after being rectified, a 500-600V DC bus is obtained. This standard drive technology has been used during more than 30 years in industry, so it is extremely robust, reliable and, due to the large manufacturing scale, cost effective.

The problem arises when a 48V or even a lower voltage energy source is feeding part or the entire energy requirements of a lift. There are two possible scenarios. The first attempt consists of trying to keep the already developed and well-known lift drives by interfacing the 48V energy source and the 600V bus by a DC/DC power converter. The second approach is simply to redesign the entire traction system and build a 48Vdc compatible drive. Next, these two scenarios will be explained.

5.1 Integration of 48V source in a standard lift traction system

This is the case of Figures 1.b, 2.a, 2.b and 3, where a DC/DC converter is in charge of the energy exchange from the low-voltage storage system to the high-voltage DC bus. First of all it is important to point out that neither the low voltage level not the high voltage side operate at a constant voltage. In the low-voltage side, batteries or ultracapacitors can be installed. If a 48V battery module is considered, its voltage can evolve from 42V to 53V, depending on the SOC. If ultracapacitors are considered, the situation is even more variable: its voltage can evolve from 24V to 48V, depending also on the state of charge.

Looking at the high voltage side, the situation is not better. If the drive is motoring, energy is removed from the DC bus and, thereafter, its voltage decreases. In the same way, if the drive is regenerating, energy is delivered to the DC bus and its voltage increases. The lower voltage limit is determined by the dynamics of the DC/DC converter (i.e. the time it requires until a satisfactory voltage regulation is achieved), whereas the higher voltage limit depends on the same regulation dynamics (if a bidirectional DC/DC converter is used) but also on the voltage value at which the braking resistor switches on. Most of the commercially available drive manufacturers establish a non-error voltage range from low 400V to 700V or 800V.

A cost effective solution is made possible by a large manufacturing scale, so it is desirable to get a DC/DC converter that can operate with a broad range or almost all the existing commercial drives. For doing so, it must include a plug & play functionality, that is: just plug in the power wires, switch on the device, and the system must operate, without producing any disturbance in its regular operation and without any need for modifications in the existing equipment. Thus, if a low-voltage energy source must be integrated on a standard lift traction system, a DC/DC converter with the next features is required:

- Rated power: 4kW to 15kW (depending on the lift)
- Input voltage: 42V to 53V or 24V to 48V
- Output voltage: 400V to 800V
- High dynamic response
- Bidirectional energy transfer ability (if ERS functionality)
- Plug & play capability
- High efficiency (>90%) along all voltage-range

By now there is only one commercially available DC/DC converter compatible with these features [7]. It has to be pointed out that a DC/DC power converter limits the power exchange ability, but not the usable energy amount, which depends only on the installed batteries or ultracapacitors.

5.2 Redesign of the entire traction system at 48V

In applications where the three-phase $400V_{RMS}$ line is not connected (Figures 2.a and 2.b) there is no need to keep high voltage DC bus levels, so it is possible to build the entire traction system considering a 48V DC bus, see Figure 7. This DC bus voltage limits to $34V_{RMS}$ the available line-voltage at the inverter output and the current is multiplied by a factor of 10 or more. So a new motor and inverter must be carefully designed and installed.

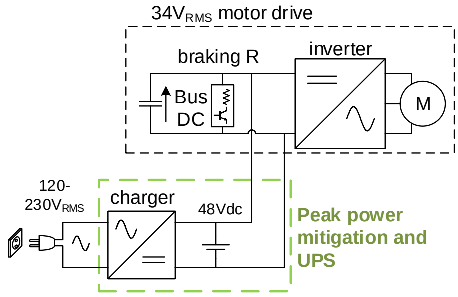


Figure 7. A 48V DC bus traction system with a 34V$_{RMS}$ motor

The new voltage level leads to high currents and therefore, in order to avoid high power losses and bulky wires, the storage device, driver and motor must be located close from each other, which sometimes becomes difficult to achieve. The main drawback of this approach is that the seller and/installer must offer and master two different traction systems for the same range of lifts.

It is possible to conclude that the inclusion of a DC/DC power converter makes it possible to get any of the required functionality by exploiting well known standard drives, simplifies the portfolio of the sellers/installers and provides a big amount of flexibility. In the other hand, the all-in 48V drive covers only part of the functionalities, does not work with ultracapacitors and, somehow, complicates the portfolio. Next, a deeper analysis of the required DC/DC power converter is shown.

6 BIDIRECTIONAL DC/DC CONVERTER

The required DC/DC converter must solve several design challenges:

- Large input to output voltage relation: the input-to-output voltage ratio is larger than 10 and could be, in some cases, above 20. This ratio makes it difficult to achieve high efficiencies.

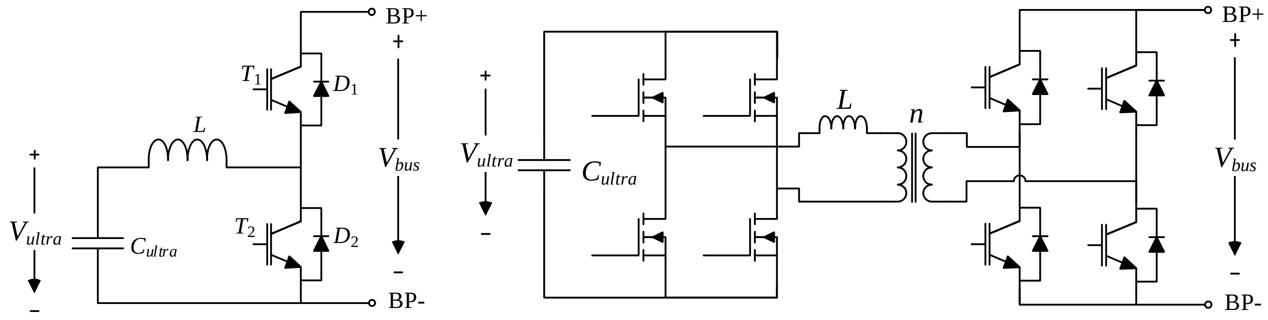
- Variable input and output voltage: when the input and output voltages are kept constant it becomes quite simple to design an optimized high efficiency converter. But it is difficult to get high efficiency values along all the operating conditions if input and/or output voltages evolve significantly. Moreover, the required power exchange is not constant so the highly variable design conditions make it difficult to achieve the design goals.

- High control dynamics: in cases where the lift is fed exclusively through the DC/DC converter (topologies of Figures 1.b, 2.a and 2.b), the same converter is the sole responsible agent of keeping the DC-bus voltage level within acceptable values. This DC-bus is randomly perturbed by input-output powers that are permanently exchanged with the motor inverter and, therefore, it is crucial to achieve very fast control dynamics capable of rejecting these perturbations.

- Plug & play functionality: the control must achieve the above mentioned dynamics without any complicated link with existing drivers. Only power wires must be connected and the device must operate in an autonomous way.

Figure 8.a depicts the basic buck-boost topology that is commonly proposed when DC/DC conversion is required. Although simple and easy to control, this transformer-less topology is not well suited when high input-to-output voltage ratios are required and leads to very poor efficiency values (below 50% in some cases). Due to the high input-to-output voltage ratio, it is almost mandatory to include a transformer in the conversion chain and, therefore, an intermediate AC stage is required. The Dual Active Bridge (DAB) of Figure 8.b is a basic topology achieving DC/AC/DC conversion with an intermediate transformer. Though the number of switching semiconductors has

been multiplied by four, their individual voltage and current values match with the switched power so the power losses falls within logical values, thus obtaining acceptable efficiencies.



a) b)

Figure 8. DC/DC converters; a) buck-boost topology, b) Dual Active Bridge (DAB)

The preferred solution in terms of efficiency is the Series Resonant Dual Active Bridge (SRDAB), see Figure 9. Based on a DAB structure, it includes a series capacitor in the intermediate AC stage, thus, a resonant tank is obtained. By switching at frequencies above the resonant one, it is possible to get soft switching behaviour under some conditions, and therefore efficiencies of around 95% are obtained.

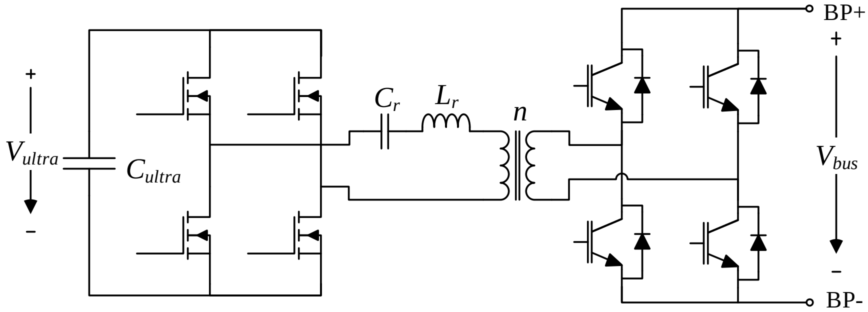


Figure 9. Series-Resonant Dual Active Bridge

Another benefit of the above mentioned soft switching behaviour of the SRDAB is the minimization of radiated and conduced interferences, thus making it easier to comply with EMC requirements. The already good efficiency of the SRDAB can be additionally improved by the use of new state-of-the art Silicon Carbide (SiC) semiconductors. So far, the only commercially available DC/DC converter compatible with this application is based on the SRDAB topology and includes SiC technology, thus providing the required flexibility of use and efficiency [7]. In addition to all the previous features, this converter can be easily parallelized and therefore, using basic storage modules and this basic DC/DC converter, a scalable portfolio can be built thus covering a large variety of energy-power requirements.

7 CONCLUSIONS

This paper analyses a variety of lift applications requiring energy storage. After this, storage requirements are classified in two groups: long term high-energy UPS type functionalities and short term low-energy ERS type functionalities. Among the available accumulation technologies, Lead-Acid batteries are the preferred choice if a big amount of energy is required whereas ultracapacitors offer the best performance for high-power low-energy applications with intensive cyclical operation. Due to commercial availability, cost and design requirements, the 48V standard is selected for energy storage modules. It is shown that basic battery modules and basic ultracapacitor modules can be used as building blocks in scalable systems thus covering the required energy-power range. This scalable system needs to be complemented by a high-gain DC/DC converter with particular features, which has become the main challenge of the proposed architectures. Nowadays, some power electronic manufacturers have understood the need and potential market of such a special converter and therefore they have included it as standard product in their portfolio. Thus, using the proposed flexible architecture, any small or medium size lift manufacturer can offer high-end solutions with minor investments, responding quickly to the market requirements for higher efficiency.

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Improving the Energy Efficiency of Lifts

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Keywords: Energy efficiency, direct approach to floor, variable speed, energy storage, ultracapacitors, solar panels.

Abstract: Obtaining the highest possible energy efficiency of a lift has been a challenge in the industry in the past years and remains so. As an electro-mechanic system, the lift has two areas of possible design improvement. Nowadays, in the electrical arena, the use of certain components and their control help to achieve an efficient performance: PMSM motors, 3VF inverters, regenerative systems, LED lighting, standby mode, etc. Nevertheless, we have identified two ways to further improve the efficiency. The first one is to add intelligence to the lift control, especially related to energy related issues. The second line of action is to further improve the energy reuse when the motor is generating. This is achieved by storing energy rather than just regenerating the energy to the grid.

1 INTRODUCTION

1.1 Starting point

Nowadays, the mechanical designs used for lifts and the use of materials, such as high-strength steel, has contributed to the improvement of energy efficiency.

With regards to the electrical package, new components and features such as those stated previously, have led to a significant improvement. The energy impact of lifts in their service life has been reduced considerably.

Taking into account the levels achieved, we present a new approach which will allow further improvements to be achieved. In this section of the introduction, there are three points to be taken into account due to the fact that they are dealt with in this paper. They are shown below together with a brief description and some of their advantages (some of them are already well-known in the lift industry). Point 1.2, “real time communications”, is important for the development of point 1.3 (“Direct to Floor system”) and to obtain other features detailed later in the paper. Point 1.3 is the starting point to achieve point 1.4

The objective of this paper is to focus on the energy improvements which are obtained thanks to the application of the three points (1.2, 1.3 y 1.4) such as the use of energy storage systems. This will be shown from chapter 2 onwards.

1.2 Real time communications

Developments in real time communication between the lift controller and other electronic devices allow significant amounts of information to be shared. In this way, the electronic controller can make many decisions. For example, this is important in order to develop a DTF solution which does not require the traditional second encoder to control the car position in the shaft (already known in the lift industry) as well as to obtain a call designation system in a DTF lift that only uses the motor encoder readings. Here, the real-time communication between the lift controller and 3VF inverter is fundamental for both devices (this DTF solution is shown in 1.3).

Other decisions can directly affect the energy efficiency of the lift. For this reason, the constant communication between the controller, the 3VF frequency inverter and the energy recovery system is fundamental. This paper focuses on this subject. Further on, we will look at how the communications allow working modes which can improve the energy efficiency.

Some examples:

1.2.1. In the lift controller, to know the state of the 3VF inverter (without using digital I/O) allows us to know the temperature of the IGBTs and confirm that this is correct before switching it off in order to avoid reducing their lifetime. More details in chapter 4.

1.2.2. In a DTF solution without the traditional second encoder, the 3VF inverter, when switched back on (leaving standby mode with the inverter completely disconnected) needs to quickly know the car position in the shaft. More details in chapter 4.

1.2.3. The fact that the controller is aware of the electrical variables of the motor throughout the entire journey in real time, allows it to calculate the car load without using traditional load weighing devices. With this solution, we also evaluate motor and shaft efficiency. This is important in chapters 1.4 and 3.

1.2.4. In energy recovery solutions, it is important that the lift controller is aware of the batteries' or capacitors' loads and their temperatures.

In the same way, it is also important to know from the 3VF inverter the electrical power which the motor is requiring or is generating.

Taking into account these points, the lift controller can make decisions regarding the lift speed during or before starting a journey and therefore achieve a more efficient energy storage or reuse. More details in chapter 6.

This information is also important to manage a standby mode in which the stored energy is used to power the lift controller. It is also necessary to ensure minimum energy storage to ensure automatic rescue.

1.3 Direct approach system (DirectToFloor)

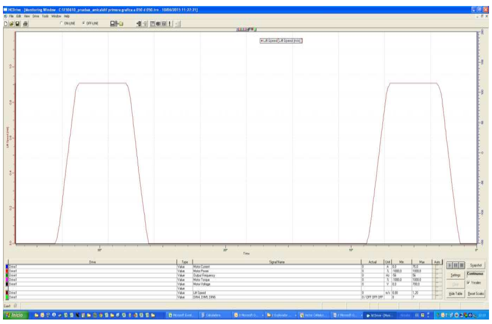
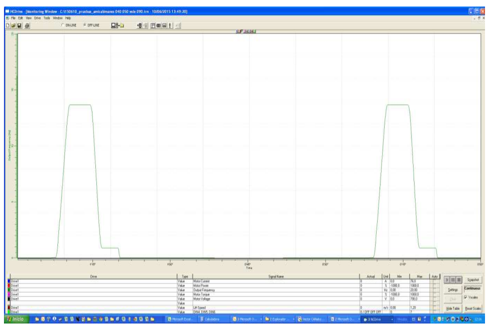


Figure 1.



Following on, the working mode which is already known and used in the lift industry is shown.

In figure 1, two graphs taken from the same lift are shown (speed vs time). On the left, the direct approach system is shown and, on the right, the traditional solution with approach speed can be seen.

This control system (DTF) has the following advantages well known among lift industry professionals.

Shorter journey times → improved passenger traffic pattern within the building.

1. Travel curve calculation depending on the distance to destination → improved comfort.
2. Reduction in time required for installation and maintenance.
3. A second encoder is not required to control the car position in the shaft.
4. The number of signals and sensors in reduced in the shaft when compared to traditional lifts.
5. Simple procedure for final adjustments.

1.4 Combined with DTF: Exceed the nominal speed of the gearless machine PMSM (VARIABLE SPEED)

There already exists, [9], a solution where the car speed can be modified depending on the differences in load between the car and counterweight. This can provide a reduction in the journey times.

This paper's solution is based on real time communication between the 3VF inverter and the controller at all times during the journey. .

An estimation of the car load and the motor and shaft efficiency is obtained during the journey.

In this way, in cases where the load difference between car and counterweight is less than the nominal value, the nominal speed of the motor can be exceeded. In this case, for example, with a traction lift designed for travelling at 2 m/s, by using this DTF solution, it is possible for the lift to easily exceed this speed and reach speeds of 2.5 m/s and without any increase in the electrical energy demand.

This solution allows travel times to be reduced by up to 20%, which improves the passenger traffic patterns in the building. This paper is not focused on this working mode, rather the energy savings it can offer.

In figure 2, the power demand for an MRL gearless lift, 1000 kg, 2 m/s, 50% balanced and with a 15.31m travel distance (IMEM test tower).

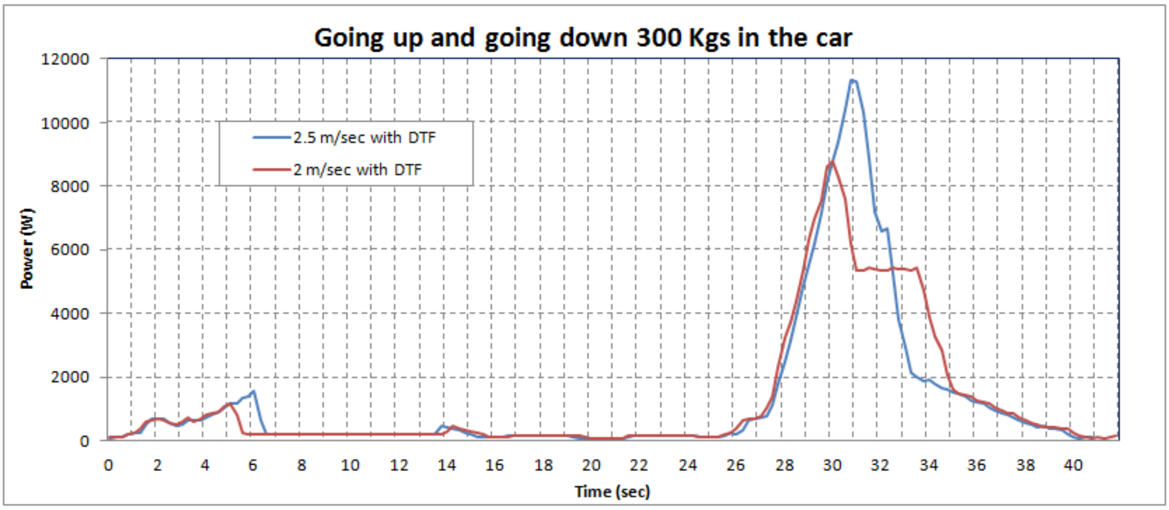


Figure 2.

2 ENERGY IMPLICATIONS OF THE DTF SOLUTION

Added to the previously identified DTF advantages, an energy saving is obtained by functioning as both a motor and a generator.

The energy saving is obtained, mainly, thanks to the elimination of the approach speed. Using DTF, the control reduces the energy losses in the motor during the journey, mainly produced because of the Joule effect in the stator.

Due to the temperature reached in the stator, an increase in the winding resistor impedance is produced, which will lead to a higher level of losses: Losses = 3 * Rf * If^2

The DTF mode, therefore, contributes to maintaining the motor temperature slightly lower.

In figure 3, the TOTAL power demand of an MRL gearless lift, 630 kg, 50% balance, 6.13m travel distance is shown. Analysis is below in table 1.

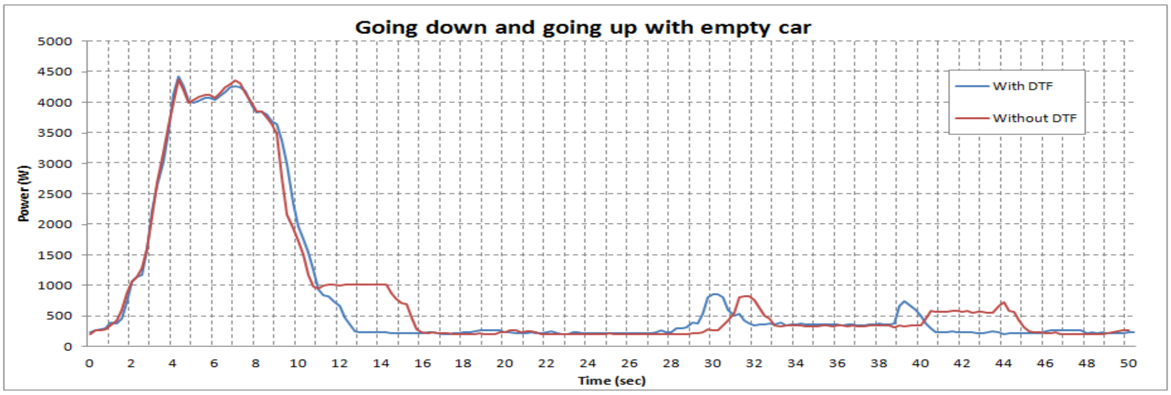


Figure 3.

	Energy	Energy	Time
Savings travelling upwards DTF	0.38 Wh	19.09%	
Savings travelling downwards DTF	0.74 Wh	7.85%	
Time savings		18.75%	3 secs (per journey)

Table 1.

In the following case, table 2, energy demands and savings are shown for an MRL gearless, 1000 kg, travelling at 1 m/s, travel distance 15.31m (IMEM test tower), empty car, 50% balanced.

Journeys: P1→ P2, P1→ P3, P1→P4. As shown, with shorter journeys, the savings are greater and more significant.

	DTF UPWh	DTF DOWN Wh	Total DTF Wh	CLASSIC UP Wh	CLASSIC DOWN Wh	Total CLASSIC Wh	Saving UP	Saving DOWN
3401 mm	1.27	8.31	9.57	2.42	9.45	11.87	**47.68%**	**12.10%**
7901 mm	1.54	16.45	17.99	2.70	17.59	20.28	**42.78%**	**6.50%**
10901 mm	1.73	21.87	23.60	2.88	23.02	25.90	**40.03%**	**4.99%**

Table 2.

The time saving also has implications in the savings made by the car lights (less time illuminated).

3 ENERGY IMPLICATIONS WHEN EXCEEDING THE NOMINAL SPEED OF THE MOTOR (VARIABLE SPEED)

The following data, figures 4 & 5, are obtained from an MRL gearless lift, 1000 kg, 2 m/s, 50% balanced, car load 100 kg. Travel distance: 15.31m (IMEM test tower).

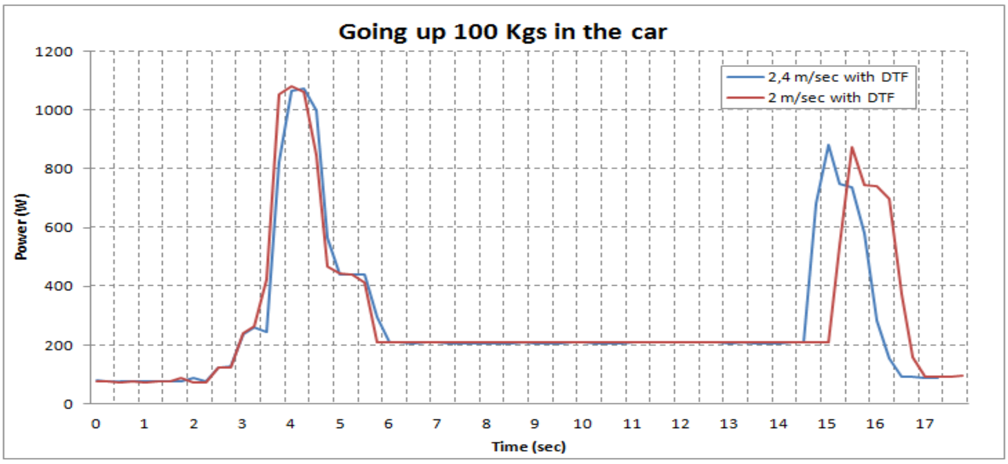


Figure 4.

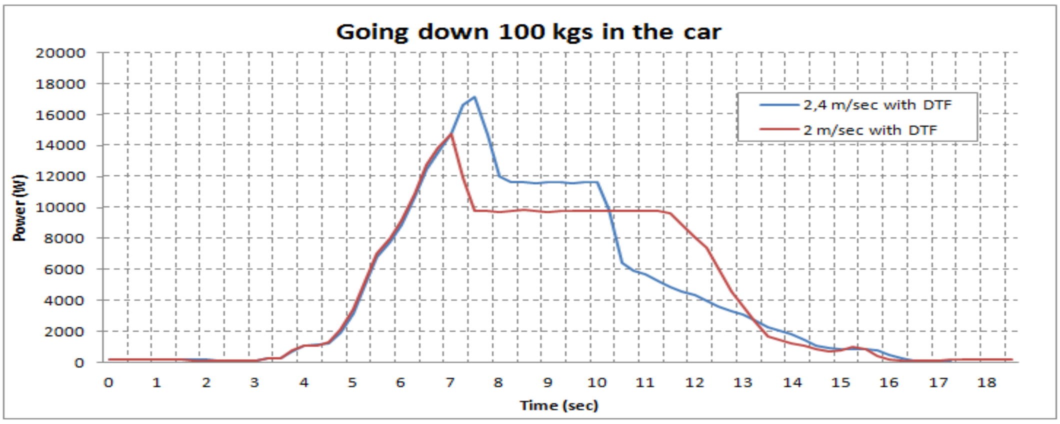


Figure 5.

In table 3, conclusions are detailed corresponding to the energy efficiency of the journeys shown in figures 4 & 5:

	2 m/sec	2.4 m/sec	4.47% Energy saving up. 0.48% Energy saving down.
Up	1.42Wh	1.36Wh	
Down	22.37Wh	22.26Wh	
Total	23.79 Wh	23.62Wh	

Table 3.

By making a calculation, using the data shown, it is possible to translate the results to **80m travel distance** (table 4):

	2 m/sec	2.4 m/sec	
Up	3.29Wh	2.90Wh	**11.85% Energy saving up.**

Down	110.28Wh	109.33 Wh	**0.86% Energy saving down.** **16.67% Approx. time saving.**
Total	113.57Wh	112.23 Wh	
Car lighting	6 LEDS	6 LEDS	

Table 4.

It is shown that the savings, both in time and in energy, increase in conjunction with the travel distance.

Values in table 4 are calculated as follows:

Reviewing the measurements carried out and shown in figures 4 and 5 and table 3:

Both in journeys travelling up and down, 3 stages exist (acceleration, constant speed and deceleration).

In order to simulate an 80-metre journey, it is taken for granted that the acceleration and deceleration phases are the same as those shown previously. The only difference would be the time spent travelling at constant speed.

Using the energy data obtained with the FLUKE 435 II analyser for the 15.31 metre journey, we obtain the Wh demanded for every 2.4 metres (for 2.4 m/s) and every 2 metres (for 2 m/s). The readings are taken each 10 millisecs.

For an 80-metre shaft and table 3 and figures 4 and 5:

Travelling upwards at speed of 2.4 m/s:

$$Wh_{travelling\ upwards\ 2.4\ m/s\ \ shaft\ 80\ mtrs} = Wh_{travelling\ upwards\ 2.4\ m/s\ \ shaft\ 15.31\ mtrs} + (80 - 15.31) * \frac{Wh\ upwards\ every\ 2.4\ mtrs\ constant\ speed}{2{,}4\ mtrs}$$

Travelling downwards at speed of 2,4 m/s:

$$Wh_{travelling\ downwards\ 2{,}4\ m/s\ shaft\ 80\ mtrs} = Wh_{travelling\ downwards\ 2{,}4\ m/s\ shaft\ 15.31\ mtrs} + (80 - 15.31) * \frac{Wh\ downwards\ every\ 2.4\ mtrs\ constant\ speed}{2{,}4\ mtrs}$$

Travelling upwards at speed of 2 m/s:

$$Wh_{travelling\ upwards\ \ 2m/s\ shaft\ 80\ mtrs} = Wh_{travelling\ upwards\ \ 2m/s\ shaft\ 15{,}31\ mtrs} + (80 - 15.31) * \frac{Wh\ upwards\ every\ 2\ mtrs\ constant\ speed}{2\ mtrs}$$

Travelling downwards at speed of 2 m/s:

$$Wh_{travelling\ downwards\ \ 2\ m/s\ shaft 80\ mtrs} = Wh_{travelling\ downwards\ \ 2\ m/s\ shaft\ 15.31\ mtrs} + (80 - 15.31) * \frac{Wh\ downwards\ every\ 2\ mtrs\ constant\ speed}{2\ mtrs}$$

4 STANDBY MODE

This working mode is very important due to the fact that the lift spends the majority of its life in this mode.

Currently, lift devices such as displays and frequency inverters have standby functions available to be controlled by the controller.

There are cases in which the not very fast start-up time of these devices and the autotest processes need to be carried out before reaching READY state and/or the need to maintain information in their memory, obliging them to maintain a low level of energy consumption.

Thanks to real time communications information can be shared between devices.

In this way, by having only the controller working in standby mode, and it having all the information from the lift available, it is able to shut down the rest of the electronic devices, further reducing the energy demands. In this paper we focus on the shutdown of the 3VF inverter and the displays although further devices exist which can be completely disconnected.

In the case of the 3VF inverter, in order to shut it down completely, it is necessary to confirm in advance that the temperature of the IGBTs is correct. Otherwise, their lifetime can be dramatically reduced.

When the inverter is completely shut down, its energy demand is zero.

This working mode allows the traditional standby energy demands to be eliminated. For example, an estimation of 2 current inverter models (2 very well-known European manufacturers).

Inverter A In = 32 Amps: 27 W when idle, 13 W on standby → 0 W

Inverter B In = 14 Amps: 19.7 W when idle, 8.7 W on standby → 0 W

In order to switch the inverter back on (exit standby mode), it is important to estimate the temperature of the DC bus pre-charge circuit. If this is not done, the inverter can be damaged or have its lifetime reduced.

When switching the inverter back on, with DTF lifts without second encoders (a second, more expensive element), it is necessary to inform the inverter about the car position in the shaft. In this way, the time required to reach READY mode is reduced and provides a quick response to the passenger request.

In the case of the displays, when switched back on, it is fundamental to know, via field bus, when ready mode is reached in order to send them the information which must be shown quickly. This solution allows them to be switched off completely rather than keeping them on standby mode. Measurements from the displays of 2 very well-known European manufacturers:

Display 7’’: 8.64 W when idle, 3.12 W on standby → 0 W

Display 3’’: 13.48 W when idle, standby mode not available → 0 W

5 REGENERATIVE SOLUTION + ENERGY RECOVERY SYSTEM

To be able to reuse the energy generated by the motor, there are mainly two alternatives; return the energy to the grid or store the energy. Returning the energy to the grid is an interesting, well-used option, and regenerative drives have been available for some time. Again the problem is the uncorrelated events of generation and use. Energy returned to the grid may be used by another system that happens to be consuming at the same time (for example a neighbour lift) or can be accounted for in countries where net metering is available. In general, it is almost impossible to determine with precision how much of that energy is actually being saved by the lift owner.

This paper uses a recently developed market-available technology of storage [2, 3] with positive results. Figure 6 shows the schematic diagram of the system that has been added to the lift

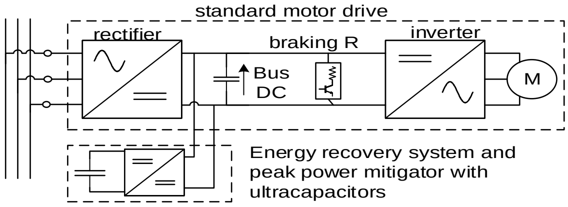


Figure 6 Electronic diagram of connection of storage system to DC bus of VVVF drive.

As can be seen, the system requires only two wires connected to the VVVF drive so it is very simple to install. Although it is not required, further information may be at the disposal of the controller (see section 6 below). The system has two parts that may be integrated in a single module: a DC/DC converter that transforms the energy into something that can be easily accumulated and the actual accumulator. This one, depending on the application, can be a set of batteries or ultracapacitors.

In this particular case, a study has been carried out with two different versions of the energy storage system. The two versions are different in terms of power handling capability and in available energy storage modules. Table 5 shows the two versions that have been evaluated. Lift: MRL Gearless 1000 kgs, 50% balanced, travel distance: 15,3 m.

Table 5. Two different versions of energy recovery systems

	Converter power	Energy stored
Version 1	3.5kW	100kJ (flexible)
Version 2	6.3kW	60kJ

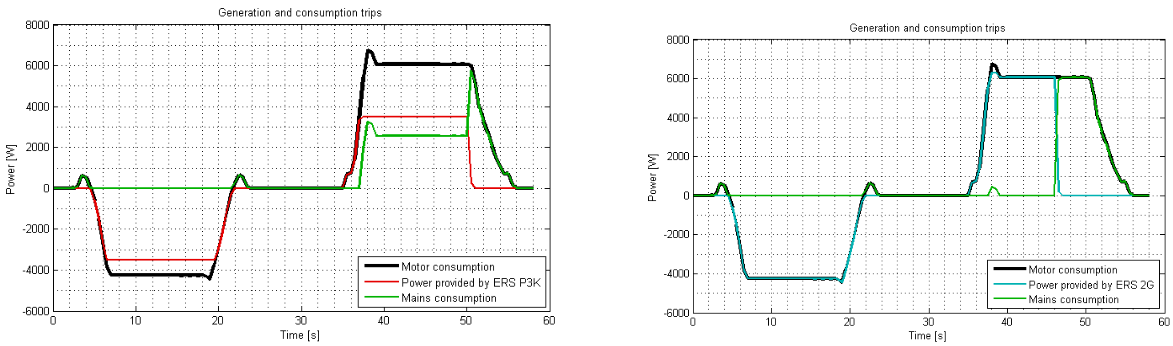


Figure 7 Power vs. time of the lift without saving system (black) and a) using version 1 and b) with version 2. Consumption from mains and energy provided by energy storage and conversion system [15,3m trip with no load in the car]

Figure 7 shows two trips of maximum generation and maximum consumption, motor power vs. time. The actual curves of a measured version 1 system effect in the lift are presented in red. The power function of the effect of a simulated version 2 system in the same case is presented in blue First of all, it is important to mention that the lift, has a remarkably high efficiency, measured at 83%. Secondly, the power handling capability of the version 1 system, limited to 3.5kW, does not allow the storage of all the available energy in the generation journey, with part of that going to the braking resistor. Nevertheless, version 2, with 6.3kW of power conversion, allows the storage of more energy. The effects can be seen in the last part of the consumption journey, with version 2 supercapacitors being depleted later than with version 1, resulting in higher savings. Table 6 shows the numerical results obtained for the particular case of version 2.

Table 6. Energy calculations for test lift for maximum ratings

Max. power consumed	6059 W
Max. generated power	4246 W
Efficiency of installation	83.71%
Energy consumed in one trip	95.66 kJ = 26.57 Wh
Energy generated in one trip	62.63 kJ = 17.40 Wh
Savings with version 1	50.05%
Savings with version 2	59.30%

Traction energy saved is estimated as 59.30% with the second version of the system. A VVVF inverter efficiency of 96% has been considered, as well as 98% unidirectional efficiency of the DC/DC converter (which implies 95% bidirectional efficiency). With version 1 of the system, savings are lower, due to the above mentioned fact.

ISO 25745-2 [1] and state-of-the-art literature [5, 6, 7] relate actual daily energy calculations to a set of parameters that have an impact in this study. In this paper we have taken these into consideration and we have measured the impact of the version 1 system in the energy savings for the different classes of operation by means of considering the number of trips, load and distance. At the time of the tests, version 2 of the technology was not available, which is why version 1 was used. 365 days per year are considered for the particular lift mentioned before table 5. The results are as follows:

Usage category 1: 98.91 kWh/year (without recovery system), 39.17 kWh/year (with recovery system).
Usage category 2: 247.03 kWh/year (without recovery system), 97.92 kWh/year (with recovery system).
Usage category 3: 592.88 kWh/year (without recovery system), 227.69 kWh/year (with recovery system).
Usage category 4: 1442.84 kWh/year (without recovery system), 571.89 kWh/year (with recovery system).
Usage category 5: 1967.42kWh/year (without recovery system), 779.82 kWh/year (with recovery system).
Usage category 6: 1520.15kWh/year (without recovery system), 524.89 kWh/year (with recovery system).

As a summary, we can conclude that the inclusion of a recovery system reduces the lift's energy consumption in a variable percentage (dependent on version and category of use) that in general is above 35%. These savings levels are the starting point for section 7.

6 COMBINING DTF + VARIABLE SPEED + ENERGY RECOVERY AND STORAGE SYSTEM

Several studies have been carried out which focus on energy recovery and storage systems such as [8]. Different behaviours and uses of the energy have been studied.

From our point of view, there are two factors to take into account when storing and reusing electrical energy.

a.-The capacity for managing the power of the DC/DC converter. In certain circumstances, the lift can generate or demand more energy than the DC/DC converter can deal with.

b.- Storage capacity in the ultracapacitors module.

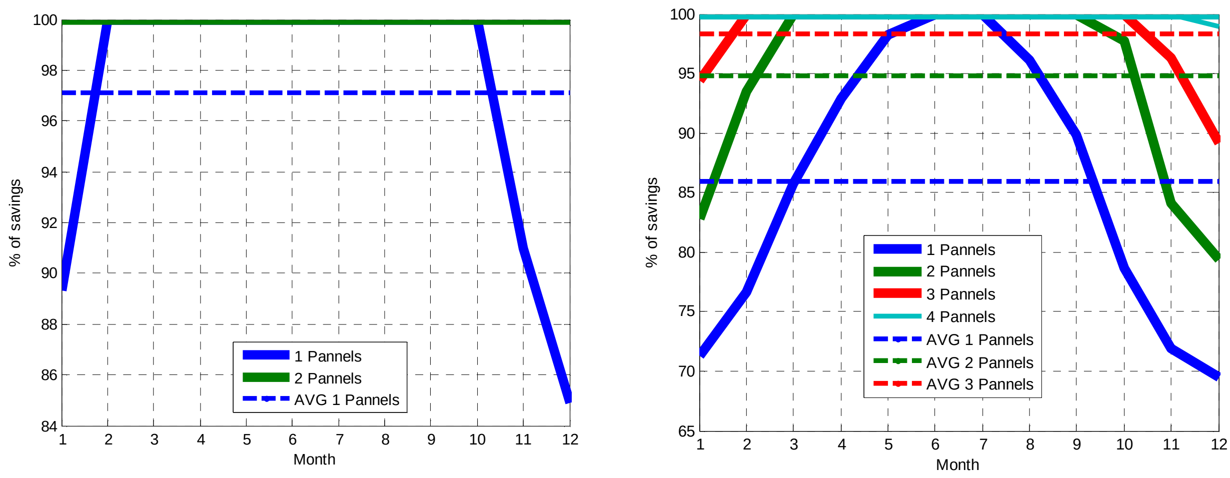
Communication using a field bus between the controller and the DC/DC converter allows, amongst other things not applicable in this paper, monitoring in real time the load state of the ultracapacitors and the flow of energy between the DC bus and the storage module.

The lift controller, using DTF and VARIABLE SPEED, can reduce or increase the travel speed (if the building's passenger traffic allows), and increase the efficiency of the generation/reuse of energy in these cases.

7 SOLAR PANELS

To be able to use alternative energy sources, especially solar panels, the generated energy needs to be transformed to a usable form of energy for the lift. In general, solar or wind energy require some storage to buffer the generation and the consumption. Again, thanks to the transformation and storage capabilities provided by the tested energy storage and recovery system, we have been able to easily add solar panels as an energy source without any need for additional electronics.

For this particular case, the energy storage capability is a relatively small one. Typically, this would be for one or two trips in maximum consumption mode. The intention was not to make a completely solar powered and self-sustainable lift. To do so, batteries are needed and there are alternatives [2, 3]. The intention was to further reduce the consumption. The test lift that has been used is the same as in section 5, with the addition of solar panels. The solar panels that have been considered are: Power: 295W, Area: 1,95 m2, Voc: 45V, Vmpp: 37V, Cells: 72



a) b)

Figure 8 Estimated savings (in %) with Version 2 and solar panels by month: a) category 2 lift, b) category 5 lift.

Figure 8 shows the expected savings depending on the number of panels installed and the month of year in Santander (north of Spain). The efficiency of the solar panels provided by the manufacturer has been taken into account and radiation has been considered to be the average statistical data for the city. It already considers that the savings obtained with an energy storage system (as mentioned in section 5, table 6). In addition, for the particular case of a category 5 lift and depending on the month of year, average savings can be increased to more than 85% with just the addition of one solar panel, without the need for any additional electronics**.** These estimations vary, of course, with latitude of installation and class of operation but they highlight very promising results for this option in terms of improving the energy efficiency.

The whole system (energy recovery system), including solar panels has a possible range of ROIs that is highly dependent on location, cost of energy and features of the lift installation. Typical cost of solar panel is slightly less than 1€ per Watt.

8 CONCLUSIONS

The use of the DTF system as standard in any traction lift provides considerable electrical energy savings, especially with traffic between floors (1-3, 3-5, etc.).

The DTF system has to be used as Standard without additional costs to the lift. The intelligence of the lift controller reduces to a minimum the adjustments (the number of components is not increased, it is reduced); and these are simplified thanks to software.

The combination of DTF with VARIABLE SPEED (over-speeding the motor) significantly reduces the journey time and provides improvements in energy efficiency.

The passenger traffic requirements in the building could be managed better without necessarily the need for more lifts or higher motor powers. This is due to the journey time reduction thanks to DTF and over-speeding the motor above its nominal speed. In accordance with [10], and for 2 lifts (duplex) example: MRL traction lift, 13 person, 13 floor, floor-to-floor distance: 4 metres, door opening time: 5 secs, building population: 100 person, car load percentage: 65%.

Estimated data at 2 m/s and at 2.4 m/s.

	Case A. 2 m/sec	Case B. 2.4 m/sec
Handling capacity 5 minutes (%)	47.72	51.7
Waiting time (secs)	34.52	31.87

Using this data, the only guaranteed conclusion which can be reached is that the increase in speed helps to reduce the two variables shown and that DTF + VARIABLE SPEED brings the data from cases A & B closer together.

Regrettably, it is not possible to define the level of improvement and how close the data from case A can be brought to case B.

It has been possible to improve standby modes thanks to real time communication and the sharing of information between devices.

The evolution of the current regeneration systems to energy recovery systems with storage capabilities has led to the intelligent management of electrical energy when storing or reusing energy.

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A Systematic Methodology for the Generation of Lift Passengers under a Poisson Batch Arrival Process

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Keywords: lift, elevator, traffic analysis, simulation, inter-arrival time, inter-service time, exponential probability density function, Poisson probability density function, batch arrivals, passenger arrival process.

Abstract. It is generally accepted that passenger arrivals for lift service follow a Poisson arrival process. Moreover, recent research has also shown that the arrivals take place in batches rather than single passenger arrivals. For these reasons, lift traffic simulation software may use the Poisson batch arrival process to generate the time of each batch arrivals and the size of each batch (i.e., the number of passengers arriving in each batch). This provides a better representation of real life conditions and produces a more realistic simulation. Alternative models for generating passengers for lift traffic simulation packages are considered. A methodology for generating batch arrival times and the size of each batch is presented.

1 INTRODUCTION

An important part of any lift traffic simulator is the passenger arrival process. The passenger arrivals represent the demand to which the lift system is subjected. The passenger arrival model should reflect the actual characteristics of the arrival process. This ensures that the output of the simulation is more representative of reality. In this paper, alternative arrival models are presented and discussed. A new methodology for generating passenger arrivals is proposed.

2 POSSIBLE PASSENGER ARRIVAL GENERATION MODELS

This section examines possible models with which passengers can be generated for lift traffic simulation. All examples in this section assume a passenger arrival rate, λ of 0.2 passengers per second.

2.1 Constant inter-arrival time

This is a simplification of the passenger arrival process. It is assumed that the time between the arrivals of consecutive passengers is constant (i.e., deterministic rather than random). The time in seconds between the arrivals of consecutive passengers or inter-arrival time Δt can be calculated:

$$\Delta t = 1/\lambda \tag{1}$$

A diagrammatic representation of passenger arrivals against time is shown in Figure 1. As the arrival rate is 0.2 passengers per second, then the inter-arrival time is 5 seconds.

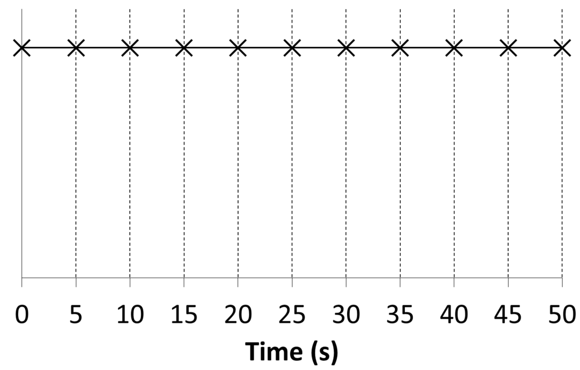

Figure 1 Passenger arrivals with constant inter-arrival time

2.2 Random inter-arrival time with uniform probability density function

This model assumes that the inter-arrival time is random. However, it contains a simplification of the passenger arrival process by assuming that the distribution of the inter-arrival time is a uniform probability distribution function (pdf). The value of the inter-arrival time has an average value of $1/\lambda$ and varies between 0 seconds and the twice the average value $2/\lambda$.

The value of an inter-arrival sample time can be evaluated using the equation 2 where *Rand* is a function that generates a uniformly distributed random number between 0 and 1. This yields the representation of passenger arrivals given in Figure 2.

$$\Delta t = \frac{2 \times Rand}{\lambda} \tag{2}$$

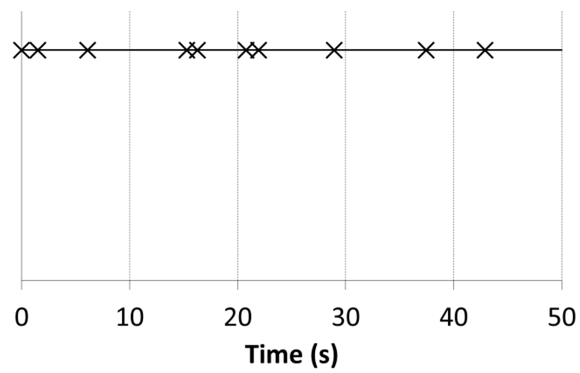

Figure 2 Passenger arrivals under a rectangular pdf process

Although this model offers a better representation of the passenger arrival process by introducing random passenger arrivals, it assumes that a passenger must arrive in the time period of $2/\lambda$ which is not necessarily true. A much longer period of time might pass without a passenger arriving. Moreover, the model gives equal probability to all possible values of the inter-arrival time, which is not an accurate reflection of reality.

2.3 Random passenger arrivals applying Poisson probability density function

The most widely accepted passenger arrival model is the Poisson process [1, 3, 4]. This assumes that the number of passengers arriving in a period of time follows a Poisson distribution, see Equation 3.

$$P(n) = \frac{(\lambda \cdot T)^n \cdot e^{-\lambda \cdot T}}{n!} \tag{3}$$

Where $P(n)$ is the probability that the number of passengers arriving in the period of time T is equal to n. Using a period, T of 10 seconds, the Poisson probability density function has been generated and shown in Figure 3. Figure 4 shows a representation of passenger arrivals.

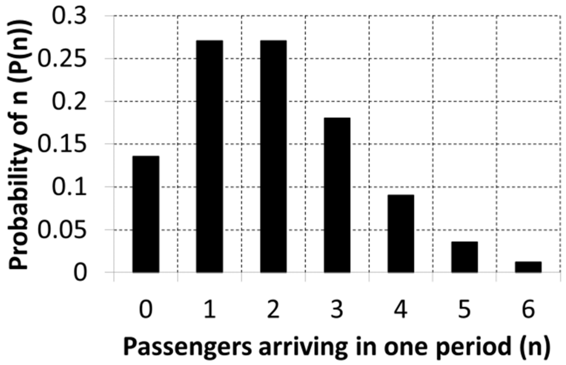

Figure 3 Probability destiny function for a Poisson arrival process

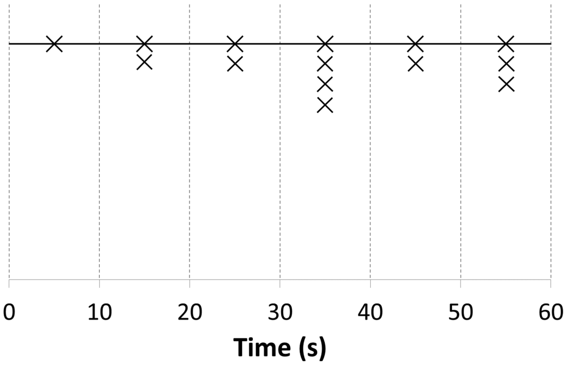

Figure 4 Passenger arrivals under a Poisson pdf process

The passengers are assumed to arrive in the middle of the period of time T (10 seconds) as the actual arrival time of each passenger is not defined. For this reason, this basic application of the Poisson process is unrealistic, even with a smaller T.

A further disadvantage of this approach is that the number of passengers generated in the time period does not necessarily correspond to the arrival rate. This inconsistency between user input and passengers generated can cause confusion to users of traffic simulation software.

2.4 Random inter-arrival time with exponential probability density function

The random variable in the previous Poisson passenger arrival model is the number of passengers arriving in a time period, T. A better approach is to use the inter-arrival time as the random variable. This can be achieved by considering the time after which one or more passengers are expected, $1\text{-}P(0)$. Substituting Equation 3 yields Equation 4. Figure 5 shows a representation of passenger arrivals.

$$\Delta t = \frac{-\ln(1-Rand)}{\lambda} \tag{4}$$

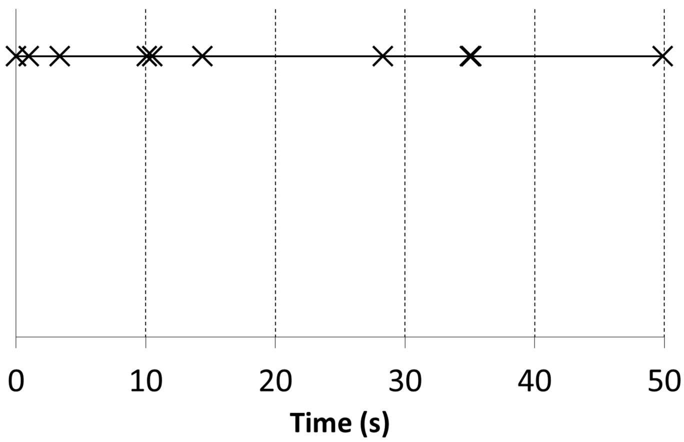

Figure 5 Passenger arrivals assuming random inter-arrival time with exponential pdf

As for the original Poisson approach, the number of passengers generated in the time period does not necessarily correspond to the arrival rate.

2.5 Random arrival time in a given time period

To address the inconsistency in passenger numbers, some traffic simulators create the exactly the number of passengers required by the arrival rate for the time period T. As only whole passengers can be generated, rounding up or down is determined using a random number. Random numbers are used to place the passengers on the time line. This achieves a similar result to the previous model with an exponential probability density function, see Figure 6.

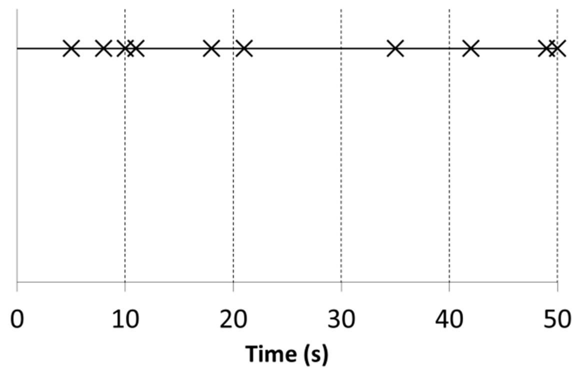

Figure 6 Passenger arrivals assuming random arrival in a given time period

A consequence of this approach is that the longer the time period *T*, the more variation there is in the demand during that period. For example, if *T* is 5 minutes, 60 passengers would be generated. If *T* is one hour, 720 passengers would be generated; however in the first five minutes, there may be 58 passengers, and in the second five minutes there may be 64 passengers.

2.6 Further considerations

It has been shown that passengers arrive in batches [5], also referred to as bulk arrivals [2]. The probability density function of the batch sizes depends on the nature of the building and the time of the day. Thus for every batch arrival, there are two parameters to generate: the time at which it occurs and the size of the batch.

3 A METHODOLOGY FOR GENERATING PASSENGERS FOR SIMULATION

3.1 Steps of the methodology

The passenger generation methodology presented in this paper combines the most useful features of the methods discussed in section 2: (i) the methodology assumes a random inter-arrival time with exponential probability density function; (ii) the total number of passengers is consistent with the expected number of passengers; (iii) the batch size may be building and time specific.

3.2 Procedure

For each floor where passengers arrive, consider the total number of passengers generated, p_{gen} during the workspace, WS. The WS is the time over which passengers are being generated in seconds. λ may be determined from the passenger demand which in turn is calculated according to population and building type.

$$p_{gen} = \lambda \cdot WS \tag{5}$$

To generate passengers for the WS:

1. Calculate the required number of passengers to be generated as shown in equation 5. Assign the first passenger's arrival time to zero seconds.
2. Using Equation 4 generate the inter-arrival times between all the consecutive passengers.
3. Repeat step 2 until the number of passengers generated is one more than the required number of passengers, $p_{gen} + 1$.
4. Discard the last passenger generated, but retain his or her arrival time. This arrival time will be referred to as WS'.
5. It is likely that the value of WS' is different from the desired workspace time, WS. Thus apply a shrink or stretch correction factor, $SF = WS/WS'$ to the whole set of arrival times. This will ensure that the total passenger generation time is equal to WS.

3.3 Example without batch arrivals

A building has a population, *U* of 1000 persons and arrival rate, *AR%* of 12% of the population per five minutes at the floor being considered. The value of the workspace is 60 seconds.

$$\lambda = \frac{AR\% \cdot U}{300} = \frac{12\% \cdot 1000}{300} = 0.4\, passengers/second \tag{6}$$

The expected number of passengers to be generated in the workspace can be calculated:

$$p_{gen} = \lambda \cdot WS = 0.4 \cdot 60 = 24 \tag{7}$$

The arrival times of each passenger are shown in Table 1, column 2. As the target number of passengers is 24, the number of passengers that are initially generated is 25. The 25th passenger will be discarded, but his or her arrival time retained. Table 1**,** column 2 needs to be shrunk or stretched such that exactly 24 passengers arrive within 60 sec. The correction factor is found by dividing the desired workspace by the actual workspace.

$$SF = \frac{WS}{WS'} = \frac{60}{63.6529} = 0.9426 \tag{8}$$

The arrival times are thus adjusted by multiplying them by SF, as shown in Table 1, column 3. The original and adjusted arrival times for the 24 passengers are shown in Figure 7 with each passenger arrival shown as an inverted triangle.

Table 1: Passenger arrival times

Passenger (#)	Arrival time (s)	Adjusted arrival time (s)
1	0	0
2	5.5392	5.2214
3	6.556	6.1798
4	9.5555	9.0071
5	10.1065	9.5265
6	10.1841	9.5996
7	13.5913	12.8113
8	15.3242	14.4448
9	16.9587	15.9855
10	22.8361	21.5256
11	25.1892	23.7437
12	27.5929	26.0094
13	32.4982	30.6332
14	36.5914	34.4915
15	38.7407	36.5175
16	39.2458	36.9935
17	39.9316	37.64
18	45.3718	42.768
19	45.4445	42.8365
20	47.1274	44.4228
21	47.587	44.8561
22	57.2073	53.9243
23	60.3254	56.8634
24	62.0606	58.499
	63.6529	60

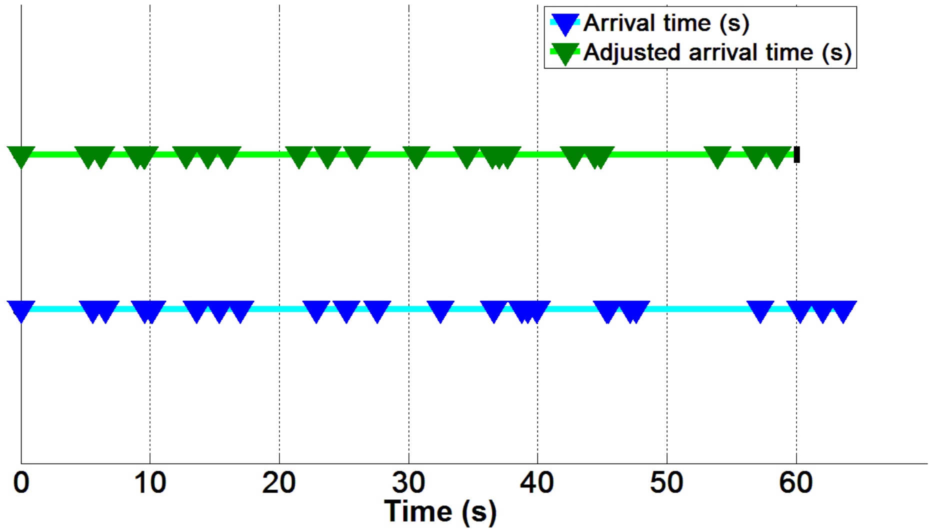

Figure 7 Initial and adjusted passenger arrivals

3.4 Example with batch arrivals

A building has a population, U of 300 persons and an arrival rate of 4% of the population per five minutes at the floor being considered. The value of the workspace is 15 minutes.

$$\lambda = \frac{AR\% \cdot U}{300} = \frac{4\% \cdot 300}{300} = 0.04 \, passengers/second \tag{9}$$

Using the value of the arrival rate above, the expected number of passengers to be generated in the workspace can be found as shown below:

$$p_{gen} = \lambda \cdot WS = 0.04 \cdot 900 = 36 \tag{10}$$

The probability density function that is to be used for the generation of the batch sizes, based on reference [5], is given in Table 2.

Table 2 Probability density function for the batch sizes

Batch size	1	2	3	4	5
Probability	37/58	13/58	6/58	2/58	0

The average batch size can be calculated from the pdf as shown below:

$$\overline{b} = \frac{1 \cdot 37 + 2 \cdot 13 + 3 \cdot 6 + 4 \cdot 2}{58} = 1.5345 \, passengers/batch \tag{11}$$

In order to account for the average batch sizes, calculate the batch arrival rate, λ_b in batches per second.

$$\lambda_b = \frac{\lambda}{\overline{b}} = \frac{0.04}{1.5345} = 0.0261 \, batches/second \tag{12}$$

Using the arrival rate for the batches found in equation (12) the batch arrival times can be generated. These are shown in Table 3 together with the batch sizes. The batch sizes are randomly generated using the batch size pdf shown in Table 2.

The 20th batch is discarded, but its arrival time is retained. Table 3 column needs to be shrunk or stretched such that exactly 36 passengers arrive within 15 minutes. The correction factor is found by dividing the desired workspace by the actual workspace.

$$SF = \frac{WS}{WS'} = \frac{15}{16.2531} = 0.9229 \tag{13}$$

The arrival times are adjusted by multiplying them by SF as shown in Table 3, column 3. It is worth noting that the initial batch sizes are not changed. The sum of the passengers arriving in 15 minutes is 36 passengers as required.

Table 3 Adjusted batch arrival times.

Batch (#)	Arrival time (minutes)	Adjusted arrival time (minutes)	Batch size (passengers)
1	0	0	1
2	0.9921	0.9156	3
3	1.9611	1.8099	2
4	2.667	2.4614	1
5	2.7586	2.546	2
6	2.7726	2.5588	1
7	3.2973	3.043	4
8	3.526	3.2542	4
9	5.3186	4.9085	3
10	7.8494	7.2442	1
11	8.0653	7.4435	1
12	9.097	8.3956	1
13	10.5448	9.7318	2
14	11.1267	10.2688	3
15	12.5041	11.54	3
16	14.3439	13.238	1
17	14.8533	13.7081	1
18	15.6866	14.4772	1
19	16.2364	14.9845	3
20	16.2531	15	N/A
		Total passengers	36

The original and adjusted arrival times for the batches are shown in Figure 8.

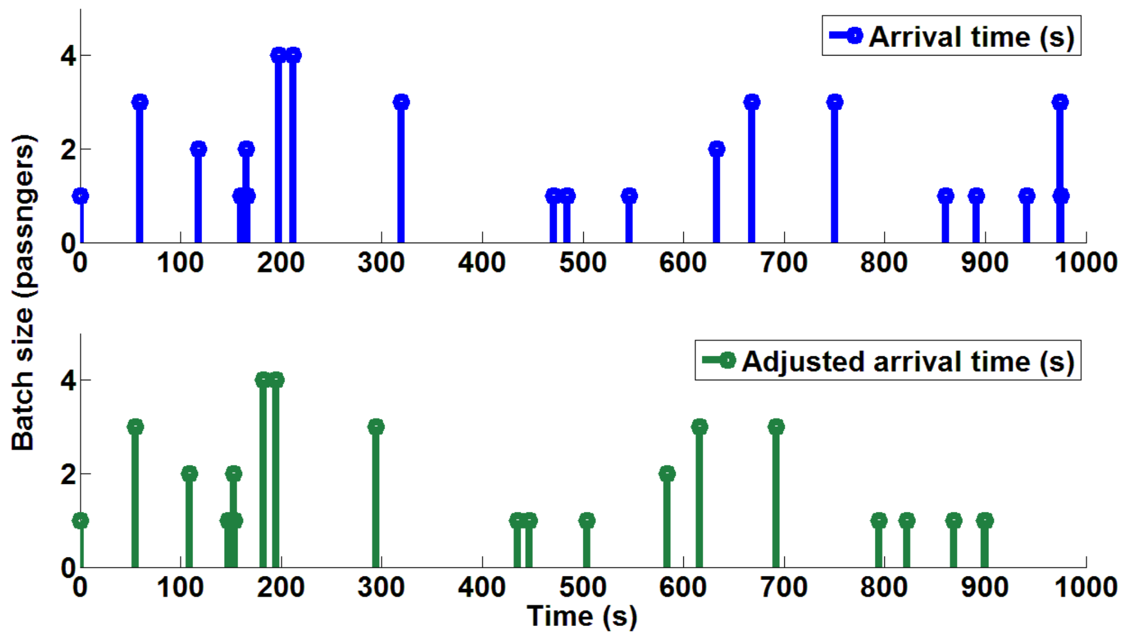

Figure 8 Initial and adjusted batch arrivals

4 CONCLUSIONS

Alternative models for generating passengers for lift traffic simulation packages have been presented.

The first model assumes a constant passenger arrival rate, where the time between passenger arrivals is deterministic and constant. This model is not representative of reality as it is known that passengers arrive randomly. However, it can be used for the verification of the value of the round trip time found using calculation. The second model assumes a uniform (rectangular) probability density function, where the inter-arrival time of the passengers randomly varies between 0 s and $2/\lambda$ seconds (λ is the passenger arrival rate in passenger per second). It assumes that a passenger must arrive at most every $2/\lambda$ seconds and gives equal probability to all values of inter-arrival time between 0 and $2/\lambda$ seconds; neither of these assumptions reflect reality.

The third model assumes that the number of passenger, n, arriving in a period of time T follows a Poisson process. The passengers are assumed to arrive in the middle of the period of time T as the actual arrival time of each passenger is not defined; this is unrealistic, even with a smaller T. The fourth model modifies Poisson to allow for exact arrival times to be defined; this is more realistic, however, the random nature of arrivals means that the passengers generated in the time period does not necessarily correspond to the arrival rate.

Another approach creates a Poisson-like arrival process, but generates the exact number of passengers expected. Further consideration is given to research that proposes that people arrive in batches.

The passenger generation methodology proposed combines the most useful features of the methods discussed. (i) the methodology assumes a random inter-arrival time with exponential probability density function; (ii) the total number of passengers is consistent with the expected number of passengers; (iii) the batch size may be building and time specific. Two examples are then given, the first assuming single passenger arrivals, and the second assuming batch arrivals with one or more passengers in each batch. The methodology also shows how to ensure consistency between the actual number of passengers generated in the workspace and the actual number of expected passengers, by using a correction factor, SF.

5 FURTHER WORK

A Kolmogorov-Smirnov goodness of fit test has been carried out on a real life survey data to confirm that the model assuming random inter-arrival time with exponential probability density function cannot be rejected. A discussion of determining the destinations of passengers will be provided. Alternative methods of passenger generation will be included in traffic simulation software, and an assessment made on the impact on example designs. This work will be published in a future paper or papers. The implication of turnstiles at the entry to the building or lift lobby also needs to be considered.

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Escalator Accidents Analysis

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Keywords: escalator, accidents, fall, entrapment, safety.

Abstract. More and more; escalators are being widely used to access locations at different levels. The user assumes that the escalators are completely safe but the harsh reality is that accidents happen and in some cases the consequences are fatal.

In order to try to prevent accidents, the first step is to find out why or under what circumstances they occur.

Different committees and organizations around the world collect data about accidents. Existing reports show that since the 1990's a steady increase in the number of accidents regarding escalators have occurred but few statistics on escalator-related accidents have been published worldwide. From the analysis of these statistics, it seems that the assessment of the accidents does not always follows the same criteria as the data is not consistent when reports are crosschecked.

This paper looks at the available records on accidents on escalators, opportunities that currently exist to gather information and parameters analysed from such information.

Also, the paper proposes a systematic approach to escalator accident records to allow that the data gathered provides relevant information that could be taken as a reference for establishing the necessary measures that guarantee the safety of users and escalator technicians.

1 INTRODUCTION

Escalators and moving walks are becoming more prevalent, more complex (longer, higher) and with increasingly exposed voids. In addition, escalators are more and more subjected to abuse, misuse and negligence and in some cases they are the primary escape route/emergency exit. The need for safer escalator designs has been recognized by those who work with escalator manufacturers and purchasers.

1.1 Why do accidents happen?

There are three variables that influence accidents on escalators [1]:

1) *Escalator design*: electrical and mechanical design of the escalator.
2) *Escalator maintenance, inspection and operation*:
    - Maintenance refers to activities such as programmed periodic preventive maintenance and/or cleaning.
    - Inspection of all safety devices and escalator components is necessary to ensure the escalator is maintained in a safe condition
    - Operation covers decisions such as keeping an escalator in service, withdrawing it from service or running it as a fixed staircase.

3) *Passenger behavior:* the way in which a passenger behaves has a significant contribution to accidents.

But one additional factor has influence in accidents: the escalator environment has also an important role. Sometimes, accidents involving escalators occur due to some special features around it. For instance:

- Incorrect design of people flow (e.g: ticketing machines too close to escalator landings in metro stations).
- Improper architectural design of the building / installation (locations where a potential situation of risk exists, e.g: open atriums, limited headroom above…).
- Poor lighting and other environmental conditions.

Every accident can be attributed to one or a combination of more than one of these factors. Design issues, as well as maintenance and operation, should be covered by the safety codes and standards. Merely considering escalator design is insufficient to address passenger accidents. Therefore, a diagram of factors affecting passenger accidents on escalators should include the environment as a factor that, once again, never triggers an accident alone; it is always combined with at least one of the other factors. This influence is represented in Figure 1.

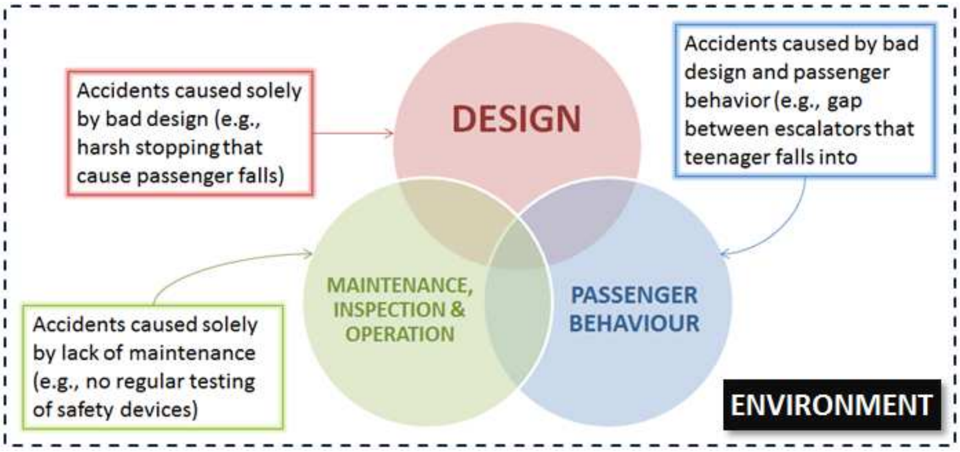

Figure 1 Areas affecting passenger's accidents on escalators [1], adding the environmental factor

1.2 The importance of accident statistics

Accidents on escalators are, in some cases, well documented in terms of the number of accidents occurring but this is not always the case. With respect to the details about how the accident actually occurred and the factors involved they are often not well documented. User accidents are difficult to record because sometimes minor accidents are not reported, escalator companies and owners are not always involved and the way of reporting the main cause of the accident is not properly indicated.

Accident statistics are important to help promote quality, safety and the highest technical standards and encouraging technical progress in the field of manufacturing, installation and maintenance of lifts and escalators [2]. The accident statistics help to:

- identify the causes for accidents, both for users and workers
- analyze hot spots and take actions, e.g. provide new safety norm proposals and influence local government for coming up with new guides or regulations
- use identified regularly occurring accidents by elevator companies to improve their product safety
- support the elevator industry and associations to build up awareness for operators and users

- convince authorities of the actions to be undertaken initially and to confirm the effectiveness of these measures thereafter.

2 ACCIDENT INVESTIGATION

2.1 Methodology

Limited information regarding accidents on escalators can be found as there is no single body worldwide that gathers data on incidents on escalators. In addition, escalator owners and manufacturers are usually reluctant to give this information.

For this analysis, data has been collected from several sources:

- General articles dealing with escalator safety
- Reports from independent organizations that involve industry, owners and third party inspection bodies
- Reports from major clients
- Thesis and dissertations from relevant experts on escalators
- In-house feedback from field experts
- Videos of incidents and media reports

The aim of the analysis was to collect the best accident data and knowledge of the available information. Each of the reports has its special characteristics, all of them valid to the purpose of this investigation:

- Different locations: metro stations, airports, shopping centers …
- Different countries: Spain, Germany, UK, Canada, USA, China ...
- Different goals: point out existing risks on escalators, reduce risks by reaching a new standard, show potential new risks, show patterns on how accidents occur…

2.2 Accident analysis

The analysis tries to answer as best as possible the questions of how many accidents are occurring and how and where they occur from the prospective of real data. The conclusions of the analysis have been detached in three different areas: the quality of the reviewed data, the analysis of the main causes of accidents and their statistics and finally the peculiarities of fall accidents.

1) <u>Accident data</u>

- Criteria to report accidents are not clear. As accident reports come from very different sources with very different purposes it is almost impossible to compare the results among them and extract similar conclusions. In addition, there is no single body worldwide that gathers all the accident-related data.
- Data is not consistent: some independent investigations made by escalator operators in Europe [3] show a higher number of reported accidents than the official ones reported by ELA [4] for the same year, where data is provided by the key manufacturers. This is probably because manufacturers are reluctant to show accidents involving their equipment.
- Significant associations between major accident causes and other contributing factors could help to reconstruct the accident scenarios and develop prevention measures. For this purpose it is necessary to construct a proper template of accident reporting that can register all of these elements involved in the accident.

2) <u>Main causes of accidents</u>

- Although there is a “belief” that the most critical part of the escalator is the step gap and many efforts have been made by different manufacturers to reduce/avoid this gap, all the statistics and information consulted show clearly that the main accident cause in escalators is *falls* (42-88% depending on the source). This is not only regarding the number of accidents but also because they often cause more severe injuries and more fatalities.

- Alternatively, *entrapment* is mostly associated with the age of the escalator and its code compliance level or maintenance status (a much stricter requirement for EN115 adopted in MTR decreased the occurrence of this type of accident to 5.7% of total accidents [5]).
- Statistics show that there are some risk groups depending on age and gender [5]:
    - Young males under 5 years are more likely to suffer entrapments.
    - Children between 5-15 years tend to fall over the escalator due to being unsupervised by an adult.
    - Accidents happening to adults from 15-65 involve rushing, carrying other tasks, playing on escalators and other kinds of misuse.
    - Elderly people (>65 years), especially women, tend more to lose balance and fall.
- There are many serious risks associated with the use of carts and trolleys on escalators and moving walks [6].The risks include overloading, carriage of children, runaway and other foreseeable misuse.

3) <u>Falls</u>

- "Slipping on landings/steps/pallets" makes up the majority of the escalator accidents.
- "Falls over the handrails" are often tied to misuse, such as jumping from one level to another, or attempting to ride by sitting on the handrail, usually in a state of intoxication. [7].
- Another type of fall is "falling from escalators". These mainly take place whenever the escalator is located in a void (as is the case in most shopping centers). Due to the height of the fall, the injuries are usually very severe (death in some cases) [7].
- One of the most important items in reducing the probability of passengers falling is ensuring that the escalator stops in a smooth manner.
- Another extreme accident that could take place on an escalator is a passenger falling 'into' the escalator step band due to a missing step or a step collapse. These accidents are rare but have drastic consequences when they take place.

3 METHODOLOGY PROPOSAL

3.1 First approach: ELA statistics

The European Lift Association (ELA) represents the lift, escalators and moving walk associations active in the European Union (EU) and also represents their component manufacturers. One of the main goals of this organization is to promote quality, safety and the highest technical standards in the elevation field.

More precisely, the ELA Statistical Committee aims to collect regular data and updated information to set up databases and to publish statistics related to lifts, escalators and moving walks. Since 2008 this committee has been collecting data of accidents by asking its partners to report the accidents that occur on lifts and escalators. The collection covered 30 countries and it is divided into the following categories:

- Workers accidents:
    1. Classification: installation, service
    2. Accident causes (e.g. "unsafe access to machine room")
    3. Severity: fatal, serious, minor
- Users accidents:
    1. Causes: technical reasons, human reasons
    2. Severity: fatal, serious (different definition for serious than for workers), others
- Additional "Fatal accident report"

Accident statistics have been collected since then but the results were not satisfactory due to: too few participants, too many discrepancies and “strange” results when comparing different countries, difficulties in classifying accidents following the risk list, etc. In addition, the number of accidents collected for a whole country is very low in comparison with data provided by single clients and incidents are not being registered.

Methodology for collecting this data consists of sending a simplified form to each association in order to have comparable figures and receiving it back filled in with the corresponding data. This simplified form is provided by ELA since most European countries have their own system of collection based on different aspects of the accident (associated risk, injury/part of the body hurt…). This report is anonymous and not linked to individual companies as there are many companies reluctant to communicate their accidents/incidents figures. The aim is to get the best knowledge of accidents possible.

From the first years of collection the reporting has also changed due to the fact that few countries have participated in the past and also the previously mentioned discrepancies in the figures. The last reporting method focuses on the main causes of accidents identified in the SNEE brochure (Safety Norm for Existing Escalators) which is also published by ELA.

However this methodology only helps to link the number of escalator accidents with the causes or the severity of each accident, ignoring important information about other facts that have proven to have influence over the occurrence of the accident such as passenger conditions (age, intoxication state…) and, more importantly, escalator characteristics (installation year, code requirements, rise, speed, location, …) which would help to prevent accidents and mitigate their consequences significantly in the future.

3.2 Client-orientated accident reporting

There are three main figures linked to an escalator in use. *Manufacturers* are responsible for the design and installation of the escalators, but the *client*, as owner of the equipment, is usually responsible for any issue caused by this equipment. *Maintainers*, hired by the client, are in charge of the operations needed to keep the escalator in proper operation, and sometimes it is usual for them not to be the same as the manufacturer.

With this in mind it is clear that the clients are the most concerned about the escalator performance so it seems reasonable that the best knowledge of the equipment is held by them as operators. In addition, some clients have more recently been monitoring their escalators. Many of them own devices that help to manage supervision of the machines, such as real-time view of the equipment status, centralized controls, traffic history playbacks, security cameras, tracking of safety devices etc…The information recorded by these devices would help to gather data about not only accidents but also incidents because, in the same way, they are a sign of an unsolved and/or unsafe situation.

For the reasons above a methodology is suggested for collecting data involving some key-clients that can provide their data and experiences.

Among the findings of the accident investigation, it was concluded that the typology of accidents also differs depending on the type of escalator installation (e.g. accident type “fall from escalators” occurs more often in places where escalators lead to a void such as shopping centers). For this reason key-clients could be classified in the same categories as the *escalator duty* which is defined by three functions: application, location and capacity (persons per hour). Then, the classification will be as follows:

- *Heavy duty:* convention centers, stadiums and airports where there is a very high traffic volume. These applications could be indoors or outdoors and designed for higher rise applications up to about 50 m.

- *Transit:* railway stations, airports and subway stations where there is a very high traffic volume. These applications could be indoors or outdoors and designed for higher rise applications (about 20 m).
- *Commercial:* department stores, shopping malls and office buildings. Most of these applications are indoors but can be installed outdoors. The maximum rise of these applications is about 9 m.

Regarding data recording, only reporting the number of accidents and their consequences has been proven to be inefficient. Relevant information that could help to clarify the accident circumstances is not normally registered. A proper accident report template should cover relevant factors plus escalator information, as well as any other factors which are judged to be relevant:

- *General information:* major cause (listed under defined categories), site and time of the accident, weather conditions, witness information (including the victim where possible)…
- *Passenger data:* age and gender of the victims, number of involved people, injured body part, severity of the injuries, position of passenger at time of incident, state of intoxication, unaccompanied children, clothing type and condition, task factors …
- *Escalator features:* year of manufactured, code compliance status, rise, speed, traveling direction, indoor or outdoor location, location of emergency stops, location of the incident (top landing, lower landing, mid part, external to the escalator…) safety signage, safety devices, technical analysis of the escalator after inspection by the maintenance staff…

The statistical treatment of this data will help to establish associations between the major causes and the contributing factors by extracting more precise information to reconstruct the accident scenarios and develop prevention measures for minimizing number of accidents on escalators and their consequences.

4 CASE STUDY: TRANSPORTS METROPOLITANS DE BARCELONA

The Metropolitan Region of Barcelona (MRB) includes a total area of 636 km^2 and a population of over three million. The demand for collective public transport in the Barcelona area was 899.6 million journeys in 2012. Of this total number of journeys, over 550 million (61.5%) were made on TMB (Transports Metropolitans de Barcelona) and 373,5 million in Metro. To ensure the accessibility at all links of the transport network, a number of lifts and escalators are installed on stations and access points. The overview of escalators installed can be seen in Figure 2.

Total number: 602	
Escalators	Moving Walks
582	20

	Escalators	Moving Walks
Ascending	82,5%	40,0%
Descending	13,3%	40,0%
Reversible	4,2%	0,0%
Horizontal	0,0%	20,0%

Length	Average	5,25 m.
	Longest	16,4 m.
	Shortest	1,3 m.
Speed	0,5 /0,65	m/s

Figure 2 Overview of TMB escalators

TMB presented at the 2014 ELA Conference the plan to upgrade the old units to EN115-1 following EN115-2 in the next 4 years based on their own accident statistics collected from 2010 to 2013. The need for this update responds to the high rate of accidents per year on the older units. The plan consists of the assignation of individual priority to each escalator depending on the classification of hazards from the standard, the number of passengers, history of accidents and organizing different adaptations required to minimize the number of interventions in each machine.

4.1 Managing information about accidents involving escalators

The computer-aided maintenance software used in the Barcelona Metro provides, for each piece of equipment on the Metro network, a technical object within the data fields to characterize each facility with all of the information necessary to carry out maintenance and is also useful for further analysis of data.

Regarding escalators; general data includes the manufacturer, model, year of manufacture, date of commissioning, standard compliance, height, tilt speed, step width, number of steps, direction of travel, number of flat steps at landings, indoor or outdoor location. There are also others with more technical information such as the type of drive chain, motor power, if it has a drain in workers area, if there's lighting under handrails and what kind, handrail lengths, etc. which are used to help the technical staff to carry out the repairs.

The same software is used to manage the corrective and preventive maintenance and any maintenance undertaken is registered in the maintenance software. Breakdowns are registered in the computer-aided maintenance software and also every incident that may occur in the metro network including accidents on escalators.

When a breakdown or other incident occurs the operator has to create a notification by using the software. In the resultant documentation produced all the information about the incident is registered: *when* (date & time), *where* (in what technical facility it occurred) and *what* happened (element, symptom, cause). These data fields have catalogs of standard codes. Some of them are filled in by the operator and others by the maintenance staff giving extra information after the inspection of the escalator. In the event of an accident the "symptom" field is used to encode the accident type e.g. fall without cause, slipping on steps/pallets/belt/and on landings, entrapment between comb and step/pallet, etc.

This allows all accident data to be linked with each one of the Metro escalators and by extracting the data it is possible to calculate the ratios of accidents and their type for each escalator or for any of the characteristics of the escalators.

4.2 Safety in escalators: Barcelona Metro Experience

Figure 3 shows the main accident statistics regarding escalators extracted from the TMB maintenance software between 2010 and 2014. The typology is based on what happened to the users or the consequences to them. The most remarkable data is that *falls* are the main consequences of accidents on escalators, being the result of 88.9% of the total number of accidents (including all types: fallings without cause, slips, massive falls, handrail speed deviations, backward motion…). Another interesting piece of data is that only 7.5% of the accidents are the result of *entrapment* (between combs and step pallets, between skirting and steps or at handrail entry).

Accident	2010	2011	2012	2013	2014	Total	
Fall without cause	202	163	120	217	200	902	48,0%
Slipping on steps/pallets/belt/and on landings	112	159	159	162	141	733	39,0%
Entrapment between comb and step/pallet	22	20	21	20	18	101	5,4%
Cuts or injuries to hands, arms..	13	12	20	4	18	67	3,6%
Trapping between skirting and steps	7	17	5		7	36	1,9%
Massive fall without cause	1	6	5	6	5	23	1,2%
Falling due to hand rail speed desviation (or stop)	2	2	3	2	1	10	0,5%
Trapping at handrail entry			2	1	1	4	0,2%
Fall due to backward motion	1			1	1	3	0,2%
Total	360	379	335	413	392	1.879	100,0%
						Average per year	375,8

Figure 3 Accident statistics on TMB escalators 2010 - 2014

In addition to this general data, TMB has quantified other interesting facts, for instance, the average accidents per year and per escalator related to the escalators' age. This can be seen on Figure 4 where it is easily noticeable that there is a high dependency on the ratio of accidents per year per escalator and its age, more or less doubling the ratio of accidents with each decade of age.

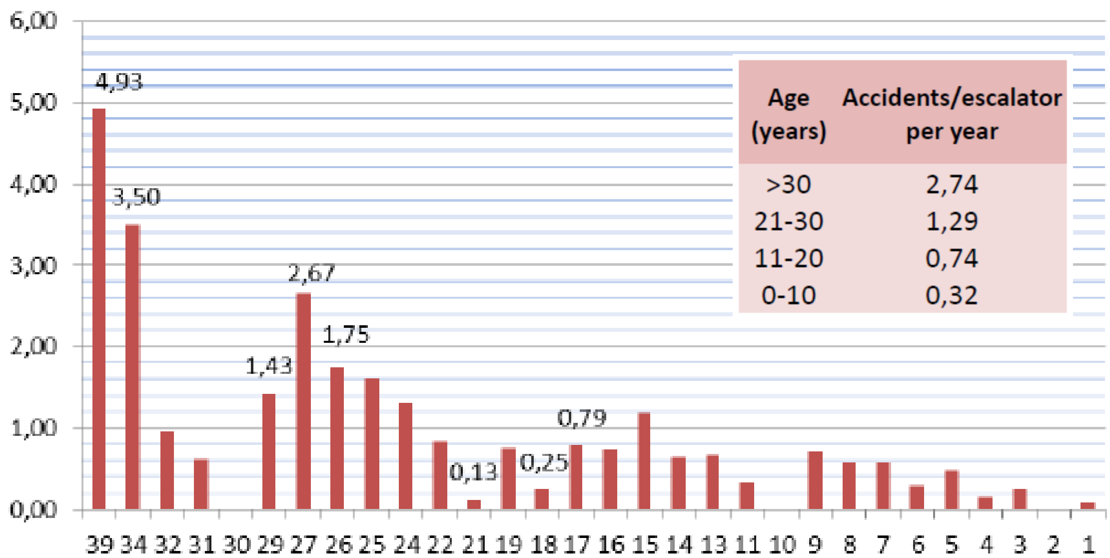

Figure 4 Average accidents per year and escalator compared to the age of the escalator (years). Updated at 31.12.13

Another example is the comparison between the location of the escalator, the climatic conditions and the running directions. It could be thought that outdoor escalators could have a higher ratio of accidents than indoor escalators (because of wet shoes after rain) or indoor descending escalators could have more accidents than ascending escalators (because people could be on a hurry in indoor descending escalators when they see the train at the station) but the truth is that the location of escalators with higher rates of accidents are indoor ascending escalators (0,777 accidents per year/escalator). The cause for this could be that passengers frequently walk up the escalators.

Location	% Escalators	% Accidents
Indoor	77,98%	85,30%
Outdoor	22,02%	14,70%

Number of accidents per year/escalator		
Indoor	0,773	210 % More accidents indoor escalators
outdoor	0,368	
Descending	0,576	19,7 % More accidents ascending escalators
Ascending	0,689	

	Descending	Ascending
Indoor	0,750	0,777
outdoor	0,319	0,388

Figure 5 Accident rate versus location and running direction. Updated at 31.12.13

These are only a few examples of what proper data collection and interpretation could tell us about accidents involving escalators. In this case statistics help to justify an investment on upgrading the safety level for older escalators which will lead at the end of the process to an expected 75% reduction in the number of accidents along the network, supposing that the upgraded escalators reach the same accident ratio as the escalators complying with EN115-1. Even only reaching half of the current ratio of accidents would be expected to reduce the number of accidents by 50%.

5 CONCLUSIONS

There is a real need to collect reliable escalator accident data which could help to identify potentially dangerous situations that can be sources of risk for users or technicians on escalators. Accident investigation is a preventive action whose starting point is, in contradiction, the prior existence of an accident. Its importance is in the objectivity of the data: an accident indicates the actual existence of a hazard and therefore a risk. The registration of these cases, and also incidents, and their statistical treatment provides evidence of how, where, when and how many accidents are occurring. After analyzing this data it is possible to throw light on why they occur.

Research made on the topic “accidents on escalators” showed that there is no common criterion to record accidents, thus data obtained is not consistent. Reports come from different sources with very diverse goals which also makes it very difficult to establish a base for comparison. In addition, the majority of the reports are focused on the consequences of accidents and passenger data, forgetting about escalators characteristics, which in many cases have a big impact in accidents.

The European Lift Association (ELA) has been collecting accident data from its partners since 2008 using a common template but the main data is provided usually by manufacturers, who are sometimes reluctant to declare accidents on their machines, so there are many inconsistencies between the data. When data from ELA reports is cross-checked with data from different sources, it seems that reliability of the data could be doubtful.

Client-orientated methodologies for collecting information about accidents and incidents on escalators (including machine features), plus clear definition of objective data and appropriate treatment of the figures, will improve the quality of the information obtained to extract the most precise information possible. The experience of Metro Barcelona shows how proper templates, data registration and statistical analysis can help to improve safety and reduce the number of accidents and their consequences on escalators to a large extent.

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Service Life of Steel Wire Suspension Ropes

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Keywords: Suspension rope, safety factor, bending cycles, EN81-1, tensile load

Abstract. The life of a suspension rope system depends on a number of factors: the overall maintenance of the ropes in terms of sufficient lubrication and tension, but more importantly the initial system design. An analysis of the EN81-1+A3 (2009) Annex N safety factor equation on four case studies was performed on a number of lifts with 2:1 reeving ratios to determine the minimum and actual safety factors for the suspension rope system. By using equations that are generally used within the wider steel wire rope industry for ropes 'running over sheaves', the actual performance of bending cycles was assessed for the four cases studied and converted into an expected number of trips.

The paper will show from the case study results that the number of bending cycles performed varied greatly for each lift with exchange periods of between 3.5 and 11 years. The results show that small changes in various parameters will raise the number of bending cycles significantly. The result of adjusting parameters to reduce the tensile load on the ropes, the increase in traction sheave diameter and using a traction sheave groove that reduces fatigue on the rope is to have ropes that will last significantly longer, with a larger number of bending cycles being performed.

High use lifts that are reeved at 2:1 or more, especially in low rise applications should consider increasing the suspension rope safety factor in order that reasonable service time is given to reduce costs to the end client.

1 INTRODUCTION

The downturn of the many economies in the world and especially in Europe has affected the incomes of many businesses and individual persons. The result of this economic downturn for the Lift Industry is that competition has caused the reduction of prices for the installation of new lifts, which are attributed to the cost of materials (especially electrical and computerised areas of the lift), the manufacturing process, and installation methods designed for faster installations. The service performed on lifts has been streamlined along with contract times for an Engineer to service the lift being also reduced in line with the competition prices required to gain or retain maintenance contracts.

With customers now demanding higher quality services for a lower price, the knowledge that suspension rope future replacement that is inevitable, costly and can be more regular than expected depends on the lift characteristics. For the customer to be satisfied they want the lift to remain in operation with down time of the lift kept to an absolute minimum and naturally the costs incurred on the lift also kept to a minimum. The life of the suspension rope will be regarded as important as the replacement can be costly and down time of the lift may also have an effect on the income revenue stream of the business. The service life of the steel wire suspension rope is assessed in the MSc Dissertation by P. Ryan [1] for initial design and inspection.

2 BENDING CYCLES FOR RUNNING ROPES OVER SHEAVES

Professor K.Feyrer of the University of Stuttgart developed an equation that calculates the 'Bending Cycles for Running Ropes over Sheaves' before the "discard point" and is therefore suitable for the lift industry (see Eq. 1[2]). The discard criteria according to tests performed by Stuttgart University is when the nominal bending cycles have been reached, this is defined when;

'There is a 95% probability that not more than 10% of the ropes have to be discarded'

2.1 Bending Cycles (N_{A10})

$$\log N = b_0 + \left(b_1 + b_4 \times \log\frac{D}{d}\right) \times \left(\log\frac{S}{d^2} - 0.4 \times \log\frac{R_0}{1770}\right) + b_2 \times \log\frac{D}{d} + b_3 \times \log\frac{d}{do} + \frac{1}{b_5 + \log\frac{l}{d}} \quad (1)$$

Where;

S is the dynamic tension per rope and is calculated

$$S = \frac{\frac{(P+0.5Q)gn}{r}}{n_T} \times f_{S1} \times f_{S2} \times f_{S3} \times f_{S4} \quad (N) \quad (2)$$

f_{S1-4} – Values are taken from table 3.12 of Feyrer [2]

f_{S1} – Roller or sliding shoes on guide rails

f_{S2} – Rope efficiency

f_{S3} – The equalisation of the rope tensions across all ropes

f_{S4} – The contract speed. Tension on ropes occur during acceleration.

b_0 to b_5 – Are constants for the type of rope and are taken from table 3.14b of Feyrer [2]

D – Traction sheave diameter

d – Rope diameter

l – Length of most stressed part of rope

The most stressed part of the rope is the length of rope (l) that runs over the traction sheave and the most number of pulleys in the system. This is determined by mapping the rope to find a dimension in millimeters that will be entered into Eq. 1.

The N (N_{A10}) value calculated will reduce as "Endurance Factors" are considered to give a corrected number of bending cycles (N_{A10cor}).

$$N_{A10cor} = N \times f_{N1} \times f_{N2} \times f_{N3} \times f_{N4} \quad (3)$$

The endurance factors are taken from table 3.15 of Feyrer [2]

f_{N1} – Ropes are well lubricated

f_{N2} – Type of rope construction and the number of strands

f_{N3} – Traction sheave groove type and angle (V groove, U undercut groove and U groove)

f_{N4} – The ropes are without any skew

For the number of bending cycles to be calculated any U groove pulleys in the system are deemed to have an endurance factor f_{N3}=1.0

2.2 Number of trips to and from the main stop (Z_A)

The calculated bending cycle value (N_{A10}) from Eq. 1 for U groove pulleys in the system along with the corrected bending cycle value (N_{A10cor}) is then used to calculate the number of trips to and from the main stop (Z_A).

$$Z_{A10} = \frac{1}{\frac{1}{N_{corT}} + \frac{1}{N_{corP}}} \tag{4}$$

2.3 Number of journeys

The calculated figure in Eq. 4 of trips to and from the main stop will have the Holeschak factor (HF) applied to determine the number of “journeys” the lift would make before the ropes have reached their discard point. The Holeschak factor is a study of lift journeys performed as lifts can have many journeys recorded while travelling to and from the main stop. There are 3 different sections that can be used in Eq. 5.

$$\frac{Z_{A10}}{HF} \times 100 \tag{5}$$

$$\text{Residential} = 100 \times No\ of\ Floors\ above\ main\ stop\ floor^{-0.115} \tag{6}$$

$$\text{Commercial} = 100 \times No\ of\ Floors\ above\ main\ stop\ floor^{-0.278} \tag{7}$$

$$\text{Industrial} = 100 \times No\ of\ Floors\ above\ main\ stop\ floor^{-0.381} \tag{8}$$

At this point Eq. 5 will give an expected number of journeys with the type of building calculation applied, that can be seen on the lift more visibly via the trip counter that is usually fitted into the lift controller.

3 SAFETY FACTOR EQUATION

From the bending cycles in Eq. 1 and the ‘correction factors‘ by Feyrer [2], the ‘Committee for European Normalisation‘ (CEN) in their consultation and writing of the EN81-1 [3] standard, that was harmonised on July 1st 1999, looked at the creation of a Safety Factor equation in Annex N that took into consideration a ‘Life Expectancy‘.

The designed safety factor equation takes into consideration the factors of traction sheave groove type, the amount of pulleys in the system, the traction sheave groove, the amount and diameters of pulleys, the rope diameter and traction sheave to rope diameter ratio to give a minimum predicted life of 600,000 bending cycles as detailed in Andrew and Kaczmarczyk [4] and Schiffner [5]. The derived Eq. 9 takes all the factors and equates a minimum safety factor.

$$S_f = 10^{\left(2.6834 - \frac{\log\left(\frac{695.85\times10^6\times N_{equiv}}{\left(\frac{Dt}{dr}\right)^{8.567}}\right)}{\log\left(77.09\left(\frac{Dt}{dr}\right)^{-2.894}\right)}\right)} \tag{9}$$

Dt – Traction sheave diameter

dr – Rope diameter

N_{equiv} – Total equivalent pulley factor

Where the equivalent pulley factor is calculated by:

$$N_{equiv} = N_{equiv(t)} + N_{equiv(p)} \tag{10}$$

$N_{equiv(t)}$ – Traction sheave equivalent pulley factor

$N_{equiv(p)}$ – Diverter equivalent pulley factor

Where $N_{equiv(t)}$ is taken from Table 1 based on groove type chosen and $N_{equiv(p)}$ is calculated from the amount of pulleys in the suspension system in Eq. 11.

$$N_{equiv(p)} = Kp(Nps + 4Npr) \tag{11}$$

Nps – Number of Simple bend pulleys

Npr – Number of Reverse bend pulleys

The factor of ratio between the traction sheave and the average of all diverter pulleys is calculated by:

$$Kp = \left(\frac{Dt}{Dp}\right)^4 \tag{12}$$

Dt – Traction sheave diameter

Dp – Average diameter of all pulleys

Table 1: Based on criteria contained in Annex N of EN81-1+A3 (2009)

Table N.1

V-grooves	V-angle (γ)	--	35°	36°	38°	40°	42°	45°
	$N_{equiv(t)}$	--	18,5	15,2	10,5	7,1	5,6	4,0
AC U-/V- AC Undercut grooves	U-angle (β)	75°	80°	85°	90°	95°	100°	105°
	$N_{equiv(t)}$	2,5	3,0	3,8	5,0	6,7	10,0	15,2

When the safety factor for the lift has been equated from Eq. 9, the traction calculations according the EN81-1+A3 (2009) Annex M must be performed with 3 primary conditions that apply to satisfy compliance to 9.3 of EN81-1+A3 (2009).

1. Traction must be maintained when the car is being loaded to 125% of contract load.
2. Traction must be maintained when performing an Emergency Stop so that the deceleration rate does not exceed the buffer deceleration rate.
3. Traction must be lost when the counterweight is on the buffers and the machine is driving in the up direction.

4 CASE STUDIES

Four case studies were performed where the minimum safety factor required in Annex N of EN81-1 [3] and actual safety factor were calculated using Eq. 9. For each of the case studies the "bending cycles" according to Feyrer [2] were calculated using equations 1, 4 & 5 to allow a comparison.

Table 2: Case Study findings

	C1		C2	C3	C4	C5	C6	C7
	MINIMUM & ACTUAL EN81-1 ANNEX N SAFETY FACTOR		BENDING CYCLES ACCORDING TO FEYRER (N_{A10})	TRIPS ACCORDING TO FEYRER FOR ALL PULLEYS. WITHOUT HOLESCHAK FACTOR	TRIPS ACCORDING TO HF (Z_{A10}) FROM C3	ON SITE TRIP COUNTER BETWEEN ROPE EXCHANGES	DIFFERENCE IN TRIPS CALCULATED IN C4 TO ACTUAL IN C5	ACTUAL TIME BETWEEN ROPE EXCHANGE
	Minimum	Actual						
Case Study No 1	17.30	21.44	774,843.4	260,014.6	353,145.35	700,000	- 346,854.65	3.5 years
Case Study No 2	16.83	21.15	5,043,110.63	2,101,296	3,287,009	5,700,000	- 2,412,991	10 years
Case Study No 3	16.79	25.31	2,995,707.095	776,588.89	1,054,743.9	2,670,000	- 1,615,256.1	11 years
Case Study No 4	17.44	20.075	634,590.81	396,062.06	537,921.698	600,000	- 62,078.3	4 years

In Case Studies 1 and 4 the actual EN81-1+A3 (2009) Annex N safety factor is 21.44 and 20.075 respectively as shown in C1 of Table 2, with the ropes calculated to last for slightly above the discard N_{A10} value of 600,000 bending cycles as seen in the C2 section of Table 2 (Case Study 1 – 774,843.9 and Case Study 4 – 634,590.81) prior to exchange. The calculated number of 'round trips' that were converted from the bending cycles from C2 can be seen in C3 where the amount of diverting pulleys and the traction sheave have been taken into consideration for the discard number of round trips Z_{A10} (Case Study 1 – 260,014.6 and Case Study 4 – 396,062.06).

When the Holeschak Factor in C4 is then taken into consideration the actual number of trips of the lifts in Case Studies 1 and 4 are less than the recorded number prior to the exchange of the suspension ropes:

- Case Study 1 – calculated in C4 = 353,145.35 trips with actual trips at 700,000 in C5.
- Case Study 4 – calculated in C4 = 537,921.698 trips with actual trips at 600,000 in C5.

In Case Studies 2 and 3 the actual safety factor EN81-1+A3 (2009) Annex N safety factor is 21.15 and 25.31 respectively as shown in C1, with the ropes calculated to last for well in excess of the discard N_{A10} value of 600,000 bending cycles as seen in C2 (Case Study 2 – 5,043,110.63 and Case Study 3 – 2,995,707.095) prior to exchange.

The calculated number of 'round trips' that were converted from the bending cycles from C2 can be seen in C3 where the amount of diverting pulleys and the traction sheave have been taken into consideration for the discard number of round trips Z_{A10} (Case Study 2 – 2,101,296 and Case Study 3 – 776,588.89).

When the Holeschak Factor in C4 is then taken into consideration the actual number of trips of the lifts in Case Studies 2 and 3 are less than the recorded number prior to the exchange of the suspension ropes:

- Case Study 2 – calculated in C4 = 3,287,009 trips with actual trips at approximately 5,700,000 in C5
- Case Study 3 – calculated in C4 = 1,054,743.9 trips with actual trips at approximately 2,670,000 in C5

The figures in C4 for all Case studies would indicate that the rope inspection may not have captured that the ropes meeting the discard criteria until the ropes had deteriorated substantially. The calculated trips for all cases in C4 against the on-site recorded readings in C5 indicate that the rope either did not deteriorate or that the ropes had already met the discard criteria and should have been exchanged earlier than they were? The fact that all the lifts had the ropes exchanged later than the calculated number would suggest that they were not changed at a time that was required and they remained in service when they should have been replaced.

If the suspension ropes were to be exchanged at the journeys specified in section C4 where the ropes have been calculated to have met the discard criteria that '*There is a 95% probability that not more than 10% of the ropes have to be discarded* (N_{A10}) which is transferred to trips according to Holeschak Factor (Z_{A10}) in section C4, then the following would have occurred from the information in Table 3.

Table 3: Exchange time of ropes according to calculated trips.

Case Study No1	$\frac{C4}{C5} \times C7 = \frac{353{,}145.35}{700{,}000} \times 3.5$	= 1.77 years to exchange
Case Study No2	$\frac{C4}{C5} \times C7 = \frac{3{,}287{,}009}{5{,}700{,}000} \times 10$	= 5.77 years to exchange
Case Study No3	$\frac{C4}{C5} \times C7 = \frac{1{,}054{,}743.9}{2{,}670{,}000} \times 11$	= 4.34 years to exchange
Case Study No4	$\frac{C4}{C5} \times C7 = \frac{537{,}921.698}{600{,}000} \times 4$	= 3.58 years to exchange

4.1 Cost Implications of changing system parameters

Using Case Study 1 where the calculated number of trips in C4 in table 2 is 353,145.35 to alter some system parameters and view the effects on the expected number of bending cycles ($\boldsymbol{N_{A10}}$)**.** Then view the cost increase of the initial design and compare to the cost over the life of the lift that is estimated at 20 years.

System changes.
Increase sheave diameter to 480 mm from 400 mm and increase number of ropes from 5 to 6. The change of system parameters was then recalculated and gave results as shown in Table 4.

Table 4: Comparison of changes in sheave and rope for operational cycles

Scenario	10mm Ropes Drako-250T (IWRC) at Fmin 67.7KN	Minimum Annex N Safety Factor	Actual Annex N Safety Factor	Bending cycles N_{corA10}	Journey cycles Z_{A10} with Holeschak Factor
1 (existing)	5 ropes with sheave diameter 400mm	17.30	21.44	774,843.4	353,145.35
2 (new)	Case a) Sheave diameter 480mm. Ropes increased from 5 to 6	15.729	25.83	2,673,426.57	1,218,450.13

Initially it can be seen for the increase of 20% of the traction sheave diameter and one extra rope that there has been an increase of approximately 345% for the expected performance of bending cycles (N_{corA10}) and trips (Z_{A10}), this relates to an estimated life increase from the current approximate life before exchange to over 10 years from 3.5 years.

The cost of the increase in costs for the materials was given by Sharkey Lifting Ireland for suspension ropes, Ziehl Abegg UK for machine and diverter pulley costs.

Table 5: Comparison of cost over 20 years if initial design changed for Case Study 1

Scenario	Cost increase for sheave and rope at initial design	Number of ropes	Cost of Ropes for 90 Metres	Labour and equipment charge for re-roping	Estimated number of rope exchanges	Cost over 20 year life of life.
1	N/A	5	€1,516.50	€6,500.00	5	**€40,082.50**
2	€910.30	6	€1,819.80	€6,500.00	1	**€9,230.10**

The labour cost to perform the re-roping of the lift along with the cost of the ropes is detailed and details a significant lift life cycle cost saving for minimal initial investment.

5 CONCLUSION

All lifts in Case Studies had mid to high usage and are multi reeving systems at 2:1 with many diverting pulleys, these lifts represent a common situation today as there are now many lifts that being installed as Machine RoomLess (MRL) and will have a minimum reeving ratio of 2:1 with machine at top of shaft and therefore having 3 diverting pulleys (2 on the car and 1 on the counterweight). Case Study 1 is an MRL with the machine in the pit area and has 6 diverter pulleys; this will be the case for all MRL's that have a machine in the pit. There are also MRL's for heavy duty (normally over 2,000 KG minimum) that will have a roping arrangement at 4:1, this will have 7 pulleys.

The EN81-1 Annex N safety factor calculation according to Berner [6] is based on information on lift built before 1980 using fibre core ropes. Lifts at that time were predominantly reeving at a 1:1 ratio and therefore would have had ZERO pulleys, discounting the diverter under the drive machine (double wrap machines being the exception), where the bending cycles that occurred would have been 2 per round trip. Also due to the diverter under the machine the angle of wrap would have been less than 180 degrees causing the traction sheave groove be manufactured to give the required traction (to meet Annex M of EN81-1+A3 (2009)) or to increase the diameter of the traction sheave using the same groove to give the required traction.

The normal case of lifts currently used is to have a wrap of 180 degrees (both MRL and Machine room) and with space a premium the minimum traction sheave to rope diameter (D/d) measurement according to EN81-1+A3 (2009) of 40:1 being desirable.

From the Case Studies the choice of groove, the diameter of the rope ratio to the diameter of the sheave and the tensions applied (static and dynamic) have a major effect on the life of the rope in terms of the bending cycles they will perform until they reach the discard point.

6 FURTHER WORK

The safety factor equation (Eq. 9) as stated by Berner [6] was designed for fibre core ropes and this is borne out with numerical constants for fibre core ropes with Table 3.14b (Discarding number of bending cycles N_A) of Feyrer [2] showing constants that are replicated in the safety factor equation ($b_2 = 8.567$ and $b_4 = -2.894$ for fibre core ropes).

To have an altered safety factor equation that replicated the different constants of other rope types, especially the other most commonly used rope type - Independent Wire Rope Core

(IWRC) where $b_2 = 8.056$ and $b_4 = -2.577$ for example, the location of the constants from Table 3.14b of Feyrer [2] and $b2$ and $b4$ in the safety factor equation are highlighted in Eq. 13.

$$S_f = 10^{\left(2.6834 - \frac{\log\left(\frac{695.85\times10^6\times N_{equiv}}{\left(\frac{Dt}{dr}\right)^{b2}}\right)}{\log\left(77.09\left(\frac{Dt}{dr}\right)^{b4}\right)}\right)} \qquad (13)$$

The effect of the b_2 and $b_4$constants on the minimum safety factor to be determined by further work after confirmation that the base equation remains. On inspection of case studies 1 and 4 (where IWRC ropes are used) case study 1 moves from 17.29 to 18.66 and case study 4 moving from 17.44 to 18.86 for IWRC. This equates to an approximate 8% increase of the minimum safety factor required in both cases.

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BIOGRAPHICAL DETAILS

Patrick Ryan has worked for Schindler Ireland since 1994 after working for Schindler UK since 1988. He served an apprenticeship with Express Lifts in Birmingham from 1980 and worked for them for 8 years. He holds a HNC in Electrical & Electronic Engineering from Birmingham Polytechnic (now University of Central England) and holds an MSc in Lift Engineering from The University of Northampton gained in 2013.

The Internet of Things, Big Data, Machine Learning, and the Lift & Escalator Industry

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Keywords: Internet of Things (IoT), Big Data, Cloud Computing, Machine Learning

Abstract. New technologies such as the Internet of Things, Big Data, Cloud Computing and Machine Learning have the potential to radically change the Lift and Escalator Industry. This is particularly true in the areas of lift and escalator maintenance, product development, and quality. Lift and escalator maintenance has evolved over the years. The various forms of maintenance have included breakdown maintenance, preventive maintenance, usage based maintenance, condition based maintenance, and task based maintenance. Using the Internet of Things, Cloud Computing, Big Data, and Machine Learning, a new form of maintenance, Data Driven Maintenance, has arrived. Data Driven Maintenance provides benefits to building owners, building managers, lift and escalator passengers, and lift companies. What these new technologies are and how they apply to the lift industry is explained. Additionally, several real world applications of these technologies on lifts are detailed.

1 INTRODUCTION

Lifts and escalators are installed once, modernized as often as every 10 to 20 years, but are maintained for their entire lives. The lifts in the Woolworth Building in New York City, an early high-rise, were installed in 1914. The lifts were modernized for the fourth time in 2010 and the lifts are now currently in service and being maintained.

Maintenance is a major source of revenue and profits for the lift industry. The Internet of Things (IoT) has the ability to change the lift industry’s maintenance business model.

2 THE INTERNET OF THINGS

The term “Internet of Things” was coined by British entrepreneur Kevin Ashton in 1999 [1]. Today there are approximately three billion (3,000,000,000) internet users. Most are humans exchanging information over the internet [2]. In 5 years, 30 to 50 billion physical objects, things, will be connected to the internet. These things also referred to as machines, will be communicating with other machines such as computers. This form of communication is referred to as Machine to Machine (M2M) communication. M2M can utilize Plain Old Telephone System (POTS) lines, Cellular communication, Ethernet connections, Wi-Fi, or many other forms of electronic communication, not all of which exist today.

3 BIG DATA

Big Data is a term with many meanings. Initially it referred to data sets that were too large or too complex for traditional software and computers to process in a reasonable amount of time. However, today Big Data has also come to mean the use of predictive analytics to extract value from data regardless of the quantity of data [3].

The processing of Big Data requires large amounts of processing power, power not found in desktop computers. Big Data is processed by from tens to thousands of servers using massively parallel software. Not all organizations have large server farms at their disposal and so must find alternative sources of processing power such as Cloud Computing.

4 CLOUD COMPUTING

Cloud computing is the opposite of On Premises computing.

With On Premises computing all the hardware and software is owned by the operator. If a business needs 100 servers to run its business, it must buy 100 servers, build an air conditioned facility to house the servers, and provide electrical power and communication support for those servers. Additionally, the operator must provide the support necessary to keep the facility operational.

If an additional 25 servers are required one day a week for data analytics then an additional facility with 25 servers must be built and operated.

The On Premises model has both a Capital Equipment Expense component and an Operational Expense component. Everything is outsourced with Cloud computing. The operator only pays for the computing and data storage on a pay as you go basis. If the operator needs 100 servers during the day, 25 servers at night and 125 servers when running data analytics, then the Cloud provider will provide only the servers required. The number of connected servers can change dynamically based on need. The Cloud computing model has no Capital Expense component. Cloud computing is purely an Operational Expense model [4].

The Cloud provider can do this because he is providing services globally. The server farm may be located in Ireland whereas one of his clients may be located in China, another in Europe, and yet another in North America. His clients are using the same Cloud servers at different times of the 24 hour day.

Cloud providers usually have server farms in several locations where data is backed up. If a natural disaster such an earthquake or tornado were to strike one facility, the parallel facility would continue to operate without any interruption perceived by the user.

It should be noted that most businesses have a mix of On Premises and Cloud computing.

5 MACHINE LEARNING & DATA MINING

Machine Learning evolved from Artificial Intelligence (AI). The goal of AI is to develop computers and software that mimic human intelligence. One of the goals of AI is learning. Machine Learning (ML) involves making predictions based on properties learned from data [5].

ML is sometimes confused with Data Mining. The goal of Data Mining is to discover previously unknown properties in a set of data.

While both ML and Data Mining are useful in the lift industry, it is this author’s opinion that ML will yield more tangible results more quickly than data mining.

There are many tools that can be used for ML. One of the more common approaches is known as Classification and Regression Trees (CART) [6]. These trees are decision trees that learn from what has occurred in the past and use that knowledge to make predictions about future outcomes. Newly developed software based on CART makes the analysis of data possible by trained practitioners who are not necessarily Data Scientists.

6 DATA SCIENTISTS AND THE DATA SCIENCE TEAM

Data Scientists are the people who have a combination of business acumen and a knowledge of data analytics or statistics. Most data scientists have advanced degrees in science such as an MSc or a PhD. Thomas Davenport suggests that the combination of business, communication skills, and analytical skills may not be found in one individual [7]. He suggests that rather than try to find one person with all those skills, it may be necessary to form a Data Science Team.

If a data scientist is engaged solely in Data Mining, then no knowledge of the product being analyzed is required. If the Data Scientist is performing predictive analytics on a specific product such as a lift or escalator, then the scientist or data science team must have product knowledge. Such a person is known as a Domain Expert.

7 THE HISTORY OF LIFT AND ESCALATOR MAINTENANCE

The type of maintenance delivered by the lift industry has evolved over the years.

Initially only reactive (breakdown) maintenance was provided. When a lift stopped working a technician would be called to the site to return the lift to service.

The industry converted to preventative maintenance. The goal of this form of maintenance was to perform maintenance before a breakdown occurs and to increase the service life of a lift.

Remote monitoring of lifts and escalators appeared in the late 1980's. While remote monitoring would alert the lift company when a lift had a breakdown, it did not in and of itself reduce the number of breakdowns.

Usage based maintenance appeared in the lift industry in the late 1990's. The concept of this scheme was to adjust the quantity and timing of maintenance based upon usage. The concept was not truly new. Motor oil in automobiles has routinely been changed after a given number of kilometers of travel.

Condition based maintenance is simply providing maintenance based on the condition of a system or part. An example of this would be mounting an accelerometer and a temperature sensor on a critical bearing and monitoring the vibration frequencies, vibration amplitudes, and the bearing temperature. When a reading begins to leave the normal operating range, bearing maintenance or replacement can be scheduled.

Task based maintenance involves the generation of maintenance task lists based on the lift type usage and condition.

8 DATA DRIVEN MAINTENANCE

Data Driven Maintenance combines all the previously described maintenance types into one system. Data driven maintenance, while new to many industries including the lift and escalator industry, is quite mature in industries such as aviation [8].

Remote monitoring reports the usage and condition of the lift to the Cloud. Using Machine Learning, predictions are made of when and what must be maintained. These preemptive tasks are then communicated to the service technician from the Cloud. The service technician will then perform only those tasks which protect the customer's assets; their lifts or escalators.

The predictive nature of Data Driven Maintenance should be able to schedule maintenance tasks that will prevent breakdowns or increase the Mean Time Between Failure (MTBF). Additionally, when a pending failure is detected, Data Driven maintenance should be able to recommend a preemptive action that can be taken to eliminate a loss of continuity of service.

For example, if door motor current is monitored, an increase in current might, over time, indicate that additional door maintenance is required on the next visit. If a sudden increase in door motor current is detected it might indicate that a door was damaged, perhaps hit by a trolley, and a technician should be dispatched to correct the problem before a breakdown occurs.

Unscheduled breakdowns are expensive. They are much more expensive than preventative or preemptive maintenance. Data Driven Maintenance can reduce and hopefully eliminate unscheduled breakdowns. This will reduce maintenance costs and ultimately maintenance prices. Additionally, fewer breakdowns will increase customer satisfaction.

9 TIMING

When can Data Driven Maintenance be implemented? The technology for Data Driven Maintenance has existed for 10 or even 20 years. However, until recently, it was cost prohibitive.

Today we have very fast and very low cost computing. The cost of data storage is now a fraction of what it was just a few years ago. Low cost data storage has made Big Data economically feasible. The Internet is available almost everywhere in the world where lifts are located. Low cost wireless data communication is also available globally.

Cost and technology have reached a point in time where the economic benefits of Data Driven Maintenance can more than cover its costs and it comes with an improvement in customer satisfaction.

10 CONCLUSIONS

Data Driven Maintenance will change the way maintenance operations are conducted. More timely information about the performance of lifts will influence product development. If a new component has a higher or lower failure rate than the component it replaces, it will be detected more quickly.

If quality is defined by breakdowns per unit per year, then quality should improve.

Perhaps maintenance will be priced based on up-time.

Data analytics will also deliver unexpected results. Only time will determine how beneficial these results will be. However, it is logical to assume that these unexpected results will benefit both the lift industry, and more importantly, our customers.

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BIOGRAPHICAL DETAILS

Dr. Rory Smith is Visiting Professor in Lift Technology at the University of Northampton. He has over 46 years of lift Industry experience and has been awarded numerous patents.

Optic Technology for the Entrapment Issues of Side of Step, Comb Plate and Lift Doors

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Keywords: Escalators; entrapment; side of step; skirt panel; comb plate; lift doors; optic cable.

Abstract. This paper describes the prevalent issues that are apparent with side of step, comb plate and lift doors and how a better solution can be introduced. There have for many years been designs which have partly solved the problem, but are generally mechanically biased and in some cases are not used at all by the manufactures, as is the case of skirt panel detection and lift doors. Due to the increased number of reported incidents and the recent fatalities of strangulation, some consumers have developed an unbiased opinion that escalators and lift doors are dangerous. It has become more apparent that safety at the main entrapment points of skirt panel, comb plates and lift doors can be increased to be more reliable and functional with optic technology.

Step to skirting panel entrapment has been for many years a major incident issue, and only recently a small boy in the UK had an incident on an escalator and got his hand caught at this such point.

With reference to the comb bearer, incidents of entrapment have resulted in fatalities in Canada and Belgium. Issues of entrapment are caused by the type of footwear i.e. crocks and clothing.

A scenic lift door is a viewing area especially for small children, resting their hands on the glass. As the car arrives the doors open, the fingers have the potential to become trapped at the door frame.

These three main trapping points would undergo their regular maintenance schedule and the relevant safety checks would be carried out, with the equipment within its recommended tolerances. But with all moving parts the potential for entrapment is possible.

An optic cable installed into a module unit, sending a light signal out and monitored on its return for any distortion, has the function ability to assist with eliminating these potential trapping points. A light signal is monitored going out to its return on a multitude of parameters within the module box. When a pre-set distortion point has been reached, “which can be as sensitive as 0.01mm of movement”, a signal will be sent immediately to stop the unit at its safety function. The sensitivity of this function is due to the self-calibrating function in the system.

1 INTRODUCTION

The optic technology was originally developed for the automotive industry. It has been widely used on buses, designed to indicate to the driver when the entrance step was sufficiently acceptable to the pavement, so passengers could enter without an uneven step.

Johan Sevenants took the optical system in 2009 and came to the conclusion that it could be developed initially for the escalator industry, to help solve the potential issues that arise from side of step entrapment. It was enhanced further to help identify step to step entrapments at the two transition areas.

The system was then introduced to work alongside the existing comb plate safety switches to help identify foreign object entrapments such as screws which cause a considerable amount of damage to the step band.

The next and most recent move forward for the optical technology was to help with lift door entrapment at the door frame caused for example by children who rest their hands on the glass.

2 HOW IT FUNCTIONS

Principle operation optical detection:

Micro-spectrometry is the measurement of change in the light spectrum, and this is the basis of this innovative detection system. Light is a clear signal that can be measured very accurately and reliably with advanced electronics.

The closed system is made up of a plastic optical cable and an advanced electronic module. Use is made of a patented system involving the entire spectrum of light that is coupled into the optical cable. Through the software, various colours "put apart", to which the base values are assigned. These base values, as well as the desired bandwidth, are stored in the core of the system and form the limits of detection. When pressure is put upon the cable provided with mechanical break points for distortions in the cable, these distortions result in a change of the spectral distribution of the light in which the changing values belong. Including these new values beyond the set limits of detection, a signal will be given.

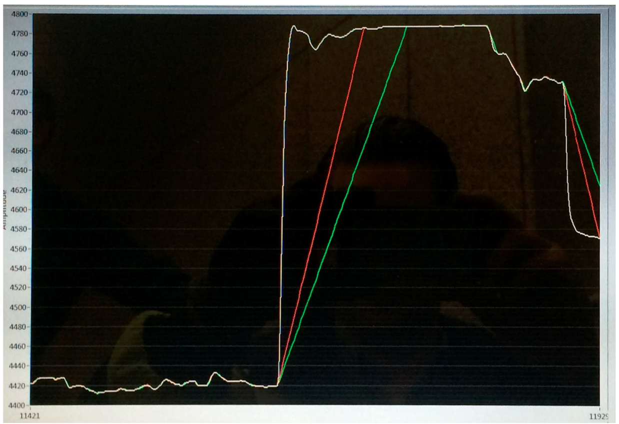
Only the kink points caused by the mechanical light changes, at the application of pressure using the pre-determined sensor points, finally provide for the detection. Changes in composition of the light as a result of factors such as dirt, wind, rain, hail, fog, snow, moisture and temperature cannot therefore exert any influence on the operation of the system.

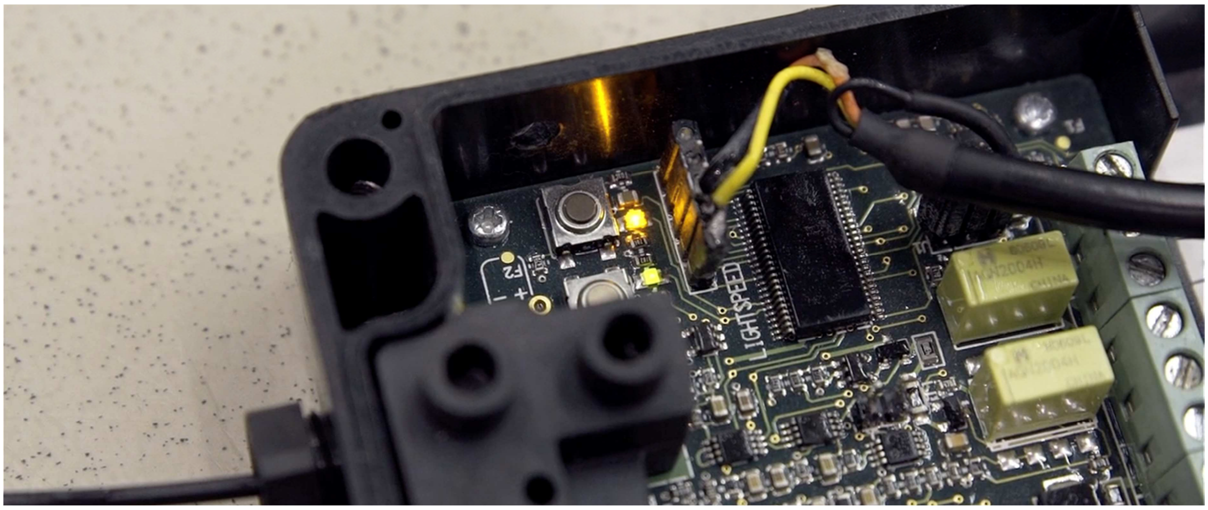
The various parameters of the system to adapt by application are tailor-made, making unique multiple detection combinations possible, making the system intelligent so that it can then have the function to carry out auto calibration. The system for auto calibration functions such that if an object has become trapped and activated the system and has not been removed after for example 10 seconds, the system will auto calibrate to this new position. Safety has been re-instated to the machine.

When the pre-set distortion point has been reached “which can be as sensitive as 0.01mm of movement” a signal will be sent from the module unit to immediately stop the unit at its safety function.

i. 0,01mm of movement is enough for activation

ii. Accurate in wide range i.e. less than 0,1N to over 10 tons



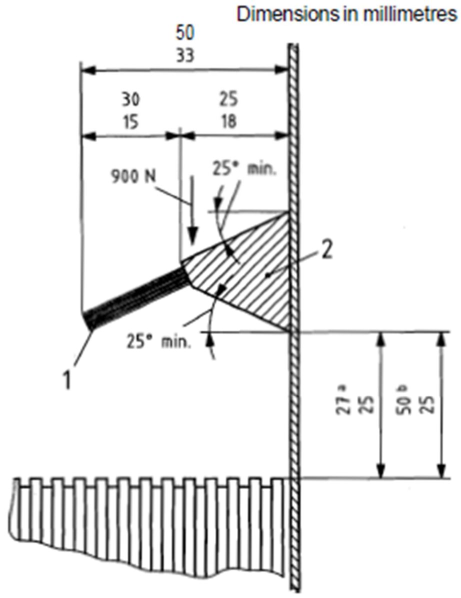


3 SKIRT PANEL | SIDE OF STEP

Side of step (=Step to skirting panel) entrapment has been for many years a major incident issue, involving clothing, shoes and especially children sitting on the steps. Only recently a small boy in the UK had an incident on an escalator and got his hand caught at this such point. We also know that units that have skirting brush are often used to clean shoes, and this can cause the shoe to become trapped in between the skirt panel and step.

The system is pressure sensitive to “force overtime” - the system measures 240 times a second and it is not susceptible to impact blows to trigger the distortion. As is often the case there can be issues of passengers kicking the skirt panels, but the system understands that no pressure is being engaged so will not activate.

The Skirt Panel detection is mounted at strategic points behind the skirt panels. The sensor points are installed at the centre point of the panel where the most distortion can take place.



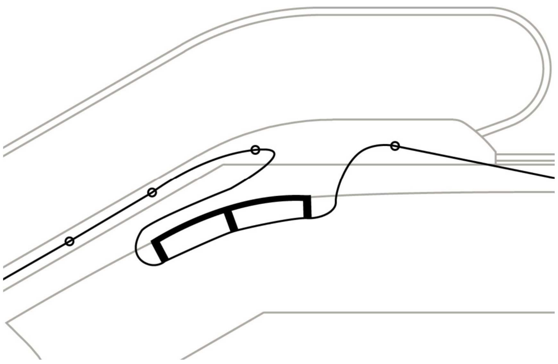
NEN-EN115-1:2008+A1:2010 (Article 5.5.3.3)

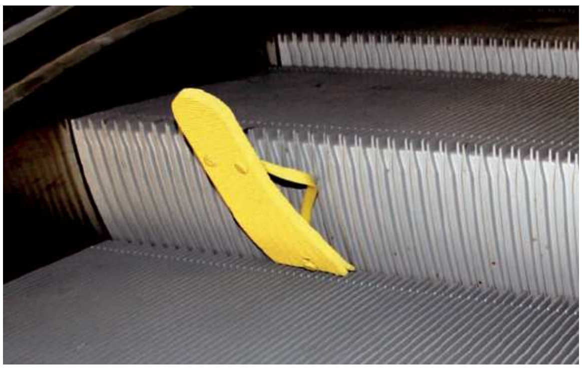
The skirting shall yield not more than 4mm under a single force of 1 500N acting at the most unfavourable point at right angles to the surface over an area 2 500mm² using a square or round area. No permanent deformation shall result from this.

4 STEP TO STEP

The step to step transition point at the bottom and top curves of the escalator are known to cause entrapment of shoes especially soft soled flip-flops. The passenger may have their foot too close to the leading edge and as the soft sole is depressed into the step tread, the step passes through this transition point and has the potential to grab the shoe. There was an incident in the UK on an old 1967 escalator that had a smooth stainless steel riser. This riser had somehow become removed from its position and as such there was a void into the step. The passenger had placed their foot on the steps with their toe edge into the void. The unit was running in the up direction and so as the steps reached the upper transition curve the foot became trapped.

With the step to step optic system mounted at the step roller guides, if an object is getting trapped between two steps, the upper step will be lifted. The optical system will be activated by touching the counter guide of the step rollers.





i. Mechanical setup
   a) Both sides of step
   b) Step to step
ii. Outputs
   a) Alarm
      1. 1 potential free contact
      2. NC at power
iii. Pressure sensitive
iv. Auto calibration

5 COMB PLATE

The Comb Plate detection is mounted just in front of the comb plates, on the comb bearer behind the skirt panels. It is mounted in this manner so as not to interfere with the existing safety switches. It can be retro fitted to any manufacture and model of escalator and has the added function of being able to detect vertically and horizontally. As we know for most manufacturers the comb bearer will only function in one movement.

The system is pressure sensitive, but it is not susceptible to impact blows to trigger the distortion. As is often the case there can be issues of passengers jumping from the transition point to the comb bearer, "especially on down running units", but the system understands that no pressure is being engaged and so will not activate. The added function of being pressure sensitive is that if a foreign object becomes trapped in the comb plate, i.e. a screw, as the screw enters the gap between the teeth of the comb platethe pressure point will be reached and the unit will shut down. This helps eliminate further damage to the comb and the step flute. So instead of having the whole step band scored, there may only be a certain number of steps scored.

The comb bearer incidents of entrapment which resulted in fatalities in Canada and Belgium in the past years may have been avoided as these deaths were of strangulation. The items that were the cause of death may have been detected using the optic system. The issues of entrapment are generally caused by loose clothing, long dresses, scarves, coats, etc. Most common of all is footwear in particular crocks, flip-flops and wellington boots. These have a soft soled base to them that causes the sole to become squashed on the step tread, which has been known to then become a trapping point at the comb plates if the passenger does not lift their foot before exiting the escalator.

NEN-EN115-1:2008+A1:2010 (Article 5.7.3.2.5/6)

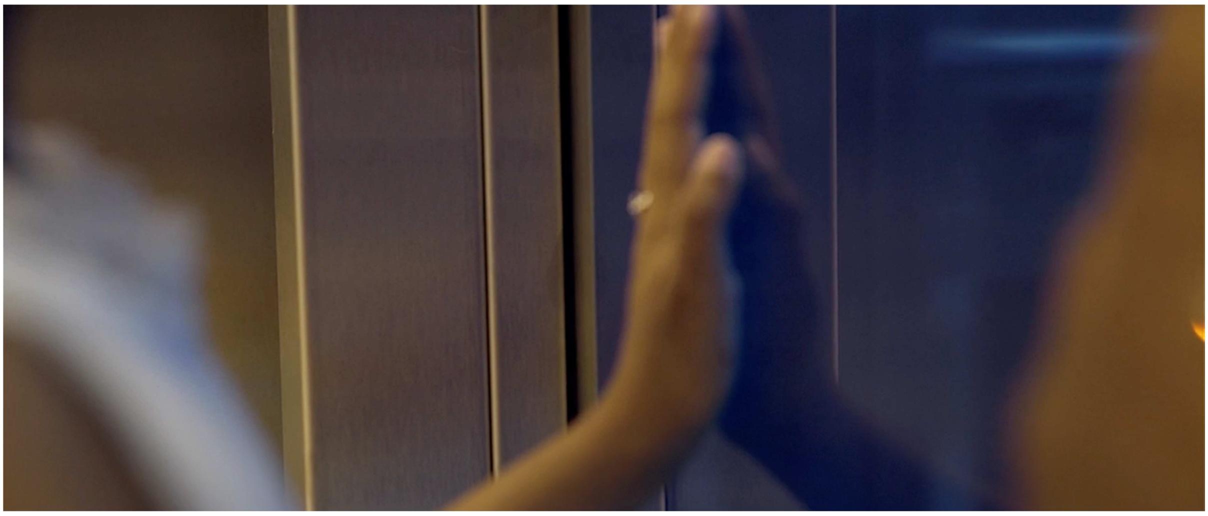
5.7.3.2.5 – The combs shall have such a design that upon trapping of foreign bodies either their teeth deflect and remain in mesh with the grooves of the steps, pallets or belt, or they break.

5.7.3.2.6 – In the case of objects being trapped which are not dealt with by the means described in 5.7.3.2.5 and in the case of comb/step/pallet impact the escalator or moving walk shall be stopped automatically.

i. Mechanical setup
   a) Horizontal & vertical detection
ii. Alarm
   a) 1 potential free contact
iii. Pressure sensitive
iv. Auto calibration

6 CENTRE OPENING LIFT DOORS

A scenic lift door is a viewing area especially for small children, who often rest their hands on the glass doors. As the car arrives the doors open, the fingers have the potential to become trapped at the door frame.



NEN-EN81-1:1998+A3:2009 (E) (Article 8.6.7.5)

"To avoid dragging of children hands, automatic power operated horizontally sliding doors made of glass of dimensions greater than stated in 7.6.2. Shall be provided with means to minimise the risk, such as:"

1. Reducing the coefficient of friction between hands and glass
2. Making the glass opaque up to a height of 1,10m
3. Sensing the presence of fingers, or
4. Other equivalent methods

i. Mechanical setup

   a) Both the lift car and landing doors
   b) System is auto-calibrating
   c) Suitable for metal and glass doors
   d) Plug and Play installation
   e) Available for multiple door heights

ii. Outputs
   a) Preventive system
      1. Alarm
         - NC or NO at power
   b) Corrective system
      1. Alarm
         - 1 potential free contact
   c) Pressure sensitive
   d) Auto calibration

7 CONCLUSION

These three main trapping points would undergo their regular maintenance schedule and the relevant safety checks would be carried out, with the equipment within its recommended tolerances. But, due to the nature of moving parts, the potential for entrapment is possible. The main concern is always to the passenger, but when an incident occurs, there may well be damage to the unit, which results in expensive litigation and repair costs.

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iv. NEN-EN81-1:1998+A3:2009 (E) (Article 8.6.7.5)

BIOGRAPHICAL DETAILS

Stephen Williams has been in the escalator industry for over 16 years. Starting as a service engineer completing NVQ level 3 escalator service, repair. Through the years developing all the field skills involved with escalators from handrail vulcanisation and all major escalator related repairs to eventually completing NVQ level 4 Escalator field tester. He has field experience with installation projects in the UK, Ireland and Middle East from the installation of single piece units to large multiple jointed units. Leading to coordinating the survey and building associated works that can transpire around the project. He also helps Johan Sevenants with the development of various innovative products within the lift and escalator industry.

Johan Sevenants has been in the lift and escalator industry for more than 25 years and holds a degree in Mechanical Engineering. His knowledge as project manager in the installation of more than 1000 escalators have helped to understand simple solutions to complicated projects. The majority of his time is taken up with the research and development for innovative products and services within the lift and escalator field, all over the world. He is co-owner of several companies who develops and promotes these products and services.