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The Passenger Transfer Efficiency Coefficient (PTEC) for Double Deck Elevators under Incoming Traffic Conditions

Lutfi Al-Sharif, Enas AlOsta, Noor Abualhomos, Yazan Suhweil

lal-sharif@theiet.org

Mechatronics Engineering Department, School of Engineering
The University of Jordan, Amman 11942, Jordan

Keywords: Elevator, lift, high rise buildings, double deck elevator, round trip time, up-peak traffic, incoming traffic, Monte Carlo Simulation.

Abstract. One of the sources of efficiency in the operation of double deck elevators is the simultaneous transfer of passengers into and out of the elevator cars, thus leading to a reduction in the value of the round trip time, and thus an increase in the handling capacity.

However, due to the randomness of passenger destination selections, this reduction is not optimal. This paper presents this phenomenon as an efficiency coefficient, denoted as the Passenger Transfer Efficiency Coefficient (PTEC) and is representative of the time taken by passengers to alight from the double deck elevator.

PTEC is mainly applicable to passengers alighting, rather than passengers boarding. This is true in the case of a single pair of entrances. For the case of multiple pairs of entrances, the PTEC applies to both alighting and boarding operations.

A set of equations are derived in order to calculate the PTEC. The results from the equations are verified using the Monte Carlo simulation method. The method of stepwise verification has been used in order to verify the equations.

Nomenclature

L the number of elevators in the group
N the total number of floors above the pair of main entrances
P the number of passengers per deck
P_e the number of passengers for the even deck
P_o the number of passengers for the odd deck
PTEC passenger transfer efficiency coefficient
S is the expected value of the number of stops in a round trip
t_p the passenger alighting or boarding time in seconds
U is the total building population in persons
U_i is the population of the i^{th} floor in persons
U_e is the total population of the even floors in persons
U_o is the total population of the odd floors in persons

1 INTRODUCTION

Double deck elevators offer a very efficient means of moving people within buildings ([1], [2] and [3]). By placing two conventional single deck elevators one on top of the other and attaching them rigidly, shaft space is saved. Passengers board both decks at the same time, whereby passengers heading to an odd floor board the lower deck and passenger heading to the even floors board the upper deck. The elevator then moves two floors at a time. Once a stop is made, passengers alight simultaneously from the upper and lower decks to the even and odd destination floors respectively.

There are three sources of efficiency that arise from using double deck elevators:

1. For incoming traffic, the effective number of stops is reduced due to the fact that the potential number of floors is halved ($N/2$ instead of N). This reduces the value of the round trip time and thus increases the handling capacity.
2. The passenger boarding and alighting time is reduced due to simultaneous boarding and alighting of passengers on the two decks.
3. Due to the fact that the two elevator cars are mounted on top of each other, the elevator handling capacity is increased without a major increase in the core space usage.

Double deck elevators are mainly used in two broad applications ([4], [5]):

1. They are as effective as shuttles between the ground floor and sky lobbies. The efficiency arises from the fact that there are only two stops (or three stops) thus reducing the value of the round trip time. The elevator car capacity in such situations is made relatively large.
2. They are currently increasingly being used in low and medium rise buildings in cases where the floor populations are relatively high. For example, double deck elevators can be very effective in buildings with more than 250 persons per floor (examples are given in [6]).

The use of double decker lifts has an impact on the value of the round trip time, by reducing it. The reduction in the value of the round trip time leads to a shorter round trip and hence an increase in the number of passengers that the elevator system can transport in five minutes. This leads to an increase in the handling capacity. This is one of the main benefits of using double deck elevators, whereby the other is the reduction in core space.

Barney [4] presents a comprehensive list of the double decker installation around the world and their applications. Siikonen [7] presents the equations for the expected number of stops (S) and the highest reversal floor (H) for the case of equal and unequal populations and derives a parameter for the passenger transfer efficiency. Genetic algorithms have been widely applied in elevator traffic control systems examples of which can be found in ([7], [9], [10] and [11]). More specifically, Sorsa *et al.* [8] use genetic algorithms to achieve optimal control of double deck elevators.

Two pieces of work on double deck elevator formulae are given by Kavounas [12] and Peters [13] and [14]. Kavounas derives a formula for the highest reversal floor and the expected number of stops. Peters [13] and [14] presents formulae for the general case under Poisson arrival conditions. However, it is difficult to carry out comparison with the results in these papers as they do not present any closed form equations (instead, calculations that they present are iterative and require computer implementation).

The published research in the area of double deck elevator does not address the following two points:

1. No mathematical formula has been derived for the passenger transfer efficiency (i.e., the quantification of the benefits of simultaneous passenger alighting at the destination floors). The main aim of this paper is to derive a formula for the passenger transfer efficiency. This is critical in enabling the correct calculation of the round trip time ([15], [16], [17]).

2. No verification has been carried out to ensure the accuracy of the derived equations. The derived equations presented in this paper have been verified using the Monte Carlo Simulation method (MCS).

Section 2 introduces some necessary assumptions and numbering conventions used in this paper. Section 3 introduces the concept of the passenger transfer efficiency and derives equations for the PTEC for the cases of equal floor populations. Section 4 discusses a similar parameter presented by Siikonen. Section 5 presents a numerical example to understand the effect of the number of passengers, P, and the number of floors, N, on the coefficient. Conclusions are drawn in section 6.

2 ASSUMPTIONS AND NUMBERING CONVENTIONS

In this section, some of the assumptions are clearly stated as well as the numbering notation for the building. It is necessary to clearly state some of the assumptions that will be made within this paper and provide some background required for the derivations.

Throughout this paper, it will be assumed that a single pair of entrances is used for boarding. There is only one pair of entrance floor, which is in effect a single entrance scenario. Each passenger can only enter the building through one floor: the odd entrance for odd destination occupant floors and the even entrance for even destination occupant floors.

It will also be assumed that all traffic is incoming traffic. Incoming traffic is traffic that originates at an entrance floor and terminates at an occupant floor. This is not an unreasonable assumption to make. The reason for this is that double deck elevators are usually operated in double deck mode under incoming traffic conditions during which they are most efficient. The design of double deck elevators is still based on the morning incoming traffic (up peak traffic). It is possible to operate double deck elevators in single deck mode outside peak hours. Under single deck mode, one of the decks is deactivated and the other deck serves passengers as a single deck.

It is also necessary to define the concept of a twin pair of floors, one of which is odd and the other even. This concept is critical to all the derivations that will follow in this paper. A twin pair of floors is, as the name implies, *consecutive* floors at which the double deck will make a *simultaneous* stop and deliver passengers. For brevity in the analysis below, the pair of twin floors will be simply referred to as twin floors. The lower floor will be assumed to be the odd floor and given the subscript o for odd; the upper floor will be assumed to be the even floor and given the subscript e for even. A general overview of the arrangement of a building that is served by double deck elevators is shown in Figure 1.

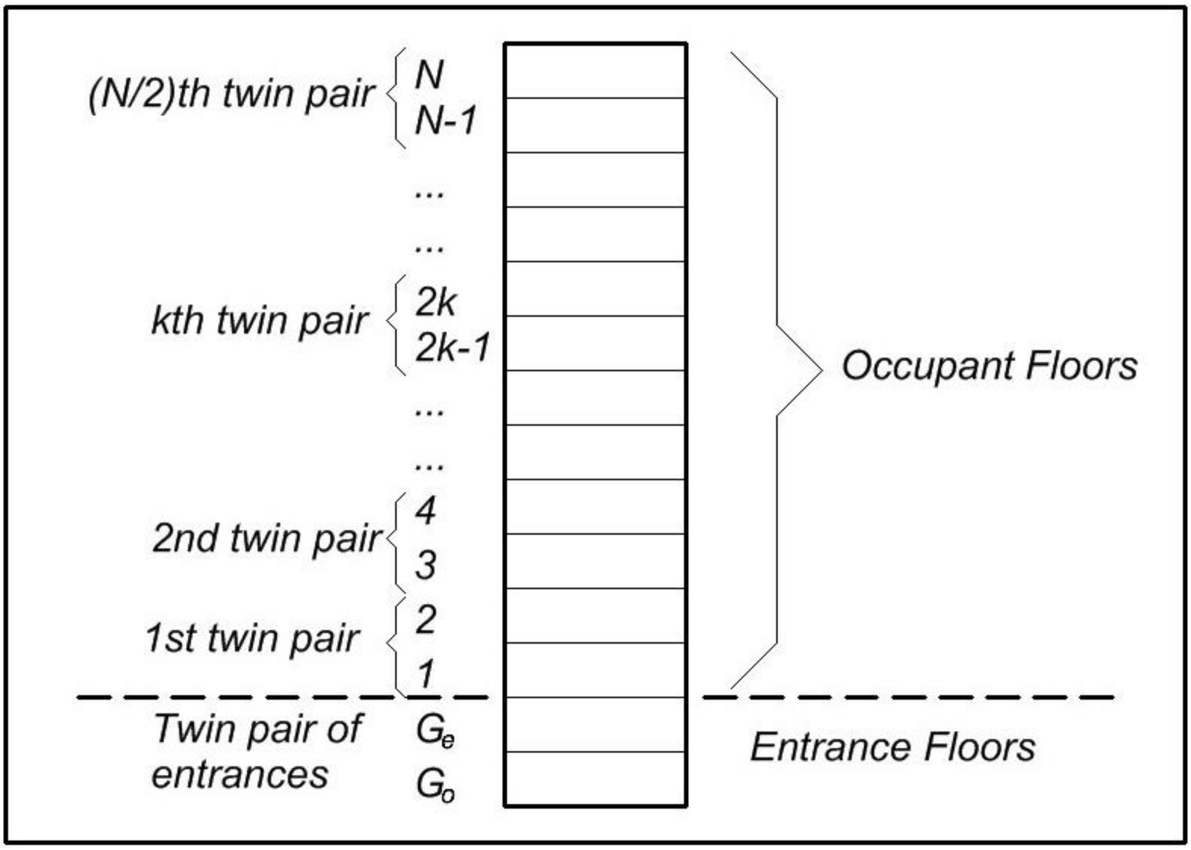

Figure 1: General overview of a building served by double deck elevators, showing the numbering convention used.

It will also be assumed that the number of occupant floors is even. This is the most efficient arrangement. However, some notes are given in [18] as to how the case of an odd number of occupant floors can be addressed.

3 DERIVATION OF THE FORMULA FOR THE PASSENGER TRANSFER EFFICIENCY COEFFICIENT

The passenger transfer efficiency coefficient (PTEC) is unique to double deck elevator systems (or to multiple deck systems in general). It is a measure of the efficiency of the passenger transfer time (i.e., boarding and alighting). There are two phases of passenger transfer in any elevator: boarding time and alighting time.

Based on a single pair of entrances, passenger transfer efficiency during boarding is not a concern (noting that it is assumed that all the traffic is incoming only). It is assumed that all P passengers for each deck (i.e., the upper deck and the lower deck) start boarding at the same time and finish boarding at the same time. Thus there is no wasted time and full efficiency is automatically attained.

However, the issue of passenger transfer efficiency is more of a concern during alighting. As there are many occupant pairs of floors (that will act as destinations for passengers) it is likely that different numbers of passengers are destined for the odd and even floors of the same stop. The most efficient scenario would take place in a double deck elevator when an equal number of passengers from the two decks alight at the same stop. In this case it can be stated that there is no wasted time, as there is no wasted waiting time at one deck while one or more passengers are alighting from the other deck.

For example, if at one of the double decker stops, five passengers alight from the upper (even) deck and one passenger alights from the lower (odd) deck, then the actual alighting time is equal to the time required for the five passenger to alight from the upper deck. The difference between the numbers of passengers intending to alight at this stop has effectively caused a loss of time. Had the number of passengers intending to alight been equal (i.e., three passengers for the upper deck and the three passengers for the lower deck) then the total alighting time would have been only equal to the time required for three passengers to alight, resulting in a saving equal to the time required by two passengers to alight. It is this efficiency (or inefficiency) that this parameter aims to capture. The formula for the case of equal floor population will be derived in this section.

In order to derive a formula for the *PTEC*, it is necessary to find an expression for the probability of the number passengers destined for the odd floor of the twin pair of floors being equal to *i* and the passengers destined for the even floor of the twin pair of floors being equal to *j*.

Each of these events shall be denoted as A and B respectively, as follow:

> A is the event under which *i* passengers are destined for the odd floor of the pair of twin floors.
>
> B is the event under which *j* passengers are destined for the even floor of the pair of twin floors.

For each of these events, the probability distribution function is effectively a binomial distribution (i.e., a passenger can either head or not to a certain floor). For each deck, it is assumed that *P* passengers will board the deck in each round trip at the main entrance.

It is now necessary to find the probability of *i* specific passengers going to a floor. This implies that other *P-i* passenger did not go to that floor. The probability of the joint event is the product of the two probabilities:

$$\Pr(i_s\ going\ to\ a\ floor\ and\ (P-i)_s\ not) = \left(\frac{2}{N}\right)^{i} \cdot \left(1-\frac{2}{N}\right)^{P-i} \tag{1}$$

This can then be applied to the odd floor of the twin floors and the even floor of the twin floors as shown in the two equations below. (It is implied that if *i* specific passengers go the floor then *P-i* passengers will not without the need to explicitly state it in the formula).

$$\Pr(P_o = i_s) = \left(\frac{2}{N}\right)^{i} \cdot \left(1-\frac{2}{N}\right)^{P-i} \tag{2}$$

$$\Pr(P_e = j_s) = \left(\frac{2}{N}\right)^{j} \cdot \left(1-\frac{2}{N}\right)^{P-j} \tag{3}$$

As the two events are independent, then the combined event whereby *i* specific passengers head to the odd floor and *j* specific passengers head to the even floor of the twin pair of floors is:

$$\Pr(P_o = i_s \cap P_e = j_s) = \left(\frac{2}{N}\right)^{i} \cdot \left(1-\frac{2}{N}\right)^{P-i} \cdot \left(\frac{2}{N}\right)^{j} \cdot \left(1-\frac{2}{N}\right)^{P-j} \tag{4}$$

In the terminology used in the derivations so far the term *specific* passengers has been used. This emphasises the fact that the derivation involves a specified set of *i* passengers and a specific set of *j* passengers. But the event will take place if any combination of *i* passengers in the odd deck are destined for the odd twin floor and if any combination of *j* passengers in the even deck are destined for its twin even floor. There are a number of different ways in which *i* passengers can be picked out of a total of P passengers and a number of different ways in which j passengers can be picked out of P passengers in even deck. These are in effect combinations and standard formula for combinations can be used as shown in the equation below.

$$\Pr(P_o = i \cap P_e = j) = {}_PC_i \cdot \left(\frac{2}{N}\right)^i \cdot \left(1 - \frac{2}{N}\right)^{P-i} \cdot {}_PC_j \cdot \left(\frac{2}{N}\right)^j \cdot \left(1 - \frac{2}{N}\right)^{P-j} \qquad (5)$$

This equation is now used to populate a dedicated matrix as shown below. The row index represents number of passengers heading to the odd floor of the twin pair of floors and the column index represents the number of passengers heading to the even floor of the twin pair of floors. The matrix is a P+1 by P+1 square matrix, as it is important to include the possible case whereby there are no passengers alighting from either deck.

$$\begin{bmatrix} \Pr(0_o0_e) & \Pr(0_o1_e) & \ldots & \Pr(0_oj_e) & \ldots & \Pr(0_oP-1_e) & \Pr(0_oP_e) \\ \Pr(1_o0_e) & \Pr(1_o1_e) & \ldots & \Pr(1_oj_e) & \ldots & \Pr(1_oP-1_e) & \Pr(1_oP_e) \\ \vdots & \vdots & \ldots & \vdots & \ldots & \vdots & \vdots \\ \Pr(i_o0_e) & \Pr(i_o1_e) & \ldots & \Pr(i_oj_e) & \ldots & \Pr(i_oP-1_e) & \Pr(i_oP_e) \\ \vdots & \vdots & \ldots & \vdots & \ldots & \vdots & \vdots \\ \Pr(P-1_o0_e) & \Pr(P-1_o1_e) & \ldots & \Pr(P-1_oj_e) & \ldots & \Pr(P-1_oP-1_e) & \Pr(P-1_oP_e) \\ \Pr(P_o0_e) & \Pr(P_o1_e) & \ldots & \Pr(P_oj_e) & \ldots & \Pr(P_oP-1_e) & \Pr(P_oP_e) \end{bmatrix}$$

Where: $\Pr(i_oj_e)$ is the probability that i passengers go to the odd floor and j passengers go to the even floor.

It is worth noting the following points about the different areas of this matrix:

1. The diagonal elements of the matrix represent the cases where the numbers of passengers destined for each of the odd and even floors of the twin are equal. For example, $\Pr(3_o3_e)$ is the probability of three passengers being destined to the odd floor of the twin pair of floors and the three passengers destined to the even floor of the same twin pair of floors.

   $$P_e = P_o$$

   In this case, the actual passenger transfer time is the time required for either deck as they are equal (i or j). This is the most efficient case as there is no loss of efficiency in passenger transfer.

2. The upper triangle of the matrix (i.e., above the diagonal as shown in the figure below) represents the cases where the number of passengers destined for the even twin floor is larger than the number of passengers destined to the odd floor of the twin pair of floors. In other words:

   $$P_e > P_o$$

In this case, the actual passenger transfer time is the time required for the even deck passengers to alight, which is the column index, *j*. In this case, there is a loss of efficiency in passenger transfer, proportional to the difference between *i* and *j*.

3. The lower triangle of the matrix (i.e., below the diagonal) represents the cases where the number of passengers destined to the odd twin floor is larger than the number of passengers destined to the even twin floor. In other words:

$$P_o > P_e$$

In this case, the actual passenger transfer time is the time required for the odd deck passengers to alight, which is the row index, *i*. In this case as well, there is a loss of efficiency in passenger transfer, proportional to the difference between *i* and *j*.

$$\begin{bmatrix} \Pr(0_o 0_e) & \Pr(0_o 1_e) & \cdots & \Pr(0_o j_e) & \cdots & \Pr(0_o P-1_e) & \Pr(0_o P_e) \\ \Pr(1_o 0_e) & \Pr(1_o 1_e) & \cdots & \Pr(1_o j_e) & \cdots & \Pr(1_o P-1_e) & \Pr(1_o P_e) \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ \Pr(i_o 0_e) & \Pr(i_o 1_e) & \cdots & \Pr(i_o j_e) & \cdots & \Pr(i_o P-1_e) & \Pr(i_o P_e) \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ \Pr(P-1_o 0_e) & \Pr(P-1_o 1_e) & \cdots & \Pr(P-1_o j_e) & \cdots & \Pr(P-1_o P-1_e) & \Pr(P-1_o P_e) \\ \Pr(P_o 0_e) & \Pr(P_o 1_e) & \cdots & \Pr(P_o j_e) & \cdots & \Pr(P_o P-1_e) & \Pr(P_o P_e) \end{bmatrix}$$

The next step is to find the expected maximum number of passengers alighting. Use will be made of the three areas of the matrix: one equation will be developed for the upper triangle of the matrix, one for the diagonal of the matrix and one for the lower triangle of the matrix.

The expected value of the maximum number of passengers alighting at each stop for the even number of passenger can be found by summing the product of the probability of each number of passengers alighting by their number from the upper triangle of the matrix. The limits of the summations ensure that the number of passengers alighting on the upper (even) deck is larger than the passengers alighting from the lower (odd deck). *Note that the operator is the expected value or the average.*

$$\mathrm{E}(P_e)|_{P_e>P_o} = \sum_{j=1}^{P}\sum_{i=0}^{j-1}\left(j\cdot\left({}_PC_i\cdot\left(\frac{2}{N}\right)^{i}\cdot\left(1-\frac{2}{N}\right)^{P-i}\cdot{}_PC_j\cdot\left(\frac{2}{N}\right)^{j}\cdot\left(1-\frac{2}{N}\right)^{P-j}\right)\right) \qquad (6)$$

The same is repeated for the lower triangle of the matrix as shown in the equation below.

$$\mathrm{E}(P_o)|_{P_o>P_e} = \sum_{i=1}^{P}\sum_{j=0}^{i-1}\left(i\cdot\left({}_PC_i\cdot\left(\frac{2}{N}\right)^{i}\cdot\left(1-\frac{2}{N}\right)^{P-i}\cdot{}_PC_j\cdot\left(\frac{2}{N}\right)^{j}\cdot\left(1-\frac{2}{N}\right)^{P-j}\right)\right) \qquad (7)$$

Equations (6) and (7) contain two terms: one involves the number of passengers alighting at the even floor and the other the number of passengers alighting at the odd floor.

As for the diagonal terms, there is only one summation and the index runs from 1 to P (the case where both P_e and P_o are zero is disallowed, as there would not be a stop in the first place if there are no passengers heading to either floor of the twin).

$$\mathrm{E}(P_e)|_{P_e=P_o} = \sum_{i=1}^{P} \left(i \cdot \left({}_P C_i \cdot \left(\frac{2}{N}\right)^{i} \cdot \left(1 - \frac{2}{N}\right)^{P-i} \right)^{2} \right) \quad (8)$$

Combining all the three cases, it is possible to evaluate the expected value of the maximum number of passengers alighting per twin pair of floors. The expected value is the summation of the three contributions to the expected value in the three cases.

$$\mathrm{E}(P_{max})|_{\text{twin}} = \mathrm{E}(P_e)|_{P_e>P_o} + \mathrm{E}(P_o)|_{P_o>P_e} + \mathrm{E}(P_e)|_{P_e=P_o} \quad (9)$$

However, there are $N/2$ twin number of floors, where N is the total number of floors above the main entrance. Thus the expected value of the maximum number of passengers alighting in a round trip is:

$$\mathrm{E}(P_{max})|_{\text{RTT}} = \frac{N}{2} \cdot \left(\mathrm{E}(P_e)|_{P_e>P_o} + \mathrm{E}(P_o)|_{P_o>P_e} + \mathrm{E}(P_e)|_{P_e=P_o} \right) \quad (10)$$

Finally, the PTEC is the ratio between the expected value of the maximum number of passengers alighting in each round trip divided by the number of passengers per deck.

$$\text{PTEC} = \left(\frac{N}{2 \cdot P}\right) \cdot \left(\mathrm{E}(P_e)|_{P_e>P_o} + \mathrm{E}(P_o)|_{P_o>P_e} + \mathrm{E}(P_e)|_{P_e=P_o} \right) \quad (11)$$

The equations derived above for the value of PTEC have been rigorously verified using the Monte Carlo simulation method ([19], [20], [21]) with excellent agreement. More details of numerical examples can be found in [18].

It is expected that the value of the PTEC will improve (i.e., become smaller and more efficient) under destination group control ([22], [23], [24], [25], [26], [27]). This is the current of future research whereby the formula is re-derived under destination group control conditions.

PTEC can range from 1 to 2. It attains it minimum value of 1 when all passengers alight simultaneously at the destination floors. It attains its maximum value of 2 when passenger only alight from one deck at every stop.

4 THE COEFFICIENT PRESENTED BY SIIKONEN

Siikonen derived a coefficient for passenger transfer loading [7]. The derivation will be presented below:

The probable number of stops equals to:

$$S_d = \frac{N}{2} - \sum_{k=1}^{\frac{N}{2}} \left(1 - P_{2k,d}\right)^{2\mathrm{P}} \quad (12)$$

Where $P_{2k,d}$ is the probability of passenger going to $2k$-1 or $2k$ floor.

$$P_{2k,d} = \frac{U_{2k-1}}{U} + \frac{U_{2k}}{U} \quad (13)$$

The probable number of stops for upper deck only equals to:

$$S_s = \frac{N}{2} - \sum_{j=1}^{\frac{N}{2}} \left(1 - P_{2j,s}\right)^{\mathrm{P}} \tag{14}$$

Where $P_{2j,s}$ is the probability of passenger going to even floor.

$$P_{2j,s} = \frac{U_{2j}}{U_e} \tag{15}$$

Then, the total passenger transfer time will equal:

$$= \left(2 - \frac{S_s}{S_d}\right) * t_p \tag{16}$$

This equation assumes that inefficiencies will occur in both alighting and boarding, whereas in this paper the authors have assumed that inefficiency only takes place in alighting and not in boarding. Siikonen also assumes that the population of every twin pair of floor is equal (i.e., the population of the even floor of the twin pair is equal to the population of the odd twin pair) so that the numbers of stops for single deck for odd and even are equal.

5 NUMERICAL EXAMPLE

In order to gain a numerical appreciation of the range of values of the coefficient (i.e., the PTEC), a numerical example is presented in this section for a realistic range of values for *P* and *N*. As discussed earlier in this paper, the coefficient will range from the smallest possible value of 1 (representing full efficiency in passenger alighting from both decks) to the maximum possible value of 2 (representing zero efficiency in passenger alighting from both decks).

Assuming a building with equal floor populations and equal capacity for both decks and an even number of floors above the pair of main entrances, the PTEC was calculated for a range of value of *P* and *N*. The results are shown in Table 1.

Table 1: The value of the PTEC for a number of buildings.

	N (number of floors above the main entrance)					
P (each deck)	10	12	14	16	18	20
10	1.3474	1.3848	1.4187	1.4485	1.4763	1.5012
13	1.3062	1.3411	1.3713	1.3992	1.4243	1.4474
17	1.2699	1.3001	1.3274	1.3521	1.375	1.3958
20	1.2486	1.278	1.3029	1.3262	1.3475	1.3679
26	1.2186	1.2445	1.2666	1.2875	1.3069	1.3247

As can be seen from the results, the value of the PTEC ranges from around 1.2 up to 1.5. As the number of passengers per deck increases, the efficiency increases (with smaller value of PTEC) as expected. Moreover, as the number of floors above the main entrances increases, the efficiency decreases (with a larger value of PTEC) as expected.

6 CONCLUSIONS

A new parameter has been introduced that measures the efficiency of the passenger transfer time denoted as the PTEC (passenger transfer efficiency coefficient). It represents how efficient the transfer of passenger is when alighting at the destination floors. The PTEC can be used in the calculation of the round trip time whereby it provides an accurate measure of the passenger transfer time. In general, the round trip time equation contains a passenger transfer element that accounts for the time taken up by passenger in boarding and alighting. In this case, the PTEC can be used to amend the time required by passenger to alight at their destinations by taking into consideration the time saving that results from simultaneous passenger alighting from both decks.

The PTEC has been derived for the case of equal floor populations. The derived equations have been verified using the Monte Carlo Simulation method with excellent agreement. A similar coefficient presented by Siikonen is also studied assuming equal alighting probabilities for even and odd decks. A numerical example is given for a number of buildings in order to show the effect of the number of passengers per deck (P) and the number of floors above the pair of main entrances (N) on the value of the coefficient. It is shown that the value of the coefficient increases with the increase in N and decreases with the increase in P.

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[22] Peters R. Understanding the benefits and limitations of destination dispatch. Elevator Technology 16, The International Association of Elevator Engineers, the proceedings of Elevcon 2006, June 2006, Helsinki, Finland, pp 258-269.

[23] Smith R and Peters R. ETD algorithm with destination dispatch and booster options. Elevator Technology 12 2002; 12: 247-257. The International Association of Elevator Engineers (Brussels, Belgium), proceedings of Elevcon 2002, Milan, Italy, June 2002.

[24] Joris Schroeder, “Elevatoring calculation, probable stops and reversal floor, “M10” destination halls calls + instant call assignments”, in Elevator Technology 3, Proceedings of Elevcon ’90, International Association of Elevator Engineers, 1990, pp 199-204.

[25] Sorsa J, Hakonen H and Siikonen M L. Elevator selection with destination control system. Elevator Technology 15 2005; volume 15. The International Association of Elevator Engineers (Brussels, Belgium), proceedings of Elevcon 7th to 9th June 2005, Peking, China.

[26] Lauener J. Traffic performance of elevators with destination control. Elevator World (Mobile, AL, USA) 2007; 55(9): 86-94.

[27] Al-Sharif L, Hamdan J, Hussein M, Jaber Z, Malak M, Riyal A, AlShawabkeh M and Tuffaha D. Establishing the Upper Performance Limit of Destination Elevator Group Control Using Idealised Optimal Benchmarks. Building Services Engineering Research and Technology, 2015; 36(5):546-566. September 2015.

BIOGRAPHICAL DETAILS

Lutfi Al-Sharif is currently professor of building transportation systems at the Mechatronics Engineering Department at the University of Jordan, Amman, Jordan. His research interests include elevator traffic analysis and design, elevator and escalator energy modeling and simulation and engineering education.

Enas AlOsta, Noor Abualhomos and **Yazan Suhweil** all graduated from the department of mechatronics engineering at the University of Jordan, Amman, Jordan in 2017.

My Story of Lift Traffic Analysis, Design and Control 1960 – 2020

Gina Barney

Gina Barney Associates, PO Box 7, SEDBERGH, LA10 5GE, England.
www.liftconsulting.org

Keywords: history, lifts, lift analysis, lift control, lift design

Abstract. This paper, relying on the first 60 years[1] of lift traffic design, provides an objective view of the developments in lift traffic design since 1960. The paper will look at the contributions of, amongst others: Alexandris, Barney, Beebe, Closs, Dos Santos, Godwin, Lim, Peters, Port, Schroeder and Strakosch. Lift traffic developments are of necessity intertwined with lift traffic control algorithms and technology, including Call Allocation and interactive lift system simulation during the same period. A view ahead will be indicated. Footnotes indicate sources for their easy reference by readers rather than being in-line text.

1 INTRODUCTION

This story is my story and will be told in a narrative style in the first person as I was and am still there. Rather than run a time line, I will tell this story based on the people that made it, as evidenced by material in the public domain and by personal contact. There will be material in the archives of lift manufacturers and elsewhere that is missing from this story (unknown-knowns). Most of people mentioned are still alive today, some I know personally others only by reputation. Inevitably there will be people and events left out of this story. Additions/corrections to the story are welcome. An example of this is that during the writing of this story a colleague reminded me of a citation in an article to a paper Dos Santos and I published in 1974[2].

GINA (*née* GEORGE) BARNEY

My first encounter with the lift industry was in January 1968, when Michael Godwin (Adrian Godwin's father) came to the University of Manchester Institute of Science and Technology (UMIST), where I was a Lecturer, seeking help with the stopping and levelling of Ward-Leonard drives. This was a technical problem. David Closs, a student at UMIST, was looking for an MSc project. He resolved this technical problem in September 1968. His work pump primed my interest and my near 50 years work in lift traffic analysis, design and control.

Subsequently I was fortunate to work with many clever people as you will see, who sometimes had eureka moments and were gone, but some have become equally enthused for lift traffic analysis, design and control. The work at UMIST continued to 1993, when I retired and since then I have carried on the work independently.

There are four books and a landmark paper that I have authored/co-authored which objectively report my work and the work of others in the field where it is known. They are:

Landmark Books

Book (1) Barney, G.C. and Dos Santos, S.M., 1977, "*Lift traffic analysis design and control*", Peter Pereginus.

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[1] Gray, L., 2017, Lift Traffic Analysis 1890-1960, 7th Symposium on Lift and Escalator, Northampton, 2017

[2] Green, M.F and Stafford-Smith, B., 1977, A survey and analysis of lift performance in an office building, Building and Environment, Vol. 12, pp. 65-72, Pergamon Press

Book (2) Barney, G.C. and Dos Santos, S.M., 1985, "*Elevator traffic analysis design and control*", Peter Pereginus.

Book (3) Barney, Gina, 2003, "*Elevator Traffic Handbook*", Taylor & Francis.

Book (4) Barney, Gina and Al-Sharif, Lutfi, 2016," *Elevator Traffic Handbook*", Routledge.[3]

Landmark Paper

Barney, G.C. and Dos Santos, S.M., 1975, "*Improved traffic design methods for lift systems*", Bldg. Sci.

2 BACKGROUND

2.1 Traffic Analysis and Design

In the beginning from 1890 to 1960 there were many people, who laid the foundations of modern lift traffic analysis and design[4]. This list compiled by Dr Lee Gray for his paper included: Root (1890), Hill (1893), Darrach (1901), Kidder (1904, 1916), Pelham Bolton (1908), Tweedy (1912-13), Ehrlich (1914), Cook (1916 - 1932), Gumpel (1916), Gillette and Dana (1918), Jones (1923 - 1926) Grierson (1923), Marryat (1924), Kinnard (1930), Annett (1935, 1960), Phillips (1939, 1951), Molloy (1941).

In 1968 I was blissfully unaware of this work. My foundations were built on George Strakosch's landmark book published in 1967, which did inform me at least of Bassett Jones.

2.2 Traffic Control

Six "Eras" of traffic control can be identified:

Era	Dates	Traffic Control Type
I	1850–1890	Attendant simple mechanical control
II	1890–1920	Attendant and electrical car switch control
III	1920–1950	Attendant/dispatcher and pushbutton control
IV	1950–1975	Automatic group control: IVa scheduled traffic control to 1960 IVb demand traffic control from 1960
V	1975–1990	Computer based group control
VI	1990 –	Call Allocation group control

The transition from a human pulling a rope to a computer making decisions took nearly one hundred and fifty years. This story starts in Era IVb.

2.3 Traffic Simulation

The early traffic simulations used batch based processing, where paper tape, or cards, or magnetic tape drives provided the input method and line printers produced reams of paper for the output. In between the algorithms were coded, possibly in Fortran, but often in assembly language.

Interactive computing is relatively recent dating from the late 1960s/early 1970s. Today "Apps" are everywhere. Interactive traffic design only became possible when time sharing computers video display units became available.

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[3] Records 283 references and 32 bibliographic entries of all the people and publications we could find in the field.

[4] Gray, Lee, 2017, Lift Traffic Analysis 1890-1960, 7th Symposium on Lift & Escalator Technologies, September 2017

3 THE BEGINNING – MY FOUNDATIONS – MY MENTORS

BASSETT JONES

Jones, when working for the General Electric Company was interested in sizing lift motors for the duty that they had to meet [5] So he wanted to know the number of stops[6]. He was also interested in drive dynamics[7]. He was not a lift industry member.

GEORGE STRAKOSCH

He worked for Otis and later became a consultant. In 1967 he wrote a landmark book[8] that updated the work of R.S. Phillips'1939 book [9] He gave a traffic design method. This was the first significant attempt to bring traffic analysis into one place. He defined and used the concepts of five minute peaks, handling capacity and interval and established a lift's cycle time as the round trip time.

Strakosch's method was very pragmatic – basically a recipe system – and not at all formulaic. He added the times to open and shut the doors, the time that passengers take to get in and out and the time to move up and down to provide a value for a Round Trip Time.

MICHAEL GODWIN

He is very important to my history. When we met he was Technical Director of William Wadsworth, Bolton. Very innovative and intuitive, he was very much in advance of his time. It was he who suggested putting the call buttons on the landing. I do not know if he had heard of Leo Port (see Port), but sometimes great minds are separated by 12,000 miles.

He and I set up Lift Design Partnership in 1974, which became Lerch Bates Europe, in 1990, when Michael retired. I remained Chairman/Chairman Emeritus until 2002. Besides producing a radically new standardised specification for public housing lifts[10] his main technical innovation was Bush House [11](see Beebe and Lim).

To this day he is interested in linear motor driven lifts. And this is how he met and employed Haider Al-Abadi[12] for nineteen years, currently Prime Minister of Iraq.

JORIS SCHROEDER

Joris Schroeder when reading for his doctorate in 1955 derived a formula for the highest reversal floor H [13].

He was also very brave to produce the first implementation of Call Allocation at Schindler's Ebikon offices in December 1989. This was against strong company opposition and significant industry derision at the time. All the usual ill informed "*No one will use it*", etc. He used the technical specification that Dos Santos and I published in our 1977 book (Book 1). He did not fully implement the specification, such as penalty functions, dynamic uppeak subzoning, adaptive algorithm, etc. Today the industry derision has disappeared to be replaced by over enthusiastic adoption of what is (commercially) called "Destination Control", see David Closs below. Joris sadly passed away before he saw the fruits of his endeavours – a badly missed interlocutor.

Schroeder also published equations for H and S to adapt the RTT equation so that an uppeak

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[5] https://archive.org/details/generalelectricr26gene
[6] Jones, Bassett 1923, The probable number of stops made by an elevator, GE Rev., 26, (8)
[7] Bassett Jones, 1924, Time-velocity Characteristics of the High-speed Passenger Elevator. General Electric Review, Vol. 27, February 1924
[8] Strakosch, G.R., 1967, Elevators and escalators, 1/ed, Wiley
[9] Phillips, R.S., 1939, Electric lifts, Pitman
[10] Godwin, M.,1973, Formulating the specification, Lift, 15, pp141-146
[11] Godwin, M., 1986, Bush House: Lifts of the World
[12] Al-Abadi , H. J, 1980, Disc and linear forms of electronically controlled permanent-magnet claw machines, PhD thesis, University of Manchester, 1980
[13] Schroeder, J., 1955, Personenaufzuege (passenger lifts), Foerden und Heben, 1 (in German)

calculation could be performed for Call Allocation. The variable *k* is the famous look ahead.

4 THE MIDDLE 1960-2017

DAVID CLOSS

In my autobiographical note I mention David Closs as my first MSc student in 1968 and my first PhD student. After completing his MSc, Closs registered for a PhD to research the behaviour of traffic control algorithms[14]. His first analysis considered the best method for a lift to answer a set of landing calls (the "travelling salesman" problem). He concluded the best method was directional collective and elaborated four rules:

> **Rule 1** A car may not stop at a floor where no passenger enters or leaves a car.
>
> **Rule 2** A car may not pass a floor at which a passenger wishes to alight.
>
> **Rule 3** A passenger may not enter a car travelling in the reverse direction to the passengers required direction of travel.
>
> **Rule 4** A car may not reverse direction of travel while carrying passengers.

To which can be added a pragmatic rule:

> **Rule 5** Car calls take precedence over landing calls.

There are some workers[15] today who suggest that Rules 2 and 4 can be violated for the convenience of the traffic algorithm. This defies Closs.

Closs went on to analyse what he called "Call Allocation" [16], ie: to give the control algorithm a passenger's destination and not just their direction. This meant putting the destination call buttons on the landing not in the car. His analysis showed the promise of this idea.

After graduating in 1970, Closs did not stay in the industry.

SERGIO dos SANTOS

He is responsible for the major developments of: the derivation of the RTT equation; interactive simulation; the analysis of various traffic conditions and control algorithms; and most importantly a full definition of the Call Allocation traffic control algorithm in two forms: Hall Call Allocation and Adaptive Call Allocation. Sergio dos Santos took Closs' work further on.

Interactive Simulation

In May 1972 he registered for an MSc with me. By 1972 it was obvious that we would not get anywhere unless we could emulate or model a lift system in some way. In May 1972 I defined a basic simulation program comprising an input module, a control and simulation module and an output module. I gave Dos Santos this specification and went to Argentina for three months. When I got back Dos Santos had done it and had also coded a simple full collective algorithm as Closs had defined it into a fully interactive program[17]. We had LSD (Lift Simulation and Design) simulation[18] program! Dos Santos agreed to read for a PhD on this topic.

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[14] Closs, G.D., 1970, The computer control of passenger traffic in large lift system, PhD thesis, UMIST

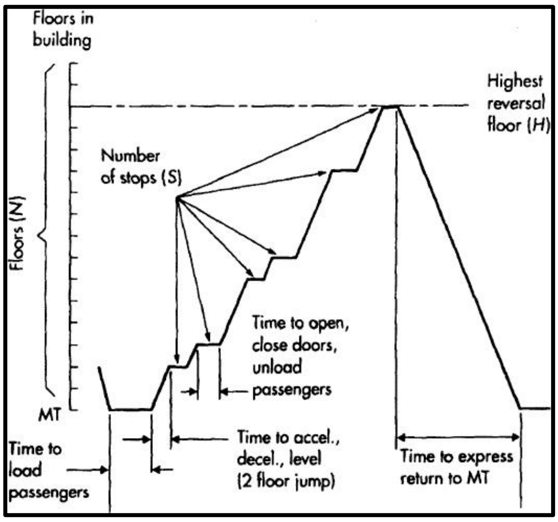
[15] Gerstenmeyer S., Peters R. D., 2014, Reverse Journeys and Destination Control, Proceedings of the 4th Symposium on Lift & Escalator Technology

[16] Sometimes called "Destination Control", which is ambiguous, it is the user that determines the destination not the traffic control algorithm! Destination Control is the commercial name for Call Allocation.

[17] In the 1970s must computers operated in batch mode.

[18] Dos Santos, S.M., 1972, Lift simulation, MSc dissertation, University of Manchester Institute of Science and Technology

Round Trip Time Formula



In the course of the programming the LSD program, it was obvious that the Strakosch "recipe" method of sizing could better be described mathematically. We defined the now classical *RTT* equation in the period of Dos Santos' work and published the first version of it in our 1975 paper as:

$$RTT = 2H\,t_1 + (S+1)\,t_2 + 2Pt_3$$

This is the basic equation and obeys Closs' rules. It can be adapted for other conditions than uppeak (not given here). The equation presentation has changed little over the last 42 years, except to make it more understandable to the mathematically challenged and now looks like:

$$RTT = 2Ht_v + (S+1)(T\text{-}t_v) + 2Pt_p$$

This equation is simple in concept and it is worth explaining.

Three independent variables (t_v, t_s, t_p) and three dependent variables (H, S, P).

The first term is for the time a lift is moving, ie: a travel distance of H floors with a time between floors of t_v.

The second term is S times (+1) the time consumed in stopping, ie: for door operations, drive control.

The third term is what the passengers do, ie: get in and out of cars taking a time of t_p.

The middle term is the most significant, as a second added here may reduce the handling capacity by 5-10%.

The variables H, and S are dependent on the number of passengers (P) in the car, when it leaves the main terminal and the number of floors above the main terminal (N).

So there is really only one independent variable and two dependent variables! And these are evaluated by Bassett Jones (1923) for S and Joris Schroder for H (1955).

Dr Lee Gray in his paper highlights George Hill's search for a "*uniform law*" for lift traffic analysis[19]. The two equations above (the only two in this paper) might do it – 82 years later?

Call Allocation Traffic Control Algorithm

Working with Closs' skeleton derivation of the Call Allocation traffic control algorithm, Dos Santos developed a full specification of the two variations of the algorithm. The first was Hall Call Allocation. The second was Adaptive Call Allocation. There were many features: penalty functions, dynamic uppeak subzoning, adaptive algorithm, etc. all described in his thesis[20] and in our jointly authored book Lift Traffic Analysis Design and Control in 1977 (Book 1). By putting this specification into the public domain by prior publication of Closs' and Dos Santos's PhD theses in 1972 and 1974 it prevented it being patented by a manufacturer (one tried and failed) and could be offered to all. The specification has never been fully implemented by any manufacturer although Schroeder was close to it. And Peters has a closer representation of HCA, but not ACA in Elevate.

Analysis of Traffic Conditions

Dos Santos and I realised that having an interactive program (LSD) meant we had a powerful tool to analyse all traffic patterns and any control systems. At the time LSD was being developed the traffic control systems were based on relays and some electronics. They were not simple. The main ones

[19] Hill, George Hill, 1893, Some Practical Limiting Conditions in the Design of the Modern Office Building, The Architectural Record, Vol 5, 445-468 (April-June 1893)

[20] Dos Santos, S.M., 1974, The design, evaluation and control of lift systems, PhD thesis, UMIST

were fixed bidirectional sectors, eg Otis VIP 260, fixed time based sectors, eg: Express Mark 4 and dynamic sectors, eg: Schindler Aconic.

The question is how do they affect actual performance?

Dos Santos programmed these algorithms into LSD and ran over 2000 simulations and produced a series of graphs for uppeak, down peak and interfloor traffic. To do this he invented traffic profiles, which you can see today as "templates". This work enabled some rules of thumb to be developed and these fed back into the design process.

Alongside this work Dos Santos also programmed the Hall Call Allocation algorithm and analysed it. During this work he developed Adaptive Call Allocation (ACA), which switched the cost function (*aka* performance index) from journey time to waiting time for low loads.

Dos Santos did not stay in the lift industry but went on to be the Rector of the Universidade do Minho, Portugal from 1985-1998.

LEO PORT

Port proposed, what we all accept now, taking the pushbuttons out of the car and putting them in the hallway/lobby/foyer/landing. It was the first proposal for Call Allocation, which is what Closs called it. Port patented[21] it as PORT–El in 1961, which he let expire in 1977. He had two implementations, one in the Law School at the University of Sydney[22] and the other was in the Australian Milk Marketing Board offices. Both installations were low rise and only had two or three lifts. Port did not have any computing power so he programmed the lifts to always go to the same floors using simple fixed logic.

He became Lord Mayor of Sydney in 1975 and died in office in 1978.

In retrospect Call Allocation traffic control systems should be called Port-El systems to honour someone, who changed the whole scene of lift traffic control.

PETER TREGENZA

The formula derived by Jones and Schroeder used the simple probability distribution function (pdf), often known as a rectangular or constant pdf. What this represents is people arriving with a constant interval between them. But do people arrive like that? It is thought that a Poisson pdf was more likely, see Alexandris. Tregenza in 1972 accepted this and developed relationships[23] for the variables S and H.

Dos Santos was subsequently able to show that a Poisson pdf gave smaller values for S and H and hence a more optimistic design than the constant pdf. This allowed the simpler formulae and processes to be the chosen procedure.

NICOS ALEXANDRIS

Alexandris was a mathematician and registered for a PhD[24] with me. Out of intellectual curiosity he was set the task to prove mathematically what had been discovered by the Dos Santos simulations, hence the title "*Statistical models in lift systems*". His first task was to survey buildings to determine the arrival process. He found it to be (probably) Poisson. By queuing theory he was able to show the 80% loading factor to be the interface between a good system and a poor system. Along the way he developed a general analysis[25].

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[21] Port, L.W., 1961, Australian patent specification 255218, 1961
[22] Port, L.W., 1968, The Port elevator system, University of Sydney, June, 1968
[23] Tregenza, P.R., 1972, The prediction of passenger lift performance, Archit. Sci. Rev
[24] Alexandris, N.A., 1977, Statistical models in lift systems, PhD thesis, UMIST
[25] Alexandris, N.A., Barney, G.C., Harris, C.J., 1979b, Derivation of the mean highest reversal floor and expected number of stops in lift systems, Applied Mathematical Modelling, Volume 3, August 1979

BRUCE POWELL

The story of random behaviour would not be complete without mentioning Bruce Powell. Powell is a long time contributor in the application of mathematical modelling to lift design and control systems. I first came across his work ca1972[26] and it might well have influenced Alexandris and Dos Santos. He shaped some of the theory we use today.

After university his career was in the lift industry initially at Westinghouse, where he was involved in coding simulation software ca1967. He later moved to Otis and in 2002 reached the inevitable destination of becoming a consultant. In 2005 he was one of the "Four Doctors".

RICHARD PETERS

I have known Richard Peters since he was an undergraduate (1986) and I and Lutfi al-Sharif were pleased to examine him for his doctorate[27]in 1997. Amongst other things (the list is long), working from first principles, he derived the Generalised Analysis method[28] which improves on Alexandris' work by providing a more extensive method of analysing any peak traffic flow, not just uppeak.

However, his most significant contribution to lift traffic analysis, design and control, by far, is the implementation of interactive computer simulation programs.

His interest in lift traffic simulation began whilst employed at Ove Arup and when he set up his own company in 1997 - Elevate was born. I worked with Peters, for five years from 2002, to develop simulation technology. That is why many of the graphs and tables resemble LSD and PC-LSD [29].

Peters' simulation has done what I never achieved by becoming a worldwide industry standard, applied by more lift professionals than any other traffic design software. LSD only achieved 20 sales – but it was programmed in FORTRAN 4, and ran on machines the size of a transit van. It could be said LSD lives on in a different guise.

I and my students have used simulation as a powerful research tool. Peters has followed this route and developed a number of dispatching concepts and design ideas in a similar manner to Dos Santos, when using LSD. As an adjunct to this work, Peters has carried out surveys on lift traffic and lift performance for research, and as a basis for making decisions about the benefits of modernisation. This work has proved that the area based traffic design method is the correct approach and validated my work.

His many contributions can be seen in the CIBSE and BCO guidance. In the former he has published a number of traffic templates based on buildings surveyed.

Peters has always been a friendly, but robust challenger of my work. The why's and the where fore's in many a profound debate. In particular my concept of sizing a lift by area and not mass. He was a sceptic until his surveys showed design by area was the more realistic scientific approach. Area based design has been in his software since 2010 and now is used by the vast majority of designers worldwide for lift selection. See Gina Barney (encore).

LUTFI AL-SHARIF

Al-Sharif worked for a lift manufacturer in Jordan. He became my PhD student in 1989[30]. In work for his doctorate he evolved a predictive method called the inverse *S-P* of deducing the number of passengers from the number of stops. It is interesting to note that Bassett Jones used this formula to determine the variance of *S* from its expected value *E(S).*

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[26] Gaver, D.P. and Powell, B.A., 1971, Variability in round trip times for an elevator car during uppeak, Transpn. Res.
[27] Peters, R.D., 1997, Vertical transportation planning in buildings, Eng.D. thesis, Brunel University
[28] Peters, R., 1990, Lift traffic analysis: Formulae for the general case, Building Services Engineering Research & Technology, 11(2), 1990
[29] These can be seen in Book 3.
[30] Al-Sharif, L., 1992a, Predictive Methods in Lift Traffic Analysis, Ph.D. Thesis, Oct 1992, UMIST,

Another lift control problem that Al-Sharif investigated was bunching[31]. This phenomena is very destructive of lift performance.

After a brief excursion on escalators for London Underground and consultancy, he returned to the University of Jordan. He is currently very active in lift research and education.

As a result I am pleased he has joined me as co-author in the second edition of the *Elevator Traffic Handbook*, Book 4.

In the book he makes a new suggestion that he calls the HARINT plane. This is a visualisation of the conventional iterative process to balance the two design parameters handling capacity and interval. This method provides a route to determine the necessary value of *P*, which is the number of passengers a car must accommodate.

He hopefully can ensure a continuing life to the *Elevator Traffic Handbook* (Book 4).

He has moved Manchester, England to Amman, Jordan.

SINHO LIM

S.H.Lim was another one of my PhD students[32]. Observations by Lim of legacy controlled lift systems had indicated that the response times to answer landing calls follow an exponential curved shape. This distribution curve has a large number of calls answered in zero time or during the first time band. However, there is a long tail to the distribution with some calls waiting very long periods of time. He developed a new traffic control algorithm called Computer Group Control (CGC). The full text was published in Book 2 in 1985[33].

The intention of a CGC Traffic Control System is to provide an even service to all floors, where every landing call is given a fair consideration. This means that the landing call that has been waiting the longest should be given the first consideration for service. To achieve this egalitarianism, landing calls are considered to form a queue and will generally be served in the order of their waiting time. The intention of the CGC algorithm design was to bring the tail closer to the average and to sacrifice the "instant" collection of some calls by moving the exponential away from the origin to a Gaussian shape similar to the Rayleigh Distribution curve. Jon Halpern (see Acknowledgements) subsequently extended this concept and he analysed a number of other distributions[34]-[35].

JONATHAN BEEBE

Jonathan Beebe was my PhD student in 1977 and graduated in 1980. In 1980 Lift Design Partnership were appointed to modernise the lifts in Bush House (home of the BBC World Service at that time). Beebe first of all worked on the single car controller and was later joined by Lim to implement the CGC algorithm. A unique feature of the Bush House implementation was the ETA and actual time displays on the landings.

After the Bush House handover in 1984, Beebe continued to work on lift monitoring equipment. In 1989, Beebe stopped working full time in the lift industry, but maintained an interest in applying current techniques for the modelling and development of software systems to lift management.

As a result of Lim's work on CGC being published (in Book 2) the Bush House code was taken up by a continental lift company and in 1994 Beebe assisted their commercial implementation. Subsequently, from about 2007 Beebe has been continuing the development of CGC and other cost function (*aka* performance index) based algorithms. It is not known if CGC is embedded in other

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[31] Al-Sharif, L.R. 1993, Bunching in lift systems, Elevator Technology 5, IAEE Publications
[32] Lim, S.H. 1983, A computer based lift control algorithm, Ph.D. thesis, UMIST
[33] Barney, G.C. and Dos Santos, S.M., 1985, Elevator traffic analysis design and control, Peter Pereginus
[34] Halpern, J.B., 1992, Variance analysis a new way of evaluating elevator dispatching systems, Elevator World, September
[35] Halpern, J.B., 1993, Variance analysis of hall call response time, in Elevator Technology 5, proceedings of Elevcon '93, Vienna, Austria, November 1993, pp 98 – 106

company's products.

In 2003 Beebe published the Standard Elevator Information Schema[36], which in 2005 was applied in the design and prototype implementation of a city-wide remote monitoring system to be used on to all new and refurbished lifts in government buildings in Hong Kong. He continues to be active in retirement on the integration of lift systems into the Internet of Things and open standard information modelling.

MARJA-LIISA SIIKONEN

I first met M-LS in 1993 at ELEVCON, Rome, when she was awarded best paper. She worked closely with Roschier and Kaakinen[37] at Kone, Finland. She has over 50 lift papers. She instigated the "Four Doctors"[38] meeting in September 2004 to develop lift traffic definitions, which still stand today.

Over the years we have debated many things robustly. And she has 23 references in Book 4 after Peters with 26 and myself with 29. She out ranks me on Google Scholar with 803 citations to my 653. She and Peters are the only two people formally acknowledged in Book 4. Her work has centred on traffic design and traffic control systems and her group at Kone have greatly contributed to the survey data vault.

Recently she has been Convenor of ISO/TC178/WG6/SG5 revising ISO 4190-6: 1984 (to be known as ISO 8100-32).

ANA LORENTE

Computer simulation is a very powerful research tool to inform a design process. This was particularly true in recent work on the energy efficiency of lifts. I met Ana as the Spanish (AENOR) delegate to ISO/TC178/WG10 in May 2009. WG10 was developing the ISO 25745 series of energy standards. She was researching life cycle analysis for a doctorate and not making much headway. On joining WG10 she gained a purpose. To populate the equations being developed by the Working Group, values of load, distance travelled and balance factors had to be obtained. Ana volunteered to find these. She knew little about lift traffic design, but soon did and carried out thousands of simulations using Peters' simulation. The Convenor of WG10 said "*These simulations have helped accelerate the development process of these (ISO 25745) standards and provided invaluable scientific input on which to develop the classification for lifts*"

She decided to include this work in her LCA thesis and she became my latest doctoral student. She graduated in 2013[39].

Ana has illustrated the power of simulation.

GINA BARNEY (*encore*)

The forgoing relates much of my involvement in lift traffic design and control. This autobiographical note relates to my recent independent work. This is to do with the sizing of lift cars.

I became conscious of the anomaly between the stated passenger capacity (in persons), displayed on the in-car rating plate and the actual number of passengers observed in a car. In the mid1980s, I struggled with the notion that according to the BS 5655-1/2 standard of the time a 450 kg car with a platform area of 1.2 m^2 could accommodate 6 persons (ie: 0.21 m^2/person) and a 2500 kg car with a platform area of 5 m^2 was rated at 33 persons (ie 0.15 m^2/person). The former occupancy would be

[36] Beebe, J.R., Standard Elevator Information Schema, http://www.std4lift.info/, 2003-8

[37] Roschier, N.R. and Kaakinen, M.J. 1980, New formulae for elevator round trip time calculation, Elevator World, August 1980. – 7.4.1, A1

[38] Barney, G.C., Peters R.D., Powell, B.A. and Siikonen, M.L., 2005, Towards agreed traffic definitions, Elevator World: February 2005 (pp 108), Elevatori, 1/2005, Elevation, Issue 42

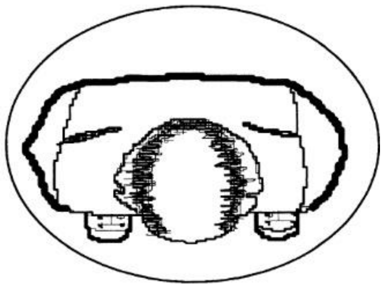
[39] Lorente, A.M., Lifts Life Cycle Analysis Modelling, Classification of Lifts Energy consumption and Rules for Environmental Statements, Doctoral Thesis Centro Politécnico Superior. Universidad de Zaragoza, 2013

comfortable, but the latter somewhat like the London Underground during rush hour.

The reason for this was that the standard calculated the number of 75 kg passengers that would be needed to fill the car to the rated load. A safety matter. It was unfortunate that architects, developers, lift companies and consultants, including me, believed this as real life.

So what should the occupancy be for traffic design?

In the USA, circa 1920s, a 150 lb (68 kg) person stood on two square feet (0.186 m^2). This equates to a 75 kg person occupying a space of 0.2052 m^2. Fruin[40] drew a person template with a body ellipse of 600 mm by 450 mm, which is also 0.21 m^2.



Strakosch in his 1967 book observed the loading of lift cars did not meet the assumed loading based on weight.

As the result of my research work in the late 1980s, I published an actual value for passenger capacity in Table 3.4 of the 1993 edition of CIBSE Guide D based on a body ellipse of 0.2 m^2 and a 5% reduction for handrails, etc. But I did not apply it properly to my designs.

Surprisingly the ISO Technical Report ISO/TR 11071-2, 1996[41] said:

> "*While the entire subject of capacity and loading has historically been treated in safety codes as one and the same, it might be more meaningful in the future writing of safety codes to cover loading as a separate issue from capacity. One refers more appropriately to the traffic handling capacity, whereas the other refers to the maximum carrying capacity which has a direct bearing on safety*."

My ideas were also expressed in the many editions of the Elevator and Escalator Micropedia from 1997[42]. But no one took any notice. The change from mass to area based lift car sizing was fully recommended in the 2000 edition of CIBSE Guide D.

In 2001, Peter Day[43,44] made a number of supporting observations and confirmed what many had reported.

The Elevator Traffic Handbook published in 2003 (Book 3) continued to inform the concept and although only 800 copies were sold it reached the people who needed it. In 2006 the ISO Technical Report ISO/TR 11071-2[45] repeated its 1996 text.

My strong stance in Guide D: 2000 alerted Richard Peters to the concept. At first Peters doubted the concept, but on confirming it for himself by on-site observations, finally introduced it into his proprietary software design program in 2010. Book 4 (with Al-Sharif) uses a wholly area based selection for lift car sizing.

The latest editions of the British Council of Offices guidelines[46] recommend area based car selection.

In conclusion it is important to size lifts to fit people, not to weigh them. That is, a method based on providing the personal space, which is comfortable for a person to occupy. This method has replaced the previous method using weight (mass) over a period of evolution commencing in the 1990s and

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[40] Fruin, J.J. 1971, Pedestrian planning and design, Metropolitan Association of Urban Designers and Environmental Planners

[41] ISO/TR 11071-2:1996, Comparison of worldwide lift safety standards - Part 2: Hydraulic lifts

[42] Barney, G.C., Cooper D.A. and Inglis, J. 1997, Elevator & Escalator Micropedia (reprinted 1998, 2001, 2006)

[43] Day, P. 2001a, Passenger comfort - Are you travelling comfortably? *Elevator World*, April. 2001

[44] Day, P. 2001b, Lift passenger comfort have we got it right?, Elevatori, September 2001

[45] ISO/TR 11071-2:2006, Comparison of worldwide lift safety standards - Part 2: Hydraulic lifts(elevators)

[46] British Council for Offices Guide for Specification, 2014

which became almost fully established in the 21st Century.

In the future all designers will use area based selection so that *P* passengers can be comfortably accommodated in a lift car.

5 THIS IS NOT THE END – IT IS JUST THE BEGINNING

"*If you can look into the seeds of time, and say which grain will grow and which will not, speak then unto me."* --William Shakespeare

Will we ever reconcile calculation and simulation?

One of the perennial problems that the lift industry has long grappled with is the reconciliation between the design of a lift system using calculation and the corresponding results obtained from such a system under simulation. It has always been disconcerting to find that lift systems designed using the conventional calculation techniques do not produce the same results, when simulated.

But why don't calculations and simulations line up? One obvious answer is that calculations can consider non integer numbers of passengers whereas in simulation they must always be whole numbers! There are many other reasons (see 17.2 of Book 4).

Why Calculate?

Simulation is a powerful research tool. Dos Santos *et al* has shown this for lift traffic design and control and Lorente has shown it for energy calculations. Simulation has been able to inform the calculation theories and has enabled them to be improved.

However my mantra is "*Calculation first – simulation second*". I can get close to a final design by simple spreadsheet calculations. Why should I waste time doing endless simulations when I can get there quickly by calculation? Simulation gives reassurance and gilds the reports in a commercial exercise.

Will Call Allocation Group Control Spell the End of Building Sectoring?

It has been long accepted that lift traffic systems installed in buildings with more than 20 floors should be sectored or zoned. It is recognised that having a dedicated bank of lifts for each section of the building can prove to be wasteful, especially if the peaks of the traffic of the different section of the building do not coincide.

Call Allocation group control systems are becoming more widely used in new lift installations, often inappropriately. One of the main advantages of using Call Allocation group control systems is the fact that they are able to group passengers such that the number of stops are reduced, and hence the passenger travelling time is kept below specified values.

It is suggested that the lifts within different groups could be combined into one group and controlled by Call Allocation group control. This will probably force the use of the dynamic sub zoning algorithm missing in current implementations of Call Allocation.

Will Call Allocation Ever be Used Properly?

First there are no full implementations of Call Allocation as specified in Book 1. Peters' simulation program is close.

Second to achieve an advantage there needs to be at least four lifts in a group. Many installations use Call Allocation as a sales gimmick.

The answer is probably not.

Better Educated and Training of Lift People

More complex control algorithms will require a new level of skill and understanding on the part of traffic design engineers. The area of traffic design skills rest with a small number of people and needs to be propagated to lower level staffs (sales staff, consultants, etc.) maybe by intelligent design engines implementing the algorithms inculcated by the true experts. Peters and I have developed a simple car selection table using an expert system[47].

Information sharing is a great opportunity to introduce a new generation of creative and imaginative engineers into the industry and thereby enhance its profile in the public perception.

Will the Paternoster Come Back?

Peters and Gerstenmeyer[48] have suggested a modern form of the Paternoster with rope less linear motor drives and have derived traffic design methodology. There are two problems: safety and security of service. Presently the Essential Health and Safety Requirements of the Lifts Regulations would not permit such a system. And if they did meet the EHSRs, then service resilience is dependent on an unobstructed shaft (broken down lift ahead).

Information Sharing

How long have I been asking for open data? Ever since BRE awarded UMIST a contract to data log lifts back in 1975.

Smart buildings, smart cities, Internet of Things, BIM Level-3, etc. require the sharing of all sorts of operational information with building owners and users. Hopefully, the ancient reticence (obstinacy-*sic*) to disclose any information about lift operation will be overcome by the realisation of the new and valuable business opportunities that greater interconnectedness opens up.

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Sadeh Hirbod for PC-LSD research work and still being in touch.

[47] Available on request
[48] Gerstenmeyer, S. and Peters, R., 2016, Proceedings of The 6th Symposium on Lift & Escalator Technology

… and many more people - too many to mention - who I have been stimulated by, worked with, supervised or have influenced.

AUTOBIOGRAPHY

Born 1935, Dr Barney left school at 16. She has the technician qualifications of ONC (1954) and HNC with distinction (1956); the graduate qualifications of BSc with honours (1959), MSc by research (1962)[49] and PhD (1965)[50]. She has the professional qualifications of CEng, FIEE and HonFCIBSE (for exceptional services to the Institution).

Following the award of her doctorate she moved to connecting particle physics analysing equipment to IBM computers and after joining UMIST designing and creating a hybrid computer for control research. Dr Barney founded a research group at UMIST into all aspects of lift systems in January 1968, whilst a lecturer and senior lecturer in the Control Systems Centre, University of Manchester Institute of Science and Technology (UMIST). From 1985 – 1990 she was Director of (computer) Networking at Manchester University retiring fully from academic life in 1993 to work full time as a consultant.

Dr Barney has authored, co-authored or edited over 20 books and over 100 reviewed papers. Notable of these are Books 1-4 indicated in the Introduction.

Gina is Technical Editor and Contributor to CIBSE Guide D: 2000, 2005, 2010 and 2015. She is a Member of BSI – MHE/4 Committees, delegate to ISO/TC178 WG6 and WG10 working groups, BRE Associate, Member of CIBSE Lifts Group and CIBSE Professional Conduct Committee, English Editor of *Elevatori*, Freeman of the City of London, Liveryman of the Worshipful Company of Engineers. Expert witness. Currently she is Principal of Gina Barney Associates.

She still finds time for ballroom, Latin, sequence and Scottish Country dancing, gardening and driving a fast car. Trustee of several Sedbergh Town charities.

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Transporting Dangerous Substances in Lifts

Michael Bottomley

MovvéO, Dean Clough, Halifax, West Yorkshire, HX3 5AX, UK

Keywords: Goods Lifts, Service Lifts, transporting dangerous substances, transporting cryogenic substances, transporting liquid nitrogen.

Abstract. Hospitals, Universities and Research Laboratories often need to transport liquid Nitrogen and other hazardous substances in lifts. Passengers are at unacceptably high risk if they travel along with these substances and employers have a duty to avoid employees being put at risk. The paper examines the design features required for a lift, management arrangements and training requirements to establish a safe system of work for these situations. The paper concludes that a code of practice is required to set best practice for what is currently dealt with on an ad hoc basis.

1 INTRODUCTION

There are many organisations which rely on lifts to transport dangerous substances around their buildings. Some substances when contained by appropriate measures present little danger to passengers travelling with them in a lift. Some substances, however, are so volatile that any risk of compromised containment will lead to serious injury or fatality. At first glance it may appear that such cases are rare and the numbers of lifts involved are few; however, as every Hospital, University College, Research Facility, Chemical plant etc. may carry these substances in lifts it quickly becomes apparent that the problem is common and control measures to mitigate these risks must be addressed. The objective of this paper is then to make suggestions which will ensure that passengers cannot travel in lifts with dangerous substances and these suggestions may in time be developed into a Code of Practice.

Cryogenic gases fall into the category of substances which are dangerous for passengers to accompany in a lift. A common example of a cryogenic gas is Liquid Nitrogen. This demonstrates unacceptable hazards to passengers travelling in a confined space such as a lift car for the following reasons.

The properties of liquid Nitrogen create four distinct hazards [1]:-

1) Because the liquid-to-gas expansion ratio of nitrogen is 1:694 at 20 °C (68 °F), a tremendous amount of force can be generated if liquid nitrogen is rapidly vaporized in an enclosed space. In an incident on January 12, 2006 at Texas A&M University [1], the pressure-relief devices of a tank of liquid nitrogen were malfunctioning and later sealed. As a result of the subsequent pressure build up, the tank failed catastrophically. The force of the explosion was sufficient to propel the tank through the ceiling immediately above it, shatter a reinforced concrete beam immediately below it, and blow the walls of the laboratory 0.1–0.2 m off their foundations. Clearly damage to a lift car would also be catastrophic.
2) As liquid nitrogen evaporates it reduces the oxygen concentration in the air and can act as an asphyxiant, especially in confined spaces such as a lift car. Nitrogen is odourless, colourless, and tasteless and may produce asphyxia without any sensation or prior warning. In these incidents, asphyxiation is usually sudden. The victims inhale air with little or no oxygen content, causing immediate collapse into a layer of dense, cold, nitrogen-enriched air. Unconsciousness followed rapidly by death is inevitable without

immediate rescue and resuscitation. Rescue attempts often result in the rescuers being overcome as well. Smaller leaks or spills, or normal boil-off from liquid nitrogen containers in confined spaces such as lift cars may give rise to lesser reductions in oxygen content, but they may still carry a risk of asphyxiation.

3) Because of its extremely low temperature, careless handling of liquid nitrogen and any objects cooled by it may result in cold burns. In that case, special gloves should be used while handling. However, a small splash or even pouring down skin will not burn immediately, because the evaporating gas thermally insulates to some extent, like touching a hot element very briefly with a wet finger. If the liquid nitrogen pools anywhere, it will burn severely. As it is heavier than air it would probably accumulate on the floor of a lift car and add to the suffering of anyone laying there through asphyxiation.
4) Vessels containing liquid nitrogen can condense oxygen from air. The liquid in such a vessel becomes increasingly enriched in oxygen (boiling point 90 K; −183 °C; −298 °F) as the nitrogen evaporates, it can cause violent oxidation of organic material. It also causes structural damage to steel.

The conclusion of any risk assessment is that the only acceptable preventative measure to control the risks is to not allow passengers to travel with these dangerous substances. The objective of this paper as previously stated is to make suggestions which will ensure that passengers cannot travel in lifts with dangerous substances and these suggestions may in time be developed into a Code of Practice.

The British Compressed Gases Association has already published a code of Practice CP30 THE SAFE USE OF LIQUID NITROGEN DEWARS UP TO 50 LITRES Revision 2: 2013 [2].

The advice provided by the guide is as follows:-

“8.2.1 The use of lifts when transporting Dewars

Transporting Dewars containing liquid nitrogen in an occupied lift is hazardous and should be avoided whenever possible. The main hazards are the operation of the safety relief device on the liquid withdrawal unit, liquid splashing or boiling liquid vaporising into the lift, creating an oxygen-deficient atmosphere. The majority of lifts have small internal volume and therefore the effects of oxygen deficiency could overcome a person in the lift in a relatively short time. Spillage of liquid nitrogen can cause embrittlement and subsequent failure of certain materials, e.g. carbon steel. If liquid nitrogen is spilled onto a lift floor, the lift should subsequently be checked for mechanical damage. When it is necessary to move a Dewar to another floor in a building using a lift a detailed risk assessment must be carried out to establish the potential hazards that may occur and to identify the risk mitigating procedures to ensure the safety of the operator or the any other person who potentially could use the lift. The preferred method of transporting a Dewar in a lift is to use a key operated lift that permits the Dewar to be carried unaccompanied in the lift and prevents any other person from getting into the lift with the Dewar. Dewars should be transported unaccompanied in key operated lifts.
Where this is not possible to use a key operated lift, a detailed risk assessment in accordance with the Management of Health and Safety at Work Regulations and the Confined Spaces Regulations shall be carried out and suitable procedures established. The risk assessment should take into consideration how other personnel could enter the lift, the type of Dewar being moved and the potential for liquid nitrogen being spilt. Refer to BCGA TIS 27, Model risk assessment for the safe use of liquid nitrogen Dewars.

Where the use of lifts cannot be avoided, one or more of the following (in order of preference) shall be adopted:

i. Dewars shall only be filled to 90 % of the net capacity to reduce the risk of spillage.
ii. Dewars fitted with liquid withdrawal devices shall be vented to less than half the relief-valve set pressure.
iii. Only an operator who has received suitable training shall be allowed in the lift during the transportation of Dewars containing product.
iv. The operator should have a fully functional oxygen depletion monitor that will warn him when the oxygen level has depleted to 19.5 %, allowing immediate evacuation from the lift before a dangerous level is reached.
v. The operator shall have control of the lift to enable immediate evacuation at the next available floor, in the event of an escape of product.
vi. The lift shall be fitted with an emergency alarm /telephone.
vii. If the lift is equipped with an extraction fan it should be switched on before the operator takes the Dewar into the lift.

In addition to the above, the following rules should be rigorously applied:

viii. Do not transport in a lift a Dewar that is venting gas; this especially applies to Dewars that have just previously been filled.
ix. Do not vent Dewars whilst in a lift.
x. Do not transport a leaking or defective Dewar in a lift.
xi. Do not transport in a lift a Dewar that has ice forming on the outside.
xii. Do not transport an overfilled Dewar in a lift.

The transportation of Dewars in lifts containing product should be supervised /monitored outside the lift by a competent person who is aware of the potential hazards and of the action to take in an emergency."

Whereas the Code offers sensible advice on the handling precautions it is somewhat deficient in the detail necessary to create a suitable lift control design. For example, on page 12 of the code it states:

"8.2.2 Stairs and doorways

Stairs present an increased tripping hazard, which may lead to a nitrogen spillage.

Where possible, avoid carrying Dewars upstairs or steps. If the negotiation of stairs is unavoidable:

(i) Two people are recommended for carrying the Dewar.
(ii) Consider the installation of a stair lift where practical."

Stannah Stairlifts however would not recommend this deviation from a stair lift's design as a passenger carrying device.

2 DESIGN CONSIDERATIONS FOR LIFTS

2.1 Tanks

If we consider the tanks that used to transport cryogenic gasses that are likely to be carried in lifts we find that they are usually in vessels called Dewars as stated in CP30. Dewars are insulated flasks which carry up to 50 litres of liquid. The maximum weight of this type of container is about 56 Kg and its size is about 850mm high with a diameter of 400mm.

Figure 1 Dewars

2.2 Service Lifts

A simple dedicated floor loading service lift designed to BS EN 81-3 [3] could be provided as a dedicated method of moving these dangerous substances. With a car size of 1000mm wide X 1000mm deep X 1200mm high and a rated load of 250Kg up to four Dewars could be carried simultaneously. The car height and the lack of car controls would make the probability of a passenger being able to accompany the goods very small in fact it could be considered "Highly Improbable". The installation of dedicated service lifts should be considered as a safe and probably a most cost effective solution in most cases in building up to 4 or 5 floors. The floor plan needed for the installation of such a device is approximately 1.5 metres square.

However, many existing buildings do not have dedicated service lifts, and in many cases there are valid reasons why they cannot be retrospectively installed. It is therefore necessary to consider design features which may, when suitably combined, provide an equivalent level of safety to that of a Service Lift.

2.3 Passenger Goods Lifts with Manual or semi-automatic doors/gates.

Lifts of this type can only travel once the car and landing doors have been closed which requires a deliberate action. The possibility of unintended travel in the lift with the dangerous substance is therefore significantly reduced. The main focus is to establish a car preference control which cancels or ignores any landing calls. This method of control can be easily established by the use of a security card triggering a card reader, or a key operated switch positioned on the car operating panel.

The safety of operation of this type of lift control system may therefore assume that the Trained and Authorised person in charge of the transportation of the substances will not chose to risk travelling in the lift. However, Lift Designers should not make that assumption. Work pressures, time management, and, in particular, familiarity with working with dangerous substances can easily make fools of us all in time. Familiarity breeds contempt and Lift Designers should therefore augment their designs to protect the contemptuous as well as the hapless and even accidental companions to dangerous substances travelling in lifts.

The objective of any suitable solution is to stop a lift loaded with a dangerous substance closing its doors and travelling to any floor other than its intended preselected destination, and then only to open or allow the doors to be opened at the destination floor once a trained and authorised person is there to unload it.

2.4 Passenger Goods Lifts with Automatic doors

There is no existing guidance for lift companies to follow, and as a result each company provides a solution for its clients on an individual basis, usually based on the requirement as defined by the client. The most common solution is provided by a series of key switches which provide a simple call and send function at the main access level. This type of system requires two trained and authorised staff on at both departure and arrival floors, and a method of communication between them. A better and more robust solution is required.

If the design is developed to cover Passenger Goods lifts with manual or semi-automatic doors then further development of a design for automatic doors should be a simple next step solution as proposed and detailed below. The features required by this design are:-

a) Selection and implementation of a “special service” feature including audio-visual confirmation thereof.
b) Cancelling or suspending all existing car and future landing calls other than selected under special service for the duration of the special service.
c) Registration of a single or possibly multiple special service calls.
d) Parking at the departure landing with car and landing doors open to allow for loading materials into the lift and exiting the lift car by all passengers.
e) Continuous operation of the departure floor landing push button to allow the doors to close and reversing the landing and car doors if the continuous pressure on the landing button is not maintained until the door close limit is broken, thus enabling travel of the lift car direct to the destination floor. Audio visual warning of these actions should/could be included by the car indicator and voice annunciator.

Continuous operation of the destination floor landing push button to allow a similar functionality required by firefighting lifts under EN81-72 [4] the so called “peek a boo” type operation to open the landing and car doors at the destination floor except in this instance the failure to maintain constant pressure on the destination floor landing button would result in the closing of the doors. Audio visual warning of these actions again should/could be included, as before. This would give the operator the opportunity of checking oxygen depletion levels before entering the lift car to unload the materials.

Once opened the car and landing doors remain open until the lift is unloaded and special service control is disengaged via the security card or key switch and normal service is resumed.

3 ADDITIONAL SAFETY CONSIDERATIONS, EVENTS AND SCENARIOS

3.1 There are some residual risks which given the severity of the hazard may in certain environments or under certain scenarios may need to be addressed for example:-

a) Two complacent or careless operators working together - one who is operating the landing controls whilst the other deliberately or accidentally remains in the lift car.
b) Lifts operating in a busy public access environment where potential passengers may not be aware of the risks in traveling in a lift with an unknown substance.
c) Potential passengers at the destination floor ignore the landing and car indication and maintain pressure on the destination landing push button opening the car and landing doors and entering the lift without checking for oxygen depletion.

3.2 There are residual risks to the structure of the lift from spillages which will require additional inspections after any such incident before the lift is put back in to general use.

3.3 There are additional risks working in the lift pits or car tops of lifts used to carry dangerous substances.

3.4 There are other less likely but more serious implications of the effects or consequences of a serious lift fault such as the high-speed operation of the safety gear and the rescue of materials from the lift car.

Risk assessments for these 4 considerations should be carried out on a project by project basis in the format of ISO 14798 [5]. For substances other than Cryogenic gases separate risk assessments could also be required.

3.5 Additional safety features

The solution to 3.1a and b would be by installing equipment to detect the presence of a passenger remaining in the lift car once the goods had been loaded. A combination of additional sensors such as PIR's and detection of the incorrect sequence of other existing signals such as safe edge detector operation, changes in loading sensing devices readings. Another simple mechanical method would be to install a retracting full width roller blind just under the car handrail height to effectively temporarily partition off the lower half of the lift car. The blind could be electrically interlocked at its retaining point thus preventing a passenger travelling without the blind in place. This measure would also be a partial solution to scenario 3.1c.

Structural surveys of the car floor and car sling after a substance spillage would have to be conducted by a competent person, who would require additional knowledge of the properties of the substance spilt and be equipped with a safe system of inspecting those areas. This is essentially a problem to be resolved by an appropriate management system.

Persons working on lift maintenance on lifts used to carry dangerous substances may require appropriate PPE and oxygen depletion sensors but again this is a management issue to establish a safe system of work.

Additional consideration of emergency release procedures in case of the entrapment of dangerous substances is required. Where there are a range of substances involved or handing of the substances involves particular risks and control procedures it would be prudent to train scientific staff in lift release as teaching lift staff science is a more daunting prospect! Such training should be site specific well documented assessed and repeated at regular intervals. Guidelines for the training of such staff are referred to in HTM08-02 [6].

4 CONCLUSIONS

As an Authorising Engineer for Lifts for several NHS Trusts and having worked with a number of Educational Institutions I have seen a range of design features applied to modify Passenger Goods lifts for carrying dangerous substances. No two solutions however appear to be the same and whilst Management systems are generally in place they do not always cover all the likely risk presented by realistic scenarios. The design solutions tabled in this short paper are intended to provoke a discussion on this subject and out of that discussion a plan put in place to develop a Code of Practice for transporting dangerous substances in lifts. The code of Practice should additionally define the extent of hazardous scenarios and events and correlate the escalation procedures required by a suitable management system. The Code should also propose the additional training that is required by all the duty holders involved.

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[6] Barney et al, Healthcare Technical Memorandum HTM08-02 2015.

BIOGRAPHICAL DETAILS OF THE AUTHOR

Michael Bottomley joined MovvéO (formerly Lerch Bates 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 36 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 1997. He is an affiliate member of the Chartered Institute of Building Service Engineers (CIBSE) and is currently Vice Chairman and a Past Chairman of the CIBSE lifts group. He is a contributory Author to the 2015 edition of HTM 08-02.

A History of the Lift Safety Gear

David A. Cooper

Keywords: Safety gear, Otis, Falling, Standards, EN81, BS2655, BS5655

Abstract. The safety gear is regarded as the last line of defence in the relatively safe world of lifts. Industry contemporaries recall Elisha Otis declaring "All safe" after cutting the ropes on a platform upon which he was standing and the safety gear preventing his uncontrolled descent. The design of safety gears has moved on significantly from an original proposal to place a bag of feathers in the lift pit to designs that now arrest uncontrolled movement in ascent. This paper is a developing research project which will look at UK patents and standards, and tracks the development of the safety gear from the embryonic days of lift installations to the present day. It will contribute to knowledge by bringing together a number of sources of information not previously brought together into a single paper and thus provide a consolidated history of the safety gear.

1 THE INVENTION OF THE SAFETY GEAR

"The significant influence of elevators dates from the invention by Elisha Graves Otis of a device capable of keeping an elevator from falling even though the hoisting ropes should break"[1]

In 1851 Elisha Graves Otis went to Bergen, New Jersey and then a year later to Yonkers, New York in his employ as master mechanic of the bedstead plants in which his employer, Josiah Maise, was an owner. It was here that he came face to face with his destiny and he designed and installed the first elevator equipped with an automatic device to prevent it from falling. [1]

He was destined to move to California, however, an unsolicited order for two safety elevators had been received from a Mr Newhouse, a furniture manufacturer in whose plant at 275 Hudson Street, New York, a serious elevator accident had just been experienced. The order for these two elevators marked the beginning, in 1853, of the now worldwide association of elevators and the name Otis.[1]

In 1853 an exhibition was held at the Crystal Palace in New York City at which Elisha Graves Otis demonstrated his confidence in his own product by standing on the platform of the elevator erected at the exhibition, raising the platform well above the heads of the assembled crowd, and then at the most dramatic point in his oratorical exposition, cutting the rope by which the platform was suspended. Those who had morbidly anticipated a leg breaking crash, however disappointed, were nevertheless impressed with the effectiveness of the Otis Safety when, as a matter of fact, nothing happened. [1] It is said that after the descending platform was arrested that Elisha Otis uttered the words "All Safe Gentlemen".

Figure 1 Elisha Otis demonstrating his safety gear in 1853

The New York Tribune reported the exhibition and made mention of the Otis invention however it should be noted that they referred to the elevator at the exhibition as one for hoisting goods and it was not until three years later that the first passenger elevator was manufactured by Otis and installed in a five-story building on the north-east corner of Broome Street and Broadway which belonged to E V Haughwout & Co, dealers in china and glassware. [1]

Sadly, Elisha Graves Otis died in 1861 owning a factory worth not more than $5,000 and employing only 8 or 10 men. [1]

2 DEVELOPMENT OF SAFETY GEAR DESIGN

According to Inglis[2] the earliest story known about safety of persons whilst travelling in a lift dates back to a Sultan who required a means of lifting people to the upper floor of his castle. It is said that a large bag of feathers was placed in the pit and one of his servants rode in the lift car whilst the rope was cut. The servant apparently survived the fall with only a broken leg and the Sultan therefore concluded that no one would be killed whilst using his lift.

Inglis goes on in his paper to a further development where an Italian invented a method of preventing injury in the event of free fall or an overspeed condition in the down direction. This is the first located mention of an overspeed condition. The invention consisted of some rods across the car above the passengers' head with the rods terminating in two rubber diaphragms at their ends. In the event of overspeed in the down direction a passenger would hold onto the bar with the diaphragms taking the force out of the impact when the car hit the buffers. There was the obvious question of how many passengers could be protected by such a device.

The development of high speed elevators necessitated the development of a new type of safety. It is elementary that the purpose of a safety device is not merely to stop the elevator platform, since this could be done with absolute certainty by simply letting the platform hit the bottom of the hatchway, but rather to bring the platform to a sufficiently gradual stop to prevent injury. The early safety, which contributed so greatly to the fame and fortune of Elisha Graves Otis, was of the instantaneous type which operated only in the event of slack or broken ropes and was useful only because it applied when the elevator had barely started to fall and before it had attained a downward speed greatly in excess of the normal speed, which was slow. Obviously, with a high-speed elevator it would be almost as disastrous to stop the elevator at high speed with a safety of instantaneous type as it would be too hit the bottom, or at any rate the stop would be more sudden than the human body could stand without injury. [1]

According to Grierson[3] up to about the year 1880 cast iron racks or ratchets were attached to the guides, and a pair of dogs, fixed at the top of the car attached to the single suspension rope, and operated by springs, formed the safety gear. Note the single rope, a situation no longer permitted for lifts although still seen in mine winding and cable car applications. When the rope failed, the springs that operated the dogs engaged with the racks on the guide posts and immediately brought the car to a dead stop. Grierson also states that "safety gear is not ordinarily fitted to counterbalance weights, only the car."

The next important development, according to Grierson, appeared around 1893 and is still extensively in use in Great Britain (bear in mind Grierson was published in 1923) was cam type guide grips. It consists of four serrated steel cams, mounted on two turned steel rods, that, when the necessity arises, rotate and bring the cams into contact with the guide rails or wood backing.

This safety gear was only suitable for slow speed cars (100 ft/min) due to being of practically instantaneous action. The design would also only protect against a too rapid descent of the lift car and was useless for excessive speed in the upward direction. Grierson noted that various manufacturers used different methods of safety gear activation including slack rope activation and a separate safety line connected between the car and counterweight.

In 1878 an overspeed governor of the fly ball type was invented for the purposes of operating a progressive safety gear. This was invented by Charles R Otis.[1]

3 SAFETY RECORD

With one exception (until the Petersen paper [1] was published in 1945) there is not a single known instance of an Otis traction elevator falling because of broken ropes or for any other reason. The one exception was furnished by a single elevator in the Empire State Building in New York on July 28th, 1945, while travelling downward at about the 17th floor, had all hoisting and governor cables severed by an aeroplane which crashed through the hatchway at the 89th floor. This rendered inoperative the safety equipment which understandably was not proof, nor intended to be proof, against aeroplane collision any more than a railway block system will protect a train from the remote contingency of a collision with a Flying Fortress. Happily, the operator (who was alone in the car) survived the crash. Since this incident cannot be regarded as a failure of the ropes or of the safety equipment, the record previously mentioned remains unimpaired. [1]

4 DEVELOPMENT OF BRITISH & EUROPEAN STANDARDS

Further work is required into researching of older standards and codes of Practice as there is clearly a gap between Otis demonstrating his safety gear in 1853 and the 1970 edition of BS2655-1. It is understood that there was a BS2655 published around 1958 but even then, this leaves a gap of over 100 years in documentary evidence of design.

Standards since 1970 have developed as follows:

1970 BS 2655-1:1970: Specification for lifts, escalators, passenger conveyors and paternosters. General requirements for electric, hydraulic and hand-powered lifts

1970 BS 2655-7:1970: Specification for lifts, escalators, passenger conveyors and paternosters. Testing and inspection

1979 BS 5655-1:1979, EN 81-1:1977: Lifts and service lifts. Safety rules for the construction and installation of electric lifts

1986 BS 5655-1:1986, EN 81-1:1985: Lifts and service lifts. Safety rules for the construction and installation of electric lifts

1986 BS 5655-10:1986: Lifts and service lifts. Specification for the testing and inspection of electric and hydraulic lifts

1995 BS 5655-10.1.1:1995: Lifts and service lifts. Specification for the testing and examination of lifts and service lifts. Electric lifts. Commissioning tests for new lifts

1995 BS 5655-10.2.1:1995: Lifts and service lifts. Specification for the testing and examination of lifts and service lifts. Hydraulic lifts. Commissioning tests for new lifts

1998 BS EN 81-1:1998+A3:2009: Safety rules for the construction and installation of lifts. Electric lifts

1999: PAS 32-1:1999: Specification for examination and test of new lifts before putting into service. Electric traction lifts

1999 PAS 32-2:1999: Specification for examination and test of new lifts before putting into service. Hydraulic lifts

2007 BS 8486-1:2007+A1:2011: Examination and test of new lifts before putting into service. Specification for means of determining compliance with BS EN 81. Electric lifts

2007 BS 8486-2:2007+A1:2011: Examination and test of new lifts before putting into service. Specification for means of determining compliance with BS EN 81. Hydraulic lifts

2014 BS EN 81-20:2014: Safety rules for the construction and installation of lifts. Lifts for the transport of persons and goods. Passenger and goods passenger lifts

2014 BS EN 81-50:2014: Safety rules for the construction and installation of lifts. Examinations and tests. Design rules, calculations, examinations and tests of lift components

5 FACTORS AFFECTING SAFETY GEAR DESIGN

A number of factors seem to have driven safety gear design over the years.

- The desire to prevent an uncontrolled descent.
- The relationship between speed and safety gear design (principally to protect passengers against injury).
- The desire to protect against uncontrolled ascent as well as descent.

As the research progresses more categories may be identified, although, it currently appears that from 1853 onward for over a century, it was simply a desire to prevent uncontrolled descent to allay passenger fears about this risk.

6 1970 BS 2655-1:1970: SPECIFICATION FOR LIFTS, ESCALATORS, PASSENGER CONVEYORS AND PATERNOSTERS. GENERAL REQUIREMENTS FOR ELECTRIC, HYDRAULIC AND HAND-POWERED LIFTS

This standard was published in 1970 and ended up with 6 amendments to its original form.

There were four separate sections on safety gear requirements which could be found in sections 2, 3, 5 and 6.

Safety gears shall comply with the following general requirements:

- Every passenger and goods lift shall be provided with a safety gear attached to the car frame and placed beneath the car platform.
- Safety gear shall also be provided on the counterweight where there is an accessible space **beneath** the travel of the counterweight.
- It shall be possible to release car safety gears by raising the car, and counterweight safety gears by raising the counterweight.
- Each car safety gear shall be operated by means of either a governor or a safety rope. All sheaves or pulleys in contact with any part of this rope, which is normally in motion at the same time as the car, shall have diameters at least 30 times the diameter of the rope.
- A car safety gear shall **not** operate to stop an ascending lift car. If an ascending lift car is to be stopped on account of overspeed then a safety gear shall be fitted to the counterweight for this purpose. Where an overspeed governor is used, it shall cause the motor control and brake control circuits to be opened in the event of overspeed in the upward direction.
- The application of the safety gear shall not cause the car platform to slope at more than 1 in 25 to the horizontal.
- The motor control and brake control circuits shall be opened by a switch on the car safety gear before or at the time the safety gear is applied.
- When the car safety gear is applied, no decrease in the tension of any rope used for applying the safety gear, or motion of the lift car in the downward direction shall release the car safety gear.
- It shall not be possible for vibration of the car frame to cause a safety gear to be applied.
- No safety gear shall depend for its operation upon completing or maintaining an electric circuit.
- The gripping surfaces of a safety gear shall be held clear of the guides during normal operation of the lift.
- Any levers or cams operated by shafts shall be fixed to such shafts by means of welding, sunk keys or by equivalent positive connection.
- Safety gears shall be designed to grip each guide and to operate on the guides simultaneously.
- Any shaft, jaw, wedge or support which forms part of a safety gear and which is stressed during its operation shall be made of steel or other ductile material.
- The drive to a car governor rope shall be effected from the car frame.
- Any connecting device between a governor rope and car frame (or counterweight) that is intended to be released when the safety gear is applied shall be retained in its normal position by a spring loaded device.
- A pawl and ratchet shall not be used as a safety gear.

7 LIFT SPEED AND SAFETY GEAR SELECTION

BS2655-1 (1970)

BS2655-1 (1970) stated 2.12.3 Safety gears of the instantaneous type may be used for lift cars having a contract speed not exceeding 0.75 m/s or 150 ft/min.

BS5655-1 (1979)

There was a shift in the 1979 standard which introduced the buffered effect for the first time:

9.8.2.1 Car safety gear shall be of the progressive type if the rated speed of the lift exceeds 1.0 m/s. It can be (a) of the instantaneous type with buffered effect if the rated speed does not exceed 1.0 m/s (b) of the instantaneous type if the rated speed does not exceed 0.63 m/s.

The buffered effect was rarely used but when it was it involved the sling having an additional and independent travelling section underneath it which had an instantaneous safety gear attached. This safety gear would operate and the forces were reduced by the lift car sling being separated from the safety gear by devices such as hydraulic pistons, (rather like buffers), which would take the forces out of the operation.

BS5655-1 (1986)

This standard mirrored the BS5655-1 (1979) standard.

EN81-1 (1990) + A3 (2009)

Again, this standard mirrored the BS5655-1 (1979) standard.

EN81-20 (2014)

However, the publication of EN81-20 (2014) saw the end of the buffered effect with the wording being amended as follows:

5.6.2.1.2.1 Car safety gear (a) shall be of the progressive type or (b) may be of the instantaneous type if the rated speed of the lift does not exceed 0.63 m/s

The philosophy behind the change in speed between the 1970 and 1979 standards for instantaneous safety gears is not known, however, it can be seen that the EN81-20 (2014) standard limits instantaneous to a maximum speed of 0.63 m/s whereas the BS2655-1 (1970) standard allowed the higher speed of 0.75 m/s so despite the buffered effect being removed the reduced speed from the 1979 standard is still adopted.

8 DIRECTION OF LIFT AND SAFETY GEAR SELECTION

BS2655-1 (1970)

As previously stated in BS2655-1 (1970) “A car safety gear shall **not** operate to stop an ascending lift car. If an ascending lift car is to be stopped on account of overspeed then a safety gear shall be fitted to the counterweight for this purpose.”

BS5655-1 (1979)

The wording changed in the 1979 standard to the following:

9.8.1.1 The car shall be provided with a safety gear capable of operating only in the downward direction and capable of stopping a fully laden car, at the tripping speed of the overspeed governor, even if the suspension devices break, by gripping the guides, and holding the car there.

It should be noted that the overspeed governor was introduced into the wording of standards at this point as a mandatory clause for all electric lifts including those with instantaneous safety gears albeit, as previously mention Charles Otis invented the flyball overspeed governor for progressive safety gears in 1878.

Prior to this BS2655-1 (1970) offered an overspeed governor as an option as follows:

2.12.3 The safety gear shall operate to stop and sustain the lift car with contract load in the event of failure of all suspension ropes or chains or their attachments, or in the event of the lift car exceeding a predetermined speed in the downward direction, when the safety gear is operated by an overspeed governor.

BS5655-1 (1986)

BS5655-1 (1986) adopted the same wording as the 1979 standard.

EN81-1 (1990) + A3 (2009)

It was not until EN81-1 (1998) Amendment 3 (2009) that the requirement to stop an ascending lift car came into being with clause 9.8.10 which stated:

9.10 A traction lift shall be provided with ascending car overspeed protection means conforming to the following:

9.10.1 The means, comprising speed monitoring and speed reducing elements, shall detect uncontrolled movement of the ascending car at a minimum 115% of the rated speed, and maximum as defined in 9.9.3, and shall cause the car to stop, or at least reduce its speed to that for which the counterweight buffer is designed.

EN81-20 (2014) varied the wording to as follows

5.6.1.1 Devices, or combinations of devices and their actuation shall be provided to prevent the car from (a) free fall, (b) excessive speed, either downwards, or up and down in the case of traction lifts, (c) unintended movement, with open doors (d) in the case of hydraulic lifts, creeping from a landing level.

9 CONCLUSION

The history of the safety gear is an interesting subject and it has been identified that there is a long gap of inactivity in design from 1853 to 1970 which requires further investigation. Sources thus far identified show development from a state of concern about the risk of falling to the quality of the fall should it happen with the introduction of acceptable forces relative to speed. Furthermore the need to address other technical issues such as uncontrolled movement in the ascending mode have also caused developments in safety gear design. Research will continue to establish development of the safety gear from its initial design in 1853 to the present day.

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BIOGRAPHY

EurIng David Cooper

BSc(Hons), MSc, MPhil, CEng, FIET, FCIBSE, FRSA

David Cooper is the Managing Director of UK based lift consultants LECS (UK) Ltd. He has been in the lift & escalator industry since 1980 and is a well-known author and speaker. He holds a Master of Philosophy Degree following a 5-year research project into accidents on escalators, a Master of Science Degree in Lift Engineering as well as a Bachelor of Science Honours degree, Higher National Certificate and a Continuing Education Certificate in lift and escalator engineering. He is a co-author of "*The Elevator & Escalator Micropedia*" (1997) and "*Elevator & Escalator Accident Investigation & Litigation"*. (2002 & 2005) as well as being a contributor to a number of other books including CIBSE Guide D. He is a regular columnist in trade journals worldwide including Elevation, Elevator World and Elevatori. He has presented at a number of industry seminars worldwide including 2008 Elevcon (Thessaloniki), 2008 NAVTP (San Francisco),1999 LESA (Melbourne), 1999 CIBSE (Hong Kong), 1999 IAEE (London), 1998 (Zurich), 1997 CIBSE (Hong Kong), 1996 (Barcelona) and 1993 (Vienna) as well as numerous presentations within the UK. He is also a Founding Trustee of the UK's Lift Industry Charity which assists industry members and/or their families after an accident at work. In 2012 David was awarded the silver medal by CIBSE for services to the Institution. David Chairs the Charity that runs the Lift Symposium and is an Honorary Visiting Fellow at The University of Northampton.

Improvement of the Learning Environment at an International Multicultural Company through the Assessment of Relevant Methodology and Technology Goals

Thomas Ehrl[1], Jonathan Adams[2], Stefan Kaczmarczyk[2] and Benedikt Meier[1]

[1]thyssenkrupp Elevator, thyssenkrupp Allee 1, 45143 Essen, Germany,
thomas.ehrl@thyssenkrupp.com, benedikt.meier@thyssenkrupp.com
[2]School of Science and Technology, University of Northampton, St. George's Avenue,
Northampton NN7 3NG, UK,
stefan.kaczmarczyk@northampton.ac.uk, jonathan.adams@northampton.ac.uk

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Abstract. "Open Teaching & Learning" in a University/academic environment becomes increasingly more important and needs to be designed in the most efficient and effective way to ensure a balanced return-on-investment. This issue is of particular importance when it comes to complex learning areas.

In this context, the paper addresses opportunities applying new learning technologies within a multi-disciplinary and multi-cultural environment to improve the efficiency and effectiveness of training.

This paper presents an in-depth analysis of state-of-the-art learning methodologies (knowledge transfer process) to ensure a higher learning engagement of all employees, taking into consideration function, age, culture and technological abilities.

The results arising from this paper will identify the pedagogic and business impact of an individualized application of a knowledge transfer strategy.

After a review of literature on the subject, the paper concludes with a proposal of the optimal knowledge transfer strategy. This strategy is to be integrated into the existing pedagogic provisions of a multi-disciplinary / multi-cultural R&D (learning) environment of a global PTS company. The strategy can also be used in an academic environment to aid problem solving and engineering knowledge transfer.

1 INTRODUCTION

Learning is a lifetime task. Especially today, facing the challenge that worldwide knowledge doubles every 7 years, the knowledge development of a workforce is of enormous importance for companies and organizations.

Mega Trends influence social life through technologies (e.g. Digitalization) and irrevocable tendencies (e.g. Urbanization). Knowledge, and therewith intelligence, is ubiquitous via mobile access to the world-wide web. All this affects the way people live and learn.

To ensure the best return-on-investment when investing into the personal development of staff, enterprises apply modern training methods to train their employees that are frequently spread all over the world. In the past, most training was delivered in a classroom. However, an increasing number of mixed training versions are offered. To ensure efficient & effective training, a number of factors must be seriously considered.

2 LEARNING

Even though more technology for learning is becoming available, the main principles remain the same regardless of what people or environment is involved. People still respond to the principles of adult education: *Learners need to be engaged. Learners need to be able to apply their learning. Learners are essentially motivated*.

It is important that the teaching material directly relates to each learner of the entire group, regardless of whether the learning is self-paced or through group events. A learning experience that is directly related to the learning goal of a learner ensures that the learner finds it easier to remember and recall in the future. [1]

With reference to the development of a learning program, it is essential that each learner is motivated and engaged with a personal benefit. It is important that each learner is able to make his/her own effect.

The fundamental needs of adult learning are summarized by the *Principles of Andagogy* [2].

- *Adults must want to learn*
- *Adults will only learn what they think they need to learn*
- *Adults learn by doing*
- *Adult learning is focused on solving problems*
- *The experience an adult has can affect there learning*
- *Adults learn best in an informal situation*
- *Adults expect to be considered as an equal partner in the process*

It has to be considered that this theory is described as a general approach and therefore can vary depending on the individual learner and the individual's background [3].

Generally, learning can be categorized into four types:

- *Auditory Learning,*
- *Visual Learning,*
- *Haptic Learning and*
- *Intellectual Learning,*

Auditory, visual, and haptic learning are somewhat related. They all focus on perceptions and inputs that come through the same type of nerve cord. Intellectual learning is different in its receptive channel.

Bloom's Taxonomy splits types of learning into the following levels:

- *Remembering (Recall or recognition of an expression.)*
- *Comprehension (Understanding of facts. Ability to organize them and bring into relation.)*
- *Application (Deeper understanding. Use/apply information for related problem solving.)*
- *Analyzing (Break-up information into smaller chunks, organize them and relate them together.)*
- *Synthesizing (Ability to structure patterns from given/known information. Develop ideas and critical doubts about the subject.)*
- *Evaluating (Ability to take in external information and relate your knowledge to them to make decisions.*

These levels work in a hierarchical order with *Evaluation* as the highest level of understanding, and *Remembering* as the lowest level. This categorization is important for the development of learning goals. They help to write the training outline and apply the learning results evaluation method to the group of learners [4].

3 TRAINING CONTENT

Based on the fact that learning can be described as a transformation process, the following model shows the important interactions within the learning process [5]:

Figure 1 - Transformation Model

Cognitive learning is the intended, or sometimes unintended, process to gain knowledge (perception, imagination, thinking, judging, language), and it starts on the day a human being is born. Over the course of time, every person develops specific skills and cognitive structures (knowledge structure) which are built through cognitive processes.

In a professional work environment, it is essential to prepare the workforce for the specific tasks that have to be fulfilled by a project. The learning portfolio of companies and organizations typically consists of - but is not limited to - the following topics [6, 7]:

- *Language skills (especially important in multi-national & global enterprises)*
- *Craftsmanly topics (skilled occupation, manual competence)*
- *Skills in all regards of Information Technology (e.g. application know-how of a specific software, general skills to be able to operate with computing devices or IT data security)*
- *So-called excellence factors like exponential thinking, self-learn/self-reflection competence, customer orientation, data smart, capability to adopt change, responsibility, information scouting & investigation, problem solving, process analysis, design thinking, agile, and user experience*
- *Soft skills (e.g. conflict management, motivation)*
- *Communication and presentation skills*
- *General management skills (e.g. instance business models, economics, and project management)*

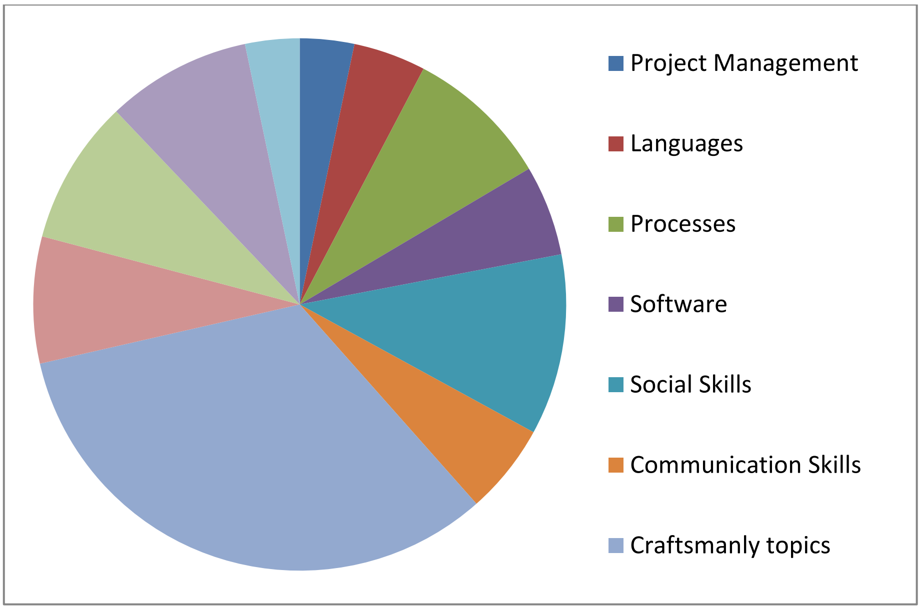

Figure 2 – Training share (analysis of training portfolio of thyssenkrupp Elevator)

Therein the value stream (in a company or workplace) and the individual learning process have to be synchronized to ensure effectiveness.

4 INSTRUCTOR-LED-TRAINING VS. ALTERNATIVES

Instructor-led-training or ILT is the classic and most common practice of training between an instructor (or teacher or facilitator) and a learner. This learning process can happen in a group or individually. The instructor is referred to as knowledgeable and experienced in the specific learning topic. Ideally, the instructor has certain skills and the ability to deliver the content or material to the learners and to apply different methods to occupy learners and to include different learning styles.

The training is typically delivered in a lecture (a classroom format) format, but can also be delivered in alternative formats such as interactive workshops (demonstrations which offers learners the chance to practice) or through virtual tools such as real-time video conferences. Mobile training trucks/busses offer mobile physical classrooms and allow the equipment to be moved to where it is needed.

This ILT represents, in general, 2/3 of corporate training and development programs [8], while more and more alternatives to ILT appear on the horizon of teaching & learning. This shift is enabled by evolving technology, ubiquity knowledge (Mega Trend), increasing number of mobile devices, growing share of digital natives, and the fast increase of computational power.

As of today, the most common alternative forms of training are as listed and defined in the following table:

Alternative learning format	Definition
Uncontrolled on-site training	On-the-job training where the learner gains informal knowledge from co-workers.
eLearning [9]	No clear definition existing. However, eLearning refers to learning experiences that use technology such as videos or web-based training (specific user interfaces).
Videocasts	Basically classroom training that was recorded on video

	and can be viewed by a learner anytime, anywhere.
Massive Open Online Course (MOOC)	Free online seminars on university level that have a huge number of participants.
Physical simulator training	Environment that copies a real-life situation (e.g.: elevator shafts in steel frames that allow group training).
Augmented reality / Virtual reality / Mixed reality training	Immersion of learners into a simulated facility giving them an experience similar to real life. Benefits: The trainee can be placed in simulated environments that would be potentially dangerous to simulate in real life. No need for a simulation facility to undergo the training. Multiple people can be trained at the same time. Different trainees can interact with one another as well as the instructor. Transport a learner to a different location.
Micro Learning	Smaller chunks of training content, generally available 24/7 via mobile applications to allow access anywhere & anytime.
Blended learning [9]	Mixed learning formats (e.g.: literature + video tape of a classroom lecture + web-based knowledge control).

Table 1 – Types of learning formats

Amongst these examples, self-directed training, which is a specific form of training, allows learners to assume responsibility of their own training (e.g. selecting content, defining right timing, and choosing the suitable delivery form).

An open learning environment (OLE) is a customer-centered system that applies design principles and considers learning activities that "support the individual's efforts to understand what he or she determines to be important" [10]. OLEs put emphasis on the self-directed learning of a learner, but also provide guidance and support to the learner when needed. This allows learners to be effectively involved into complex problem solving.

Organized, or formal, learning strategies such as workshops, certification courses, or long hour training sessions, will have different impacts on learners as opposed to those of informal learning strategies which can include mentoring, tutoring and self-directed learning. Both of these methods are valid learning environments but one or the other can be more useful depending on each situation.

Individual learning also has a main benefit derived from the core concept of being done individually as it will take less time to set-up lessons.

5 TECHNOLOGY IN LEARNING

These learning environments can be implemented online to allow for distance learning. Individual learning especially benefits from this, as there are multiple Learning Management Systems (LMS) available that can have entire training courses implemented online for individuals. Collaborative learning can also be done online. However, this tends to be more difficult as individuals have different time availabilities. Technology can help to solve these challenges.

A huge variety of technologies are available that support the learning, and therewith the learner's transformation process. Successful technologies in learning consider the principles of learning as described in section 2 LEARNING and are briefly introduced in section 4 INSTRUCTOR-LED-TRAINING VS. ALTERNATIVES. The latest Learning Management Systems (LMS) combine all facets of training & learning. Amongst the function to manage training events and track learners' progress, these systems offer a comprehensive collection of all kinds of different training types, such as

- *Mobile applications for mobile phones, computers and tablets*
- *eLearning*
- *Video*
- *Micro learning (smaller chunks at a time)*
- *Gamification*
- *Coaching functionality*
- *Tailored functional (e.g. engineering) training*
- *Implemented Virtual/Augmented/Mixed Reality training*
- *Artificial intelligence (this technology enables the system to form user-specific learning material, e.g. individual questions)*

Therein, the LMSs consider the need for personalized individual learning, social learning (learning with others). They make distance and OLEs available for enterprises and accessible for each learner any time and everywhere. This is especially important as the younger generation of learners (so-called Digital Natives) is very dependent on technology and will more likely participate in the learning journey if it can be used easily with their personal devices.

6 FACTORS OF SUCCESSFUL OPEN LEARNING ENVIRONMENTS

Without a doubt, it all starts with good pedagogy. However, there are few other factors that influence the success of learning [11]:

- *Engaged students (who are motivated, curious and ask good questions)*
- *Multiple different methods of teaching should be used individual, collaborative, lecture, group to group, etc.*
- *A constant opportunity to practice what's been learned.*
- *Fun*
- *Everyone's different work style has to be accounted for. There are online assessments such as Kolbe and other sources that can be used to get an idea of different peoples working styles so that they can be matched with a suitable training program.*
- *Expectations of the employee have to be made clear initially. This also goes for the person in charge of training, the trainee's expectations of them should be known.*
- *Progress check-ins need to be regularly made to an agreed schedule.*
- *The trainer needs to consistently ask questions.*
- *The key to effective training is communication, knowing the trainee's thoughts throughout the training process will help to adjust the training plan so that the trainee is involved and is learning quickly.*

Because of increasing diversity in workplace it is necessary to put trainees in situations that they would be unaccustomed to in their own culture. This can help to ease an employee when introduced to these situations in the workplace.

7 BENEFITS OF DIGITAL TRAINING FOR THE COMPANY AND LEARNER

Based on latest pedagogic research results, modern learning environments are open (observe and learn from others) and offer flexible access to learning resources. The benefits of modern learning environments include, but are not limited to [12, 13]:

- *Flexibility (The learner can choose time and place of study.)*
- *Efficacy (Easy access to information.)*
- *Social contact (Support relations between learners.)*
- *Cost effective (No need for travel. No need to provide buildings and physical environments.)*
- *Consideration of learning style and individual differences between learners*
- *Self-paced (Each learned studies at own pace. That increases the learners' satisfaction and motivation.)*

8 PRACTICAL EXAMPLES (OF PTS INDUSTRY)

8.1 TSG T6001-2007 "Examination Requirements for Safety Administrator and Operators of Elevators"

In 2007, the Chinese government published a requirement document TSG T6001-2007 "Examination Requirements for Safety Administrator and Operators of Elevator" to compile all necessary know-how to inspect and operate an elevator in a safe manner. Based on this and the listed requirements, an interactive learning model has been developed by the company Zhejiang Provincial Special Equipment Inspection and Research Institute, Hangzhou, PRC. The system modules follow the general structure of an elevator, its main parts, a standard installation method, and the system operation principle.

The learning tool combines different learning methodologies, from text reading to multimedia, and considers two basic roles: Operator/Worker and Safety Manager/Inspector [14].

Function module		Function description	Expression form
Safety management personnel	Theory	introduce the relevant knowledge of the elevator by graphics, animation, video	Graphics, animation, video
		Consult the statute	PDF document
	Skill operation	Review of the security management knowledge document	WORD、PDF document
		Check the actual operation	Video, animation
Driver	Theory knowledge	introduce the system and components of elevator with graphics and 3D simulation	Graphics, simulation
	Skill operation	Introduction operation with video, graphics, animation Using simulation operation process	Video, animation, Graphics, simulation
Installation and maintenance personnel	Theory knowledge	describe the basic knowledge with graphics	Graphics
		explain professional knowledge with animation	animation
		Consult the statute	PDF document
	Skill operation	Provide engineering drawings and circuit diagrams	Two dimensional drawing
		Introduction operation with video, graphics, animation Using simulation operation process	Video, animation, Graphics, simulation

Figure 3 – Learning methodology vs. system function [14]

8.2 3D Virtual Reality Elevator

A Singapore-based company[1] developed and distributes an advanced browser-based interactive 3D virtual software platform for public education and other purposes.
Platform product features are:

- *3D Online Product Display*
- *3D Instructional Product Installation and Disassembly*
- *overall Product Training*

The intended user group includes vendors, agents, internal staff, end users, operators, and other trainees. The system allows users to remotely view elevator product demos to provide a specific experience for them, since the main application of the VR training tool is to learn the operations and maintenance functionality of the elevator system. Aside from elevators, the platform is used for showcases and training demos for different industries, such as Automotive, IT, Architecture, Electronics, and Logistics [15].

Figure 4 – Screenshot of user interface for architects [15]

8.3 Immersive Reality and Service & Maintenance Application

The learning organization of a German-based elevator manufacturer[2] uses many different kinds of learning methodologies to teach & develop internal staff. Amongst others, eLearning, video lectures and games to learn about safety at work in a fun mode are implemented.
Under the umbrella of the strategic partnership with a California-based software company, the application of a mixed reality glasses demonstrates the benefit of modern electronic devices for the success of training & learning [16].

Their VR Research application is a headset solution that transports the user into an immersive reality world (for research application: CAD only elevator & escalator systems to demonstrate new

[1] Phoenix OneSoft Ltd.
[2] thyssenkrupp Elevator AG

designs and functionalities). That VR headset[3] tracks the movement of the user's head in real time (Steam VR Tracking) and offers a high resolution display with a field of view of 110°. The intuitive command navigation and haptic feedback completes the immersive feeling.

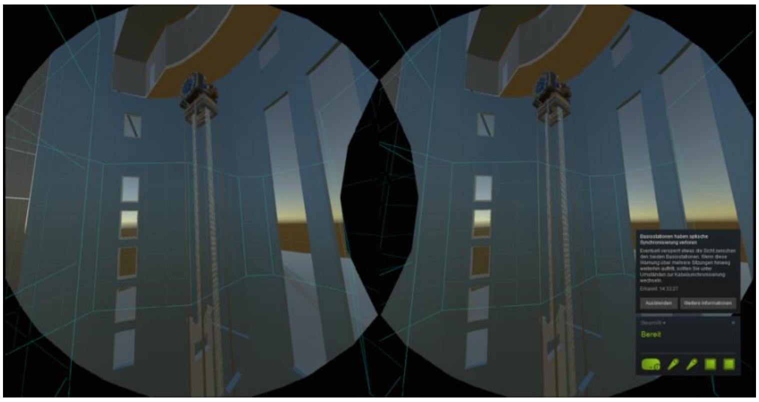

Figure 5 – Virtual Reality glasses screenshot of elevator system

Figure 6 – Mixed Reality application for maintenance training (illustration)

9 CONCLUSION

The foundation for any good training, whether it is delivered in a classroom or via an eLearning tool, is a solid pedagogic model that relates content & learner.

Modern learning environments are learner-centric and offer the opportunity for the learner to engage with other learners and a supporting function (e.g. teacher or mentor). The learner-centricity considers the different aspects of learning style, knowledge status, available time and learning pace.

Without a doubt, the efficacy of OLEs is enormous, and digital learning technologies provide huge opportunities to organizations to create digital learning assets and can be categorized based on the training format. These can be all sorts of eLearning modules such as videos, podcasts, webinars or PDF literature. Blended or mixed formats show the best learning effect.

[3] HTC Vive

Within the coming years, technology innovations and the huge demand for a wide variety of learning methods are going to make customized and user-centralized training a necessity.

The future will prove the destiny of OLEs and Micro Learning applications. New advancements in technology may even create new types of Micro Learning.

As a consequence, training should no longer be seen as a single isolated event, but more as an ongoing activity which provides learning and development opportunities for employees to their demand. Supported by the right piece of technology, training is even more efficient and therefore repays investment into time and money.

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BIOGRAPHICAL DETAILS

Thomas Ehrl, thyssenkrupp Elevator Innovation GmbH, Germany

Married since 1999, one son of 15 years

Mechanical Design Engineer (degree in 1994), Part-time PhD student with the School of Science and Technology of The University of Northampton. Professional career started in 1994.

Since 4/2008 with thyssenKrupp Elevator:

- Head of Research & Innovation Center of thyssenkrupp Elevator Innovation GmbH, Rottweil
- Engineering Training Manager at Corporate Level of thyssenkrupp Elevator AG
- Manager R&D Project Standards at Corporate Level of thyssenkrupp Elevator AG

Interests:

Travelling, sports, soccer, music, vintage English motor cycles.

A Fundamental Study Concerning the Correct Performance of Elevator Buffers

Osamu FURUYA[1], Naoki FUJIWARA[2] and Satoshi FUJITA[3]

[1]Division of Electronics and Mechanical Engineering, School of Science and Engineering, Tokyo Denki University, Ishizaka, Hatoyama-cho, Hiki-gun, Saitama 350-0394 Japan
osamu.furuya@mail.dendai.ac.jp
[2]Department of Mechanical Engineering, School of Science and Engineering,
Tokyo Denki University, 5, Senju-Asahi-cho, Adachi-ku, Tokyo 120-8551, Japan
[3]Department of Mechanical Engineering, School of Science and Engineering, Tokyo Denki University, 5, Senju-Asahi-cho, Adachi-ku, Tokyo 120-8551, Japan
sfujita@cck.dendai.ac.jp

Keywords: Elevator buffer, Shock absorber, Time response analysis, Performance evaluation.

Abstract. Various safety devices are provided to ensure the safety of lift passengers. A number of safety systems are employed to prevent injury in case of uncontrolled movement. The car and counterweight buffers (shock absorber) play an important role. This paper considers appropriate performance of the car and counterweight buffers. Buffer performance is examined to satisfy a safe condition in the revised JIS A 4306.

1 INTRODUCTION

In late years an elevator is installed in many high-rises buildings with the high stratification, and convenience largely improves. On the other hand, further safety improvements of elevators have been expected because of various accidents including the enclosure accidents. Various safety devices are installed to ensure the security of the user, even if there is trouble in the elevator itself. Plural safe systems are considered for fall accident of elevators. However, in general, as for the probability of a fall accident, a buffer is installed in the bottom of elevator hoistway.

A buffer plays a role to minimize the damage of a passenger and the building by absorbing the shock of the fall accident of an elevator car. Although the performance requirements of a buffer have been determined in the Ministry of construction notification No.1423, an issue has occurred in an examination item, a standard for judgment, the performance requirement of buffer and so on in Japan. Therefore, as for the performance of buffer, the standard was revised with a governor, an emergency stop device in JIS A 4306 in 2016[(1),] and then a review and a change were planned. In addition, the review of standard is shown in when the specialized knowledge about acceptable deceleration or acceleration applied time against a human body is obtained in the future, because the buffer must satisfy enough security.

In this study, the way of a buffer satisfying the safety requirements of revised Japanese Industrial Standards is analytically examined for an oil buffer for elevators.

2 PERFORMANCE REQUIREMENTS FOR OIL BUFFER IN JIS A 4306

The stroke of the oil buffer must be bigger than the smallest stroke calculated from the next expression.

$$L_{min} = {V_R}^2/53.4$$

in here,

L_{min} : stroke of buffer [mm]

V_R : rating speed [m/min]

The average deceleration at the time of collision in case of rating speed of 1.15 times must not be beyond $1g_n$. g_n means 9.8 m/s^2. In addition, duration of deceleration more than $2.5g_n$ must not be over 0.04 seconds.

Figure 1 shows the example of slowing down characteristic of an oil buffer. The average deceleration is calculated from following methods.

1) The average deceleration is defined as the time average value of deceleration obtained from the start time of slowing down to the end time for oil buffer. The slowing down origin of the oil buffer is set in the time when acceleration becomes 0 m/s^2. The slowing down endpoint is set with the point when the deceleration becomes 0.5 m/s^2 right before the velocity 0 m/min.

2) The average deceleration defines the value that is divided the velocity at start point of slowing down for oil buffer by the time from the start point to end point of slowing down.

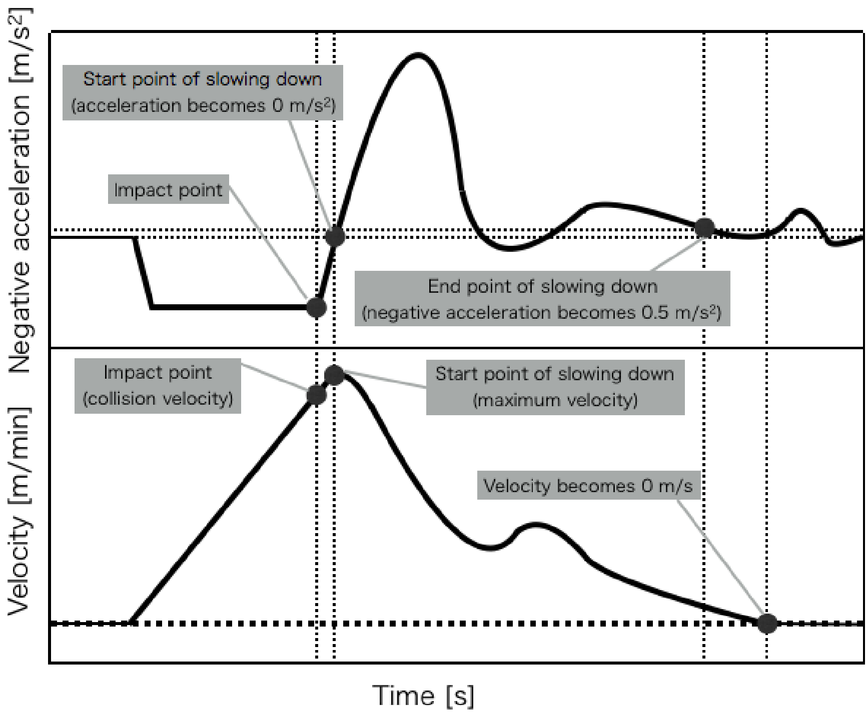

Figure 1 Example of deceleration characteristic of oil buffer

3 ANALYTICAL METHOD

In the situation that an elevator collides with an oil buffer, one degree of freedom model that is constructed from a mass m [kg], a spring of natural frequency k [Hz] and damping ratio ζ is considered to evaluate the response in sinking direction after impact between elevator car and buffer by time response analysis. Figure 2 shows the analytical model for time response analysis, and also the equation of motion is as follows:

$$m\ddot{x} + c\dot{x} + kx = 0$$

In the case of initial condition:

$$\left.\begin{aligned}\dot{x} &= v_0 \\ x &= x_0\end{aligned}\right\}$$

The responses are obtained as follows:

$$x = e^{-zw_n t}\left\{x_0 \cos w_d t + \frac{zw_n x_0 + v_0}{w_d}\sin w_d t\right\}$$

$$\dot{x} = -\zeta\omega_n e^{-\zeta\omega_n t}\left\{x_0 \cos\omega_d t + \frac{\zeta\omega_n x_0 + v_0}{\omega_d}\sin\omega_d t\right\} + \omega_d e^{-\zeta\omega_n t}\left\{-x_0 \sin\omega_d t + \frac{\zeta\omega_n x_0 + v_0}{\omega_d}\cos\omega_d t\right\}$$

$$\ddot{x} = \omega_n e^{-\zeta\omega_n t}\left[x_0\left\{\left(\zeta^2\omega_n^2 - \omega_d^2\right)\cos\omega_d t + 2\zeta\omega_n\omega_d \sin\omega_d t\right\} + \frac{\zeta\omega_n x_0 + v_0}{\omega_d}\left\{\left(\zeta^2\omega_n^2 - \omega_d^2\right)\sin\omega_d t + 2\zeta\omega_n\omega_d\cos\omega_d t\right\}\right]$$

Besides, the deceleration is calculated from the following expression:

$$\frac{v_1 - v_2}{t_2 - t_1} = \frac{\left(w_d - zw_n\right)\left\{e^{-zw_n t_1}\left(x_0 \cos w_d t_1 + \frac{zw_n x_0 + v_0}{w_d}\sin w_d t_1\right) - e^{-zw_n t_2}\left(x_0 \cos w_d t_2 + \frac{zw_n x_0 + v_0}{w_d}\sin w_d t_2\right)\right\}}{t_2 - t_1} - \frac{2 w_d x_0 e^{-zw_n t_1}\sin w_d t_1 + e^{-zw_n t_2}\sin w_d t_2}{t_2 - t_1}$$

Specifically, combination of spring element and damping element becomes very important to design the actual oil buffer. Therefore, in this analysis, natural frequency and damping ratio of the buffer is assumed analytical parameters. Response acceleration, deceleration, velocity and displacement of 1DOF model with the buffer are analyzed from the combination of each parameter. Based on the responses analyzed by time response analysis, the combination of each analytical parameters are obtained to satisfy the performance specification requirements.

The initial conditions of analytical parameters are as follows:

Mass of elevator car 2,000 kg: mass of car 1,000 kg + loading mass 1,000 kg (15 person * 65 kg/person)

Natural frequency: $0.1 \leqq f_n \leqq 5.0$ Hz

Damping ratio: $0.01 \leqq \zeta \leqq 0.5$

Initial velocity 103.5 m/min: 1.15 times of the elevator of standardized speed 90 m/min.

Total combination of analytical parameters becomes 2,500 ways in this time.

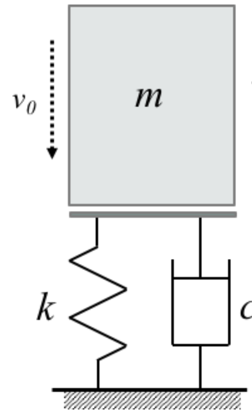

Figure 2 Analytical model for time response analysis of design way for elevator buffer

4 ANALYTICAL RESULT

Figure 3 shows the relation between natural frequency and average deceleration with each damping ratio. Besides, the figure indicates in the case of ζ=0.01, 0.25, 0.5 as a typical example. From the result, it was confirmed that the relation between natural frequency and average deceleration is almost linear characteristic. Moreover, it was confirmed that the safety requirement of average deceleration was satisfied in the range of the analytical parameter in this time, because of that the average deceleration does not exceed $1g_n$.

Next, Fig.4 shows the range of analytical parameters satisfied the safety requirement. The red plot means the plot that the deceleration over 2.5 g_n is continued more than 0.04 seconds based on the evaluation criteria. From the result, it was confirmed that the area of parameters less than 2.4 Hz satisfies basically the safety requirement. Besides, there are the parameter combinations for satisfying the safety requirement in over 2.4 Hz such as examples of near natural frequency 5 Hz and damping ratio 0.5.

Based on an evaluation standard, the combination of parameters when the maximum displacement of the buffer is less than the smallest stroke does not satisfy a safety requirement. Smallest stroke of buffer is obtained as follows in when the rating speed of the elevator car is set to be 90m/min as an initial condition.

$$\mathrm{L} = {V_R}^2/53.4 = 90^2/53.4 = 151\ [mm]$$

Figure 5 shows the relation between natural frequency, damping ratio and maximum displacement. The combination of analytical parameters in the case of maximum displacement under 0.15 [m] and also in the case of maximum displacement over 1.0 [m] does not satisfy the safety requirement. As the result, white color area satisfies the safety requirement in the analytical parameters. It is confirmed that the maximum displacement becomes a large when each parameter becomes a small. Especially, maximum displacement tends to become higher as a quadratic function when a natural frequency is smaller than 0.5 [Hz]. Therefore, Fig.6 shows the specification condition of buffer in the case of satisfying the safety requirements and the practically design possibility such as showing the white color area. As the results, it was confirmed that the following region of analytical parameters satisfies the safety requirement.

$$0.2 \leq f_n \leq 1.8\ [\mathrm{Hz}]$$

$$0.01 \leq \zeta \leq 0.5$$

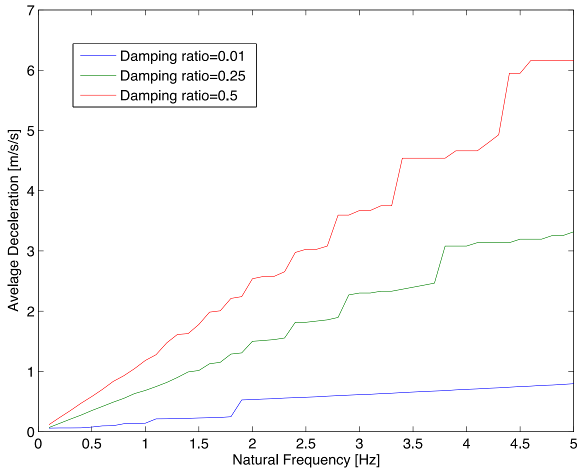

Figure 3 Relation between average deceleration and natural frequency

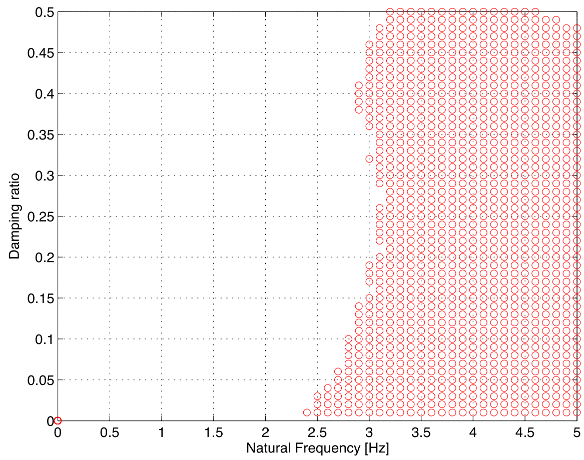

Figure 4 Relation between natural frequency and damping ratio for maximum deceleration for satisfying the safety requirements

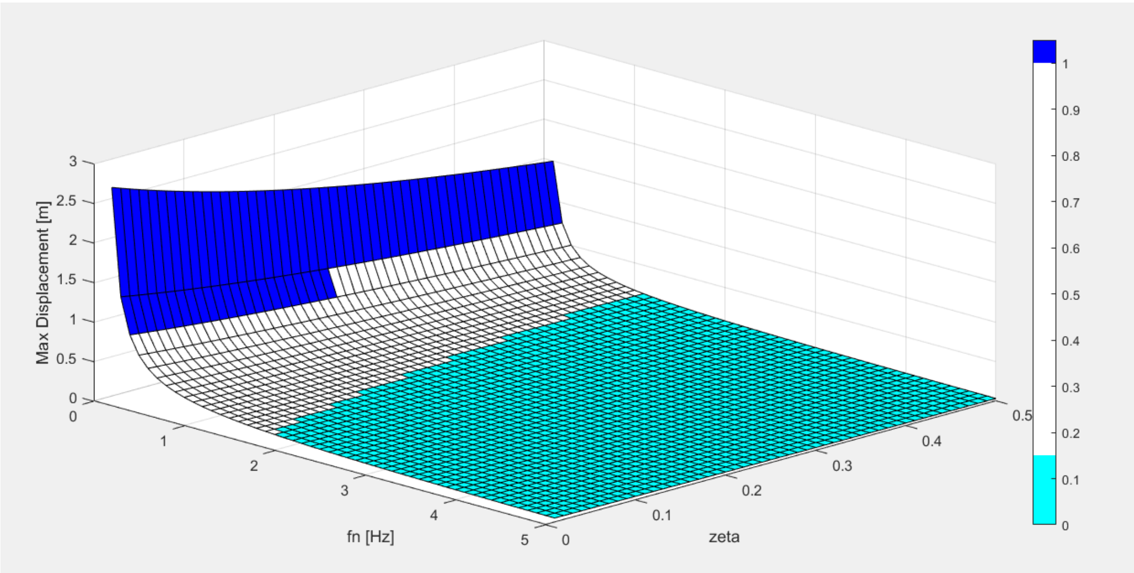

Figure 5 Relation between natural frequency and damping ratio for maximum displacement

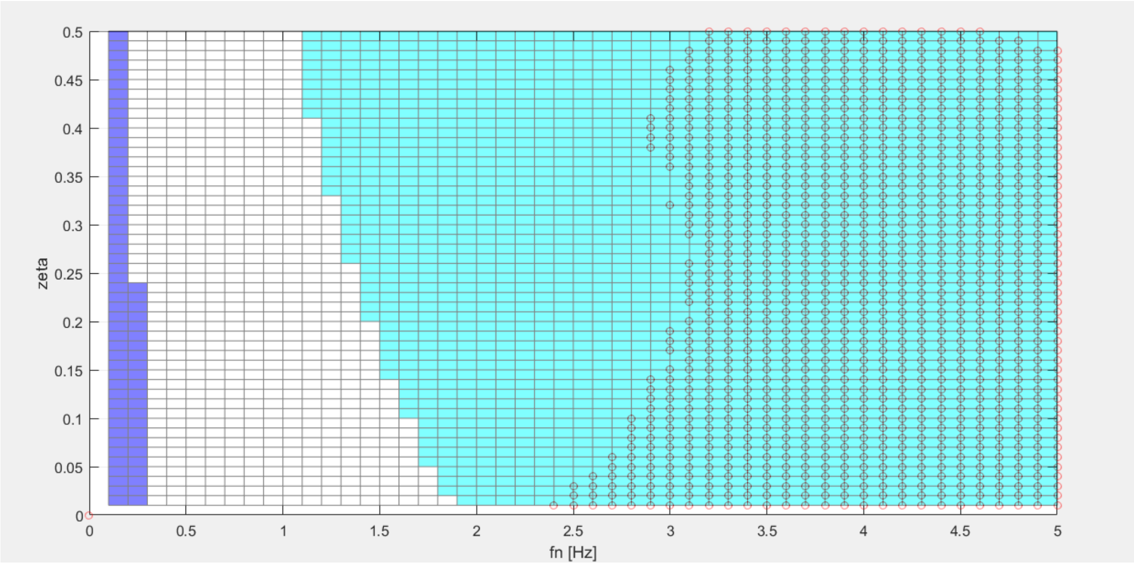

Figure 6 Design specification for satisfying the safety requirements in JIS A 4306

5 CONCLUSION

This study examined about the design way of elevator to satisfy the revised standard JIS A 4306 from the relation between a natural frequency and damping ratio in 1DOF analytical model in case under typical analytical parameters. As the result, it was confirmed that the combination of design parameters are obtained and shown visually in the figures to satisfy the safety requirements. The nonlinear time response analysis will be conducted by using analytical model of actual buffer with a nonlinear characteristic in future. Moreover, the car load will be changed to satisfy several load conditions.

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BIOGRAPHICAL DETAILS

PhD, Mechanical System Engineering, Graduate School of Tokyo Denki University, 1996
Research Associate, Tokyo Metropolitan College of Technology,1996
Lecturer, Tokyo Metropolitan College of Technology,1998
Associate Professor, Tokyo Metropolitan College of Technology:2001
Associate Professor, Tokyo City University:2010
Associate Professor, Tokyo Denki University:2016

Recent main research object is research and development of vibration control and base isolation technique and its upgrading.

Departure Delays in Lift Systems

Stefan Gerstenmeyer[1,2], Richard Peters[2,3], Rory Smith[2,4]

[1]thyssenkrupp Elevator Innovation GmbH
Bernhäuser Str. 45, 73765 Neuhausen, Germany
stefan.gerstenmeyer@thyssenkrupp.com

[2]The University of Northampton
School of Science and Technology, The University of Northampton, UK

[3]Peters-Research Ltd.
Bridge House, Station Approach, Great Missenden, Bucks, HP16 9AZ, UK
richard.peters@peters-research.com

[4]thyssenkrupp Elevator North America
rory.smith@thyssenkrupp.com

Keywords: lift, elevator, multi car, departure delay, quality of service, transit time, waiting time, walking time, up-peak, door dwell, start delay

Abstract. There is a range of lift systems with more than one car or cabin per shaft. Double deck lifts have a car with two attached cabins, serving adjacent floors at the same time. Other systems enable two independent cars to share the same shaft. The next generation ropeless lifts will allow many cars to share the same shafts.

In these systems, the interaction between the cars and cabins affect the quality of service for passengers. Departure delays occur when passenger loading and unloading times or the sequence of stops required to serve passengers is not the same. The consequence is that cars and cabins delay each other's departure. Departure delays can also occur in lift systems with a single car and cabin per shaft, for example, when destination calls are registered at a significant walking distance from the lift lobby.

To include departure delay in an assessment of quality of service, definitions of passenger and cabin departure delays, and a method to measure these delays are required. This paper describes the different types of departure delays and their causes. This provides metrics which can be applied in lift planning and dispatcher design.

1 INTRODUCTION

1.1 General

A passenger's journey consists of two different phases (see Figure 1), waiting for the lift at the arrival floor, known as waiting time (WT), and the travelling time inside the cabin, known as transit time (TT). The sum of WT and TT is called time to destination (TTD) [1].

A lift stands with its doors open at a landing to allow passenger transfer. After the transfer of passengers has finished, the door closing and departure of the cabin may be delayed by the control system.

Why these departure delays occur and how they can be measured is defined and explained in this paper.

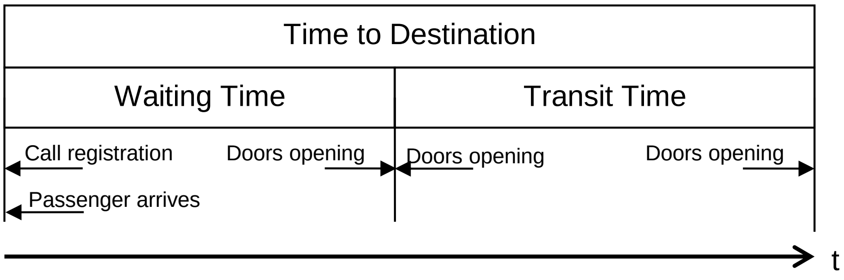

Figure 1 Passenger's time to destination – phases of a journey

1.2 Extended door dwell time

Most modern lift controllers have intelligent door dwell time algorithms. The presence of passengers is detected by the photoelectric door protection devices. If the door beams are interrupted, the control system assumes that passenger transfer is occurring and the doors remain open.

Extended door dwell time is the time after the passenger detection beams of the doors are cleared before the lift door starts closing. Door dwell time before or during passenger transfer is not part of the extended door dwell time.

The extended door dwell time is a delay experienced by passengers inside the cabin. This includes passengers who have just entered the cabin and passengers who are already inside the cabin having an intermediate stop. During the extended door dwell time, nothing happens for the passengers. It can be observed that regular lift users often press the door close button in the cabin rather than waiting for the doors to start closing for themselves after the extended door dwell time. Extended door dwell time is experienced as departure delay.

1.3 Multi car lift systems

In multi car lift systems (MCLS), multiple lift cars or cabins share the same shaft, guide rails and shaft doors [2]. Systems with more than two independent lift cars are currently in development [3]. Existing double deck lift systems have two mechanically coupled lift cabins. Departure delays in multi cabin systems occur when the loading/unloading times of the cabins are different, the number of stops is not equal, or one cabin blocks the way of another [4]. An example is illustrated in Figure 2. In a MCLS cars may delay departure to avoid collision [5, 6]. The dispatcher may consider departure delays. They should be minimised, although in special instances a departure delay is the only option [7].

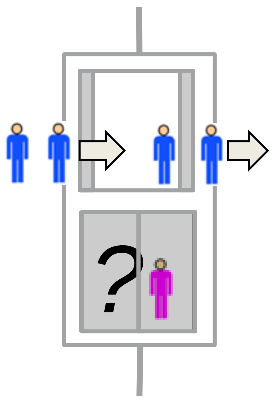

Figure 2 Double deck lift with a blind stop for a passenger in the lower cabin

1.4 Conventional systems

1.4.1 Up-peak

Departure delays are sometimes initiated by the dispatcher. In up-peak traffic conditions, it can be beneficial to delay a car's departure from the lobby to wait for additional arriving passengers so that the cabin is filled to a higher capacity factor [8, 9]. It is recommended that passengers should not be held at the lobby for more that 10 to 15 s [9].

1.4.2 Walking times

Delays may occur if passengers need to walk to an allocated and arriving lift car. In destination control systems, the walking time from a call input station to the allocated cabin (see Figure 3) is part of the waiting time of a passenger if the cabin has not yet arrived. As the walking time is part of the waiting time it can be considered as occupied waiting time which is less painful [4]. However, a passenger walking from a call input station to a cabin that is already standing with open doors at the arrival floor, delays the departure of the lift and any passengers who are already inside the cabin.

Door dwell time in conventional systems may need to be lengthened due to the arrangement of the lifts. In buildings built before lifts were automatic, it was common to place six or even eight lifts in a row. When these lifts were modernized, the dwell time needed to be long enough to permit passengers to walk from one end of the lobby to the other. Lift shafts may be arranged in line or opposite each other. Lift group layouts and lift lobby sizes affect the walking time. Long walking distances will delay the closure of cabin doors and will cause departure delays of cabins [1]. Also crowded lobbies can affect passenger transfer and cause delays.

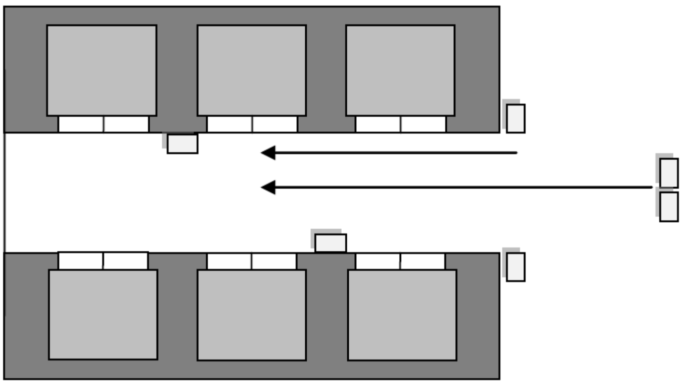

Figure 3 Floor plan with walking distance from call input stations to the lifts

1.5 Stops without passenger transfer

1.5.1 False stop

A false stop is a stop where the doors open and close without any passenger transfer (see Figure 10). A false stop occurs if a waiting passenger walks away before the lift arrives [4]. The door dwell time during a false stop is a departure delay for passengers already inside the cabin. False stops can occur in multi car lift systems if an empty cabin is shunted (moved out of the way) with a car call to allow another cabin to reach its destination. No passenger is affected, so there is no contribution to departure delay.

1.5.2 Blind stop

A blind stop is a stop of a cabin with no door operation (see Figure 15). In general, blind stops should occur only without passengers inside the cabin [7]. Passengers who are inside the cabin are confused by blind stop situations.

In a conventional system, a blind stop occurs if a lift does not have an allocated call and the cabin is parked at a floor. Passengers are not affected by this kind of blind stop. In double deck lift systems, blind stops can occur if only one of the two cabins have passengers transferring. In multi car lift systems with independent cabins in the same shafts, blind stops with passengers inside the cabin should be rare.

1.6 Quality of service

Departure delays are confusing for lift passengers [4] and reduce the quality of service. A blind stop or any other departure delay should be explained to the passengers because unexplained waits seem longer than explained waits [10]. The use of a display in double deck cabins that states "serving other deck" when a blind stop occurs is recommended [11]. For all types of departure delays, information about a departure delay can reduce passenger's anxiety about their service. However, even explained departure delays can be annoying for passengers if they are too long, as waiting needs to be appropriate [12].

There is a difference in the departure delay experienced by passengers if doors are opened or closed. A departure delay with the doors closed is known as a blind departure delay.

2 SAMPLES/RECORDS OF DEPARTURE DELAYS

During a journey, passengers experience different stop times including departure delays. The first stop time is the arrival of the cabin at the passenger's floor before it starts moving. Additional stop times during transit occur at the intermediate stops. The stop at the destination floor of the passenger is not a part of the passenger's transit time. This is illustrated at Figure 4. In this example there are 4 passenger departure delays (PDD) that are experienced by two passengers (P1 and P2). Passenger 1 (P1) experiences 3 departures delays. Passenger 2 (P2) has only one departure delay. The cabin has 3 cabin departure delays (CDD) that are experienced at least by one passenger each.

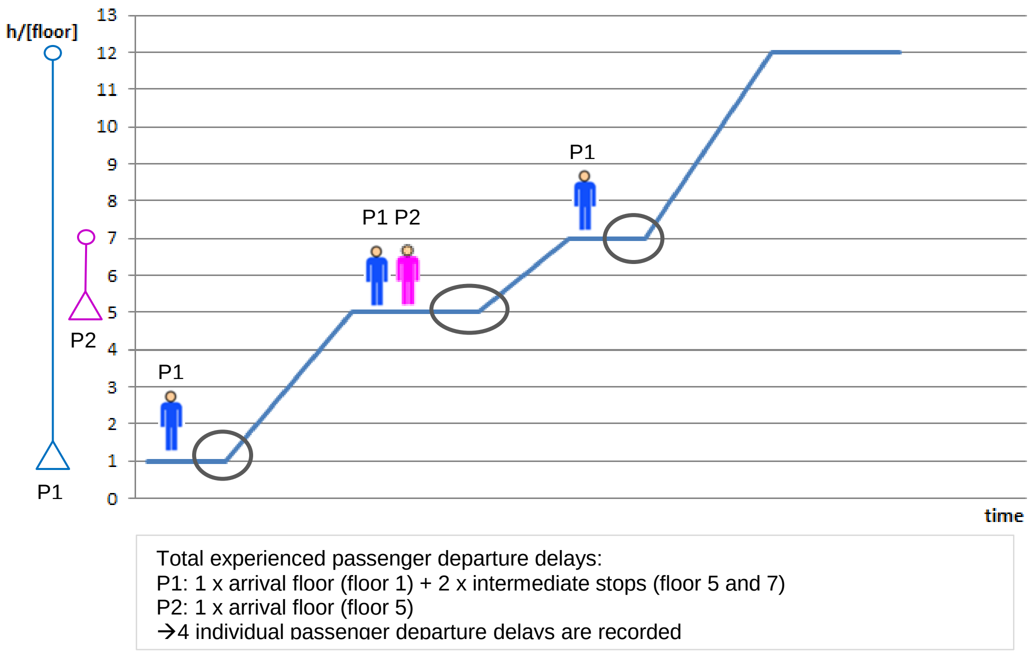

Figure 4 Experienced departure delays

3 PASSENGER DEPARTURE DELAY (OPEN DOORS)

The passenger departure delay with open doors (PDD or PDD_{OD}) is the period of time after passenger transfer is complete until the doors begin to close where there is one measurement for each stop experienced by the passenger. PDD is illustrated in Figure 5.

During passenger loading and unloading times, passengers crossing the cabin door threshold interrupt the passenger detection beams.

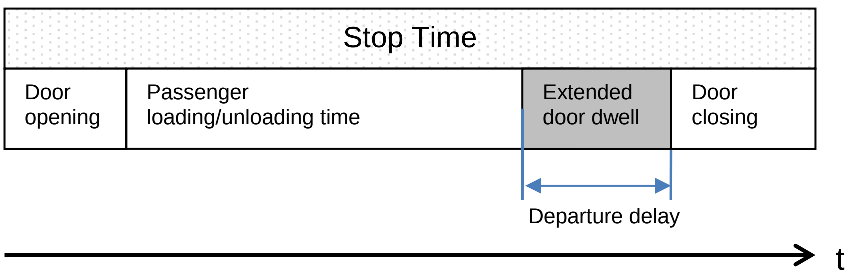

Figure 5 General passenger departure delay (normal stop)

In Figure 6 the PDD is extended because of traffic delays. For example, the dwell time may have been lengthened because another cabin blocks the way of the cabin in a MCLS. Doors are held open for better passenger comfort compared to blind delays with closed doors.

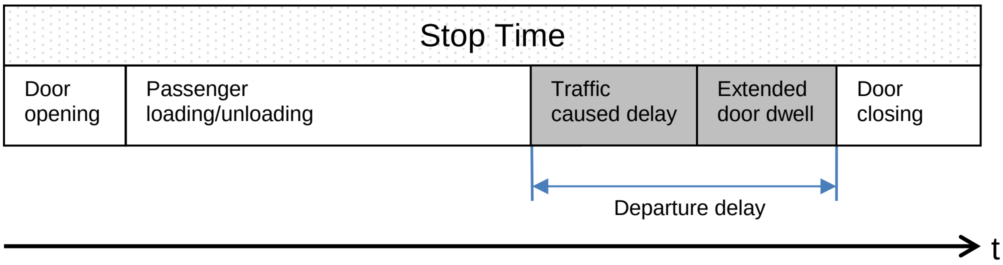

Figure 6 General passenger departure delay (normal stop + traffic caused delay)

Note 1: If there is a pause in passenger transfer, but the transfer re-starts before the doors start to close because it is less than the door dwell time and it is shorter than a "passenger transfer pause threshold" (PTPT), the departure delay does not start until the end of the final passenger transfer. This is illustrated in Figure 7. A reasonable value of PTPT is 1 sec.

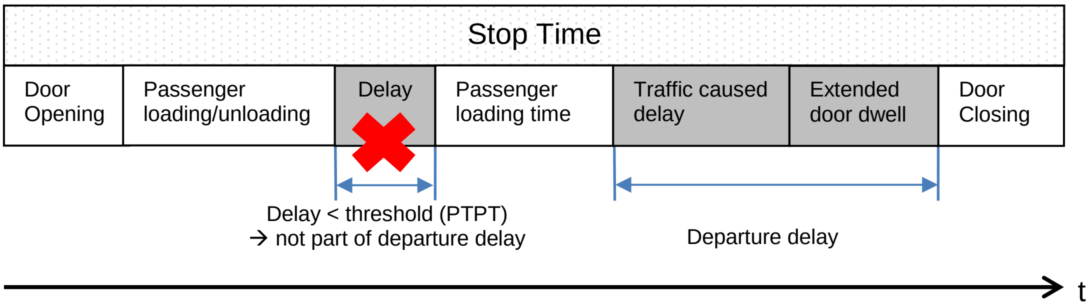

Figure 7 Short pause in passenger transfer

A short pause in passenger transfer can happen between normal unloading and loading of passengers especially where there are thick walls and deep door frames. When passengers are unloading and the walls are thick, door detection beams will be re-established for a short period of time until the loading passengers interrupt the detection beams. These short pauses are not seen as negative system delays.

Note 2: If there is a pause in passenger transfer without doors starting to close because of a traffic caused delay that is longer than or equal to a "passenger transfer pause threshold" (PTPT), for passengers already inside the cabin the departure delay includes the time during which there is no passenger transfer (passenger detection beams cleared). This is illustrated in Figure 8.

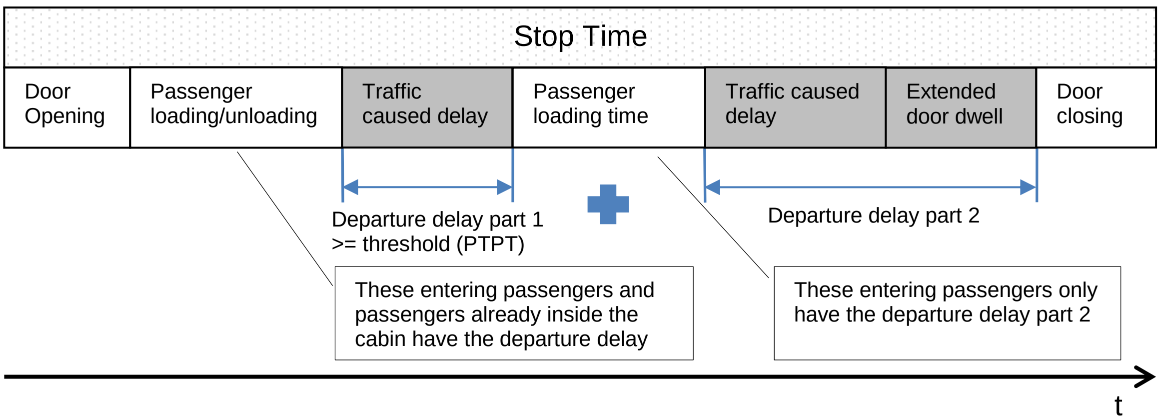

Figure 8 Pause in passenger transfer

Note 3: If the doors start to close, but are re-opened due to a new call being placed on the system, the departure delay re-starts when the next period of passenger transfer is complete. If the doors repeatedly re-open, there may be multiple periods of departure delay for a single stop, all of which are included in the departure delay for passengers already inside the cabin. This is illustrated in Figure 9.

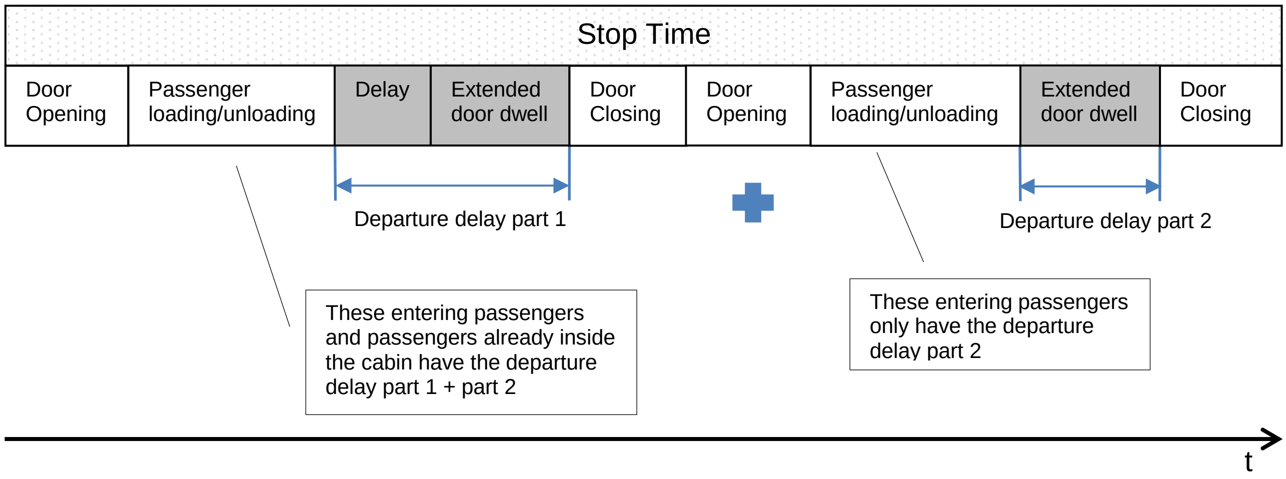

Figure 9 Door re-opening and departure delays

Note 4: If there is a false stop or passenger transfer finishes before the door is fully open, the time between when the doors are fully open and the time when the doors start closing is considered as departure delays for passengers inside the cabin. This may include door dwell time and traffic caused delays as shown in Figure 10 and Figure 11.

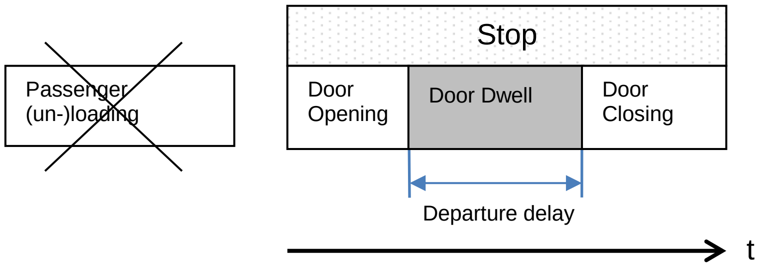

Figure 10 False stop

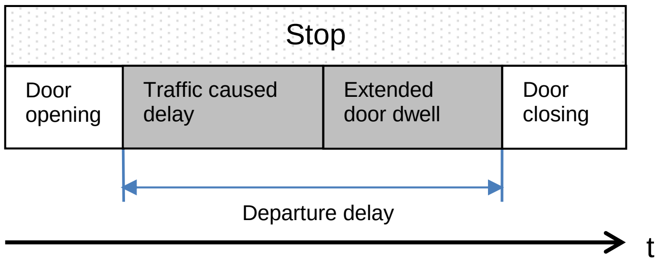

Figure 11 False stop + traffic caused delay

Note 5: If the passenger transfer is delayed e.g. because of walking times from the call input station to the already waiting cabin, the delay is included in the departure delay for passengers already in the cabin if it is longer than a "passenger transfer pause threshold" (PTPT). This is illustrated in Figure 12.

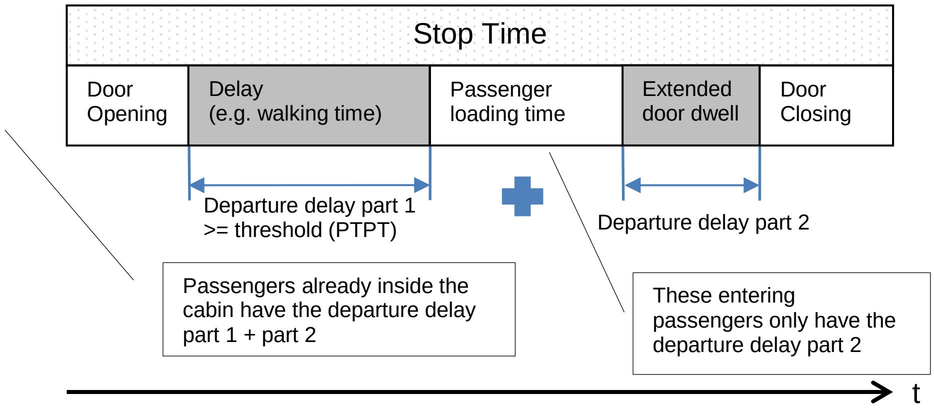

Figure 12 Delayed passenger transfer

4 BLIND PASSENGER DEPARTURE DELAYS (CLOSED DOORS)

A blind passenger departure delay (BPDD) or passenger departure delay with closed doors (PDD_{CD}) is the time between the instant the doors are fully closed and time the cabin starts moving. In single cabin shafts with no traffic caused departure delay this equates to the motor start delay [13]. This is shown in Figure 13. These start delays are caused by the locking shaft doors, the time required for relays to actuate, and the time required opening the machine brakes before the car starts moving.

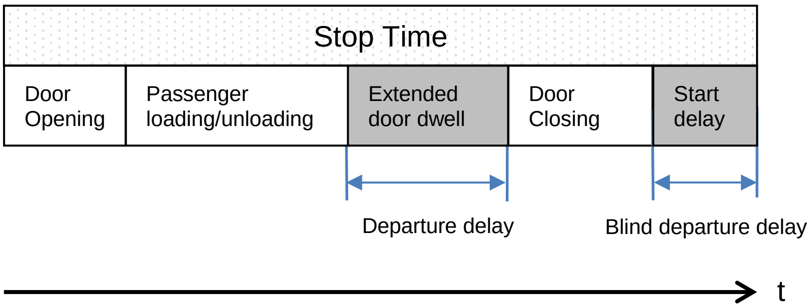

Figure 13 Blind departure delay

In a multi cabin lift system blind passenger departure delay can be extended because of traffic, see Figure 14.

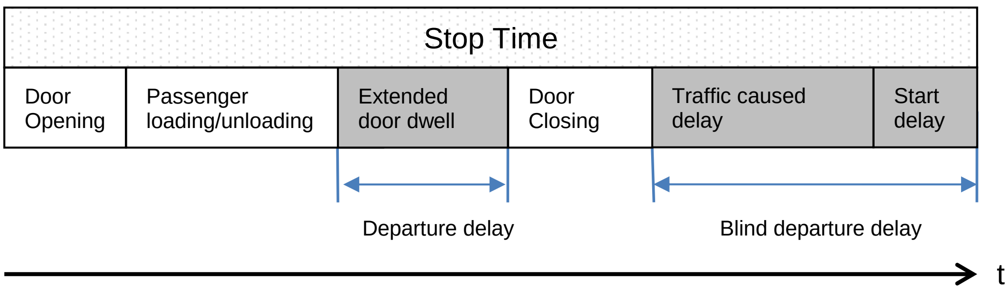

Figure 14 Blind departure delay + additional traffic caused delay

Note 6: In systems with multiple cars in the same shaft, where one car is delayed by another and the doors do not cycle during that delay, the departure delay begins as soon as the cabin stops, and ends when the cabin starts to move again. This is illustrated in Figure 15.

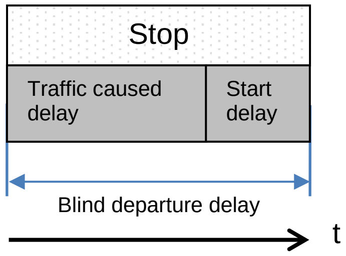

Figure 15 Blind stop

5 CABIN DEPARTURE DELAY

Passenger departure delay (PDD) is a passenger-centric measure, useful in assessing the quality of service from the prospective of the passenger. It is also helpful to have related system based measures for delay [14], cf. passenger waiting time and system response times where the system response time is equal to the waiting time of the first registered landing call of an arriving passenger at a floor [8].

The cabin departure delay (CDD) is the longest passenger departure delay at each stop. It is only measured if there are passengers inside the cabin.

The blind passenger departure delay (BPDD) is the same for all passengers in the cabin. This value is also the blind cabin departure delay (BCDD). It is only measured if there are passengers inside the cabin.

6 CONCLUSION

This paper describes the causes for departure delays, and defines them such that they can be measured in simulated and real systems. The measures can be used as quality criteria for all known lift systems: conventional one cabin per shaft, two independent cars in one shaft, double deck lift, and circulating multi car lift systems. Because the measure is system independent, the quality of service provided by different lift systems for the same traffic requirements can be compared.

In dispatching, intelligent systems may consider the "cost" of departure delay. Departure delay is part of transit time, but this part of transit time is more "painful" than when the cabin is moving.

Acceptable levels of departure delay have not been assessed and will be a matter of judgement until further studies on the psychology of waiting can provide an objective view.

GLOSSARY

WT	Waiting time (s)
TT	Transit time (s)
TTD	Time to destination (s)
MCLS	Multi car lift system
PDD	Passenger departure delay (s)

CDD	Cabin departure delay (s)
PTPT	Passenger transfer pause threshold (s)
BPDD	Blind passenger departure delay (s)
BCDD	Blind cabin departure delay (s)

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BIOGRAPHICAL DETAILS

Stefan Gerstenmeyer is working as Senior Engineer and Head of Traffic and Group Control at thyssenkrupp Elevator Innovation GmbH. He has been involved in R&D projects elating to group and dispatcher functions for lift controls including multi car lift systems. He is a post graduated research student at the University of Northampton.

Richard Peters has a degree in Electrical Engineering and a Doctorate for research in Vertical Transportation. He is a director of Peters Research Ltd and a Visiting Professor at the University of Northampton. He has been awarded Fellowship of the Institution of Engineering and Technology, and of the Chartered Institution of Building Services Engineers. Dr Peters is the author of Elevate, elevator traffic analysis and simulation software

Rory Smith is Visiting Professor in Lift Technology at the University of Northampton. He has over 47 years of lift industry experience and has been awarded numerous patents.

MMLS: The Future of Vertical Transportation for Tall Buildings

Adrian Godwin

Woking Eight, Forsyth Road, Woking, Surrey GU21 5SB, UK
adrian.godwin@movveo.com

Keywords: MMLS, Multi-Mobile, Mega-Tall, Shuttle Lifts, Sky Lobbies.

Abstract. Multiple academic papers and articles point to vertical transportation quickly becoming the “roadblock” to the viable design of super tall and mega tall buildings, despite the development of light weight ropes, high speed drives and advanced control algorithms. The space take of traditional elevators with only one or two cars per shaft is onerous and the obvious solution is to develop a system in which multiple cars can safely travel within a single shaft. The technology required to undertake the construction and delivery of the first MMLS (Multi Mobile Lift System) is now around us and, given the overwhelming business case for such systems, is more than paid for by their space saving capabilities. It is now simply a question of when, not if, these systems become safety certified for public use. This paper looks at rudimentary planning of such systems and reviews some of the practical aspects of how such systems might operate in the coming years.

1 INTRODUCTION

Perhaps the goal of being able to offer the world a Multi-Mobile Lift System, meaning a vertical transportation system with multiple lift cars travelling in one shaft, each car being independently speed controlled, could be described as the “holy grail” of the lift industry today.

An MMLS that can operate achieving:

- Overall system energy efficiency of greater than 90%
- Car capacities of, say, minimum 21 person/1600kg capacity
- Safe deceleration with the removal of power when cars are travelling at high speed, and
- Demonstrate easy emergency release of passengers from cars with no power available

will surely prove very attractive given a reasonably sensible commercial offering.

The author does not propose to review the “business case” for such systems as this has been well covered by previous papers [1, 2]. It should be understood, however, that the reason that so-called mega tall buildings are almost all of a similar tapering shape is because of the inability of today’s lift systems to move large numbers of people to extreme heights.

2 COMPARISON OF HANDLING CAPACITY

Some simple comparisons between conventional lift handling capacities and MMLS can act as a reference point for the start of a rudimentary analysis of both approaches.

The current limitation on conventional lifts is of the order of double deck 1800kg/24 person lifts travelling at an average speed of 10m/s up to a maximum of 600m height. The round trip time for such a journey is of the order 180s which means that its theoretical handling capacity per round trip in one way traffic is 38 persons (2 x 80% x 24 persons) or 63 persons per 5 minutes (300 seconds).

Given that we need to achieve an average interval of 30s or less we would need a minimum shuttle group size of six lifts. Therefore with a bank of six shuttle lifts we could move 63 x 6 = 378 persons per 5 minutes. This would mean we can only handle a maximum population of around 2,700 persons at the upper sky lobby based on a 14% 5-minute up peak handling capacity.

A multi-mobile lift system requires a minimum of two lift shafts because, as they say, what goes up must come down!

By comparison a similar car capacity in an MMLS scenario, given similar passenger loading time of 0.9s per person we could, nominally, dispatch a car every 25s. The average interval being controlled by 19 persons loading the car (17s) plus door open and close times (4s) and time for car to move away (4s). In 300s this gives us 12 cars of 19 persons or a 5-minute handling capacity of 228 persons per pair of shafts. With six lift shafts i.e. 3 MML systems we have a handling capacity of 228 x 3 = 684 persons per 5 minutes. This would mean, on a similar basis as above, we could handle a maximum population of around 4,900 persons at the upper sky lobby.

Therefore what we can take from this simple example for a 600m high destination is the following:

1. MMLS can give us a notional 80% increase in 5-minute handling capacity over a conventional lift solution to a destination 600m above ground.
2. Just one MMLS can give us an adequate "quality" of service of around 25s.
3. Conventional shuttle lifts would need to be employed in groups of six or more to address the need for adequate "quality" of service.
4. MMLS can give us the same handling capacity whether the destination is 60, 600 or 1200m above ground.
5. MMLS has no requirement for high speed and, in point of fact, speed will only influence journey time.
6. For destinations involving hotels and/or residential facilities the conventional solution loses handling capacity since time needs to be added for passengers boarding and alighting the cars to travel in the opposite direction albeit at lower flow rates.
7. MMLS has equally high handling capacity in both directions with no degradation in 5-minute handling capacity.
8. MMLS also offers the prospect of finally being able to interconnect between multiple sky lobbies and give the user a seamless and direct route to all key facilities in the building.

3 A 1,000M TALL BUILDING

In 2016 the author embarked upon an ambitious project to look at the potential lift solution for a 250 floor multi-use building standing 1,000m tall.

The purpose of the exercise was to verify if MMLS could provide the building and the design team with a commercially viable solution that would mean that there was a real payback or "Return on Investment" for even the uppermost floors of this proposed 1,000m tall building.

The vertical city proposed would contain everything needed for day to day living, working and leisure activities including:

- Apartments and "villas"
- Office space in various formats with marketing suites, exhibition halls, lecture theatres, meeting rooms and business centres
- Hotels
- Leisure facilities including theatre, cinemas, night clubs, piano bars, pubs, restaurants, museum, 10 pin bowling, fitness centres, spas, gyms and yoga retreats

- Healthcare facilities including GP facilities, dentists, chiropractors, physiotherapists, counselling and day surgery facilities.

The scale of the building would represent a small town of around 32,000 people. It is perhaps of interest to note, as regards the proposed stacking of the various uses and tenancies, that MMLS enables us to “break the rules” of the past with there no longer being the necessity to place the most densely populated floors at the base of the building.

We know that we cannot realistically expect building users to take more than two lifts to travel from the building entrance to any floor in the building. It should be noted, however, that this may not be the case with inter-floor travel since the building user may need to access a sky lobby (one lift journey) then make an inter sky lobby journey (second lift journey) and, finally, a last local lift journey to their ultimate destination.

By arranging, nominally, five 50 floor zones (all stacked one on top of each other) we have a 250 floor building with four upper sky lobbies with a nominal 4m floor to floor distance throughout. Then, by choosing 50 floor zones we know we can organize direct service to any floor from the sky lobby and not need intermediate sky lobbies within the 50 floor zones that, for now, could be all be served by conventional lifts. All floor plates assumed to be 2,500 sq m Net Internal Area.

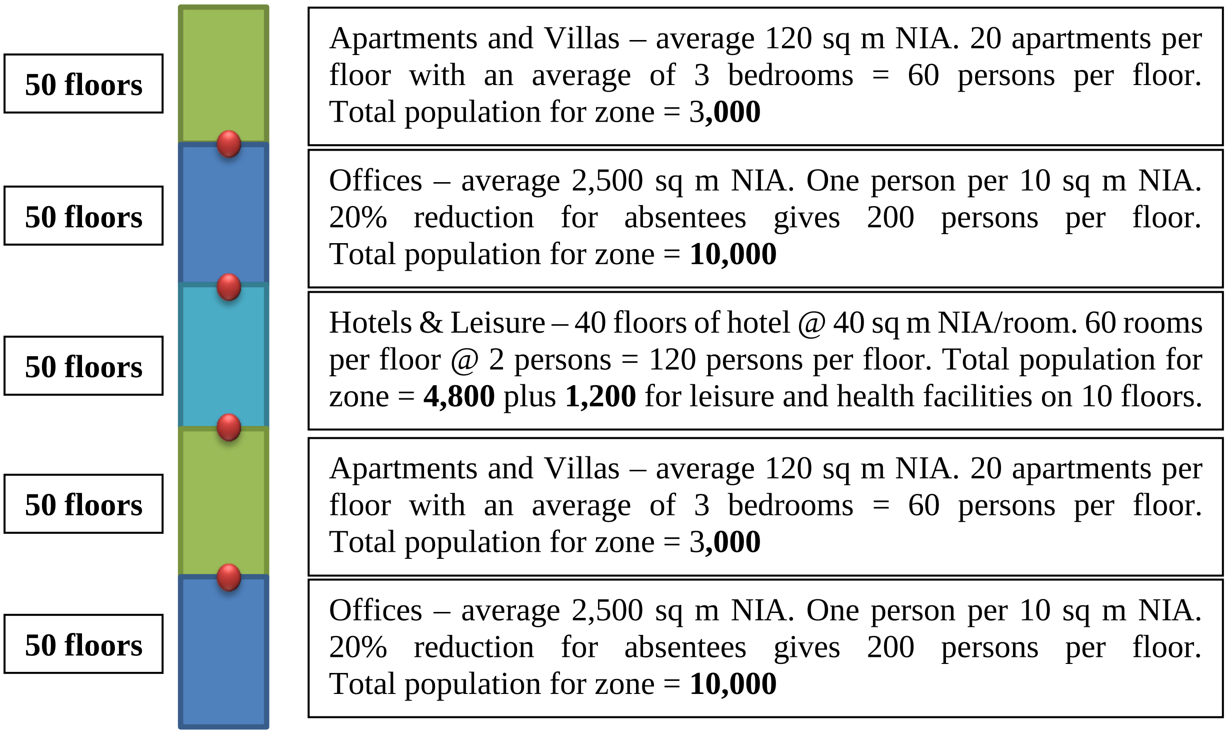

Figure 1 Stacking Use of 1,000m Tall Building

The above shows the notional uses of each sector of the 250 floor building. The idea of delivering 10,000 office users to a sky lobby 600m above ground would be extremely difficult with a conventional lift solution because, as was previously noted, if we wanted a 14% 5-minute handling capacity of 1,400 persons we would need 1400/63 = 22 lift shafts for sky lobby shuttles alone!

4 INITIAL TRAFFIC ANALYSIS

During the typical morning peak the demand for both “up” and “down” lift service in the building could, perhaps, be summarized as follows:

Type of Use	5-Minute "Up" Demand	5-Minute "Down" Demand
Offices	14% x 10,000 = 1,400	
Hotel and Leisure	6% x 6,000 = 360 *	6% x 6,000 = 360
Residential	5% x 6,000 = 300 *	5% x 6,000 = 300

* Likely to be limited "up" demand during morning "up peak".

Table 1 Aggregate Demand for Shuttle Lift Service

Based upon the above we have a theoretical 5-minute "up peak" passenger demand of approximately 2,060 persons but for the hotel and residential sector this is likely to be limited as peak demand for "up" traffic will be in the evening when the office workers are leaving the building.

One MMLS system (comprising two shafts) we indicated earlier would have an approximate handling capacity of 228 persons. Therefore, in aggregate, if we say we require approximately 1,400 plus 400 for the other uses we would need 1,800/228 = 8 systems i.e. 16 shafts for the entire upper building population above the first 50 floors.

5 CIRCULATION CONSIDERATIONS

We know our theoretical traffic simulations and calculations are based upon 5-minute passenger flow rates approximately double the "real world" maximum passenger throughput i.e. 12% plus versus around 6% or so measured in the peak 5 minutes in office buildings.

Planning of circulation spaces and security turnstiles etc is for the most part related to "real world" peak passenger throughput and circulation planning guidance provided by, for example, the CIBSE Guide D 2015.

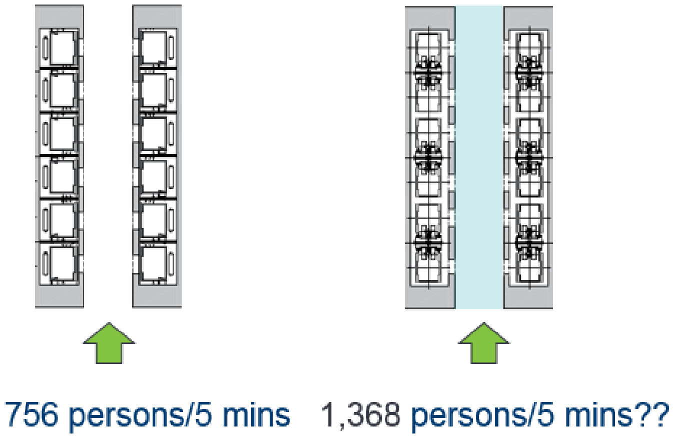

Figure 2 Comparison of Potential Passenger Flow Rates

Conventional System (left) versus MMLS (right)

If we consider we have, on the left in Figure 2, two conventional groups of six shuttle lifts each having an average interval of 30s we know that the theoretical handling capacity equates to approximately 378 passengers per 5 minutes per group per deck. Since "real world" passenger throughput is about half this we can approximate the passenger flow into this lobby space to 189 passengers per 5 minutes. Indeed this flow rate would best be arranged as 95 persons into the lobby at each end.

In Figure 2, on the right, there are six MMLS in one lobby each having a theoretical handling capacity of 228 passengers per 5 minutes then this equates to 1,368 passengers per 5 minutes. The "real world" passenger throughput is about half this so it would equate to 684pax per 5 minutes.

We can see that the lobby throughput is 95/300 = 0.32 persons per second for the conventional system. CIBSE Guide D 2015 page 2-2, section 2.5.1 indicates a maximum throughput for a corridor = vDW. Assuming 1.0m/s pedestrian speed and a density of 1.4 persons per square metre gives a maximum throughput in a 3.2m wide corridor = 1.0 x 1.4 x 3.2 = 4.48 persons/s. Even though the MMLS will see a 180% higher flow rate there may still be enough lobby width for circulation.

The reason, however, the typical lift lobby works is not because of the limitation on the width of the lobby for circulation but on its innate handling capacity and space to handle queueing and for passengers to be able to pass others waiting for lifts to arrive. Figure 3 indicates the comparative queuing in these two lobbies.

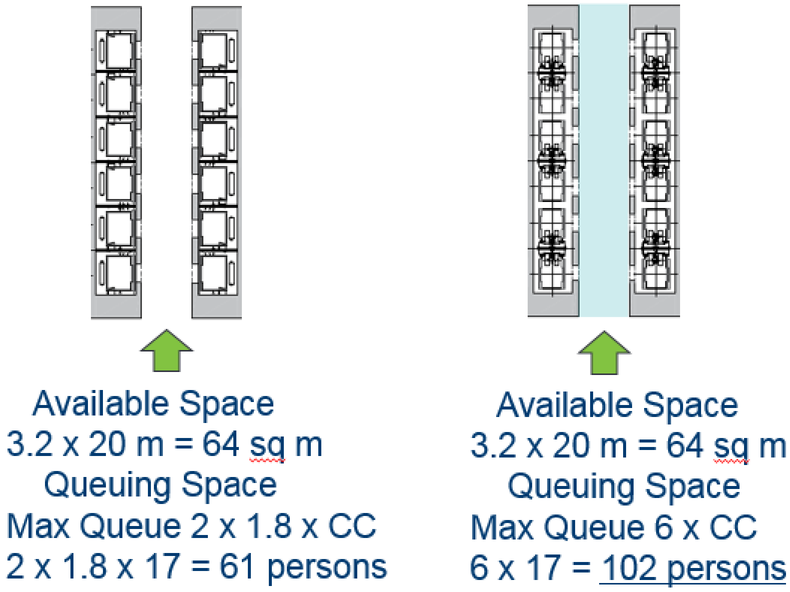

Figure 3 Comparison of Potential Queueing Space

Conventional System (left) versus MMLS (right)

Again, from a simplistic standpoint, the conventional system works as there is approximately the same amount of space in square metres as there are passengers waiting. The MMLS lift lobby is unlikely to be viable in terms of throughput and queuing combined since the lobby space would not even be able to contain the number of potential waiting passengers.

6 CORE PLANNING CONCEPTS

The largest local lift service requirement is for the 10,000 workers at the upper sky lobby and a basic design using double deck lifts would probably look like four groups of eight 1600kg capacity cars with a range of speeds. Again, representationally, shown as something like Figure 4.

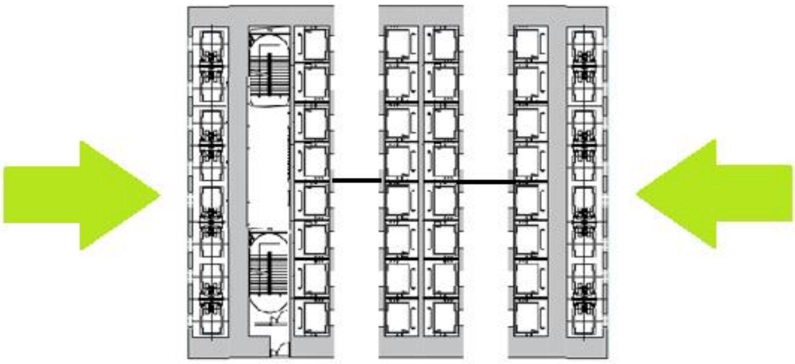

Figure 4 Local Double Deck Passenger Lift Service for 50 Office Floors with MMLS on Outer Sides of Core for Good Circulation

MMLS lobbies are placed to the outside of the core since they only need to stop at the sky lobbies every 50 floors.

The hotel, leisure and residential floors do not require as many local lifts and will easily fit into the space shown above for the local office lifts.

In order to make the circulation and "quality" of service criteria work well it is proposed to use multiple main floor levels for boarding and alighting of all tower users at the main lobby.

Indeed it would probably be useful to consider using an entry floor and an exit floor or entry and exit lobbies on the same floor or on alternative floors to avoid conflicts of circulation with such large flows of intending passengers arriving and others departing from the building.

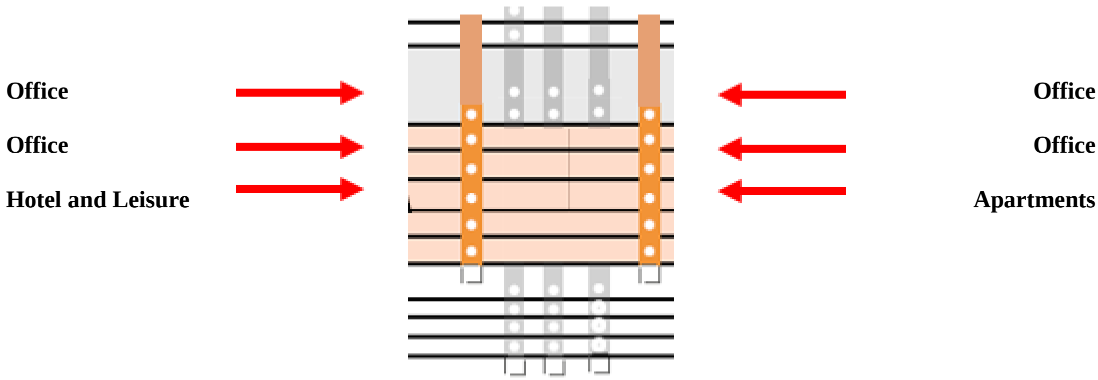

Figure 5 MMLS and "Through" Cars enable Multiple Lobbies to be Generated at the Base of the Building

Another interesting feature of this arrangement is that, dependent upon demand, MMLS cars can be diverted to service the relevant lobby and user group very easily. The building shuttle system is no longer constricted to serving one use in the building. This flexibility is important for a multi-use tower where fluctuations in visitor numbers and peak traffic demands for each tenancy could vary throughout the day.

At the main floor six out of eight of the MMLS would be notionally assigned to moving office workers. These can be arranged such that office workers are split by destination floors into two, three or even four stacked main lobbies on opposite sides of the core. On the floor below can be located the hotel/leisure and residential lobbies. Since each system can exhibit an average interval of around 25s then provided users are split up by destination to enter the correct lobby the requisite handling capacity and average intervals can be delivered. This can include signage to groups or zones of upper floors and the ability to place users travelling to "odd" floors in a different main floor lobby to those travelling to "even" floors. In this way users arrive at the correct upper main floor to board the local double decks directly without the need to move between upper floors using escalators.

7. OVERVIEW OF CORE EFFICIENCY

The core in figure 4 will take up approximately 309 x 24m in plan area = 720 sq m. The net area for each floor plate is 2500 sq m. Therefore in relative terms the gross floor space is approximately 3,220 sq m. This gives an approximate notional net/gross figure of 78% which would be impossible to achieve with conventional lift systems as we have today.

Within the hotel, leisure and residential areas it would be possible to introduce local atriums and reduce gross area. Also within the office zones, by careful design, additional floor area could be clawed back from the core as local lift groups drop off.

Not considered so far is the goods, logistics and waste strategy. On current mega tall buildings the author is advising to move towards shuttle and local goods/service lift arrangements. This is far more efficient than attempting to serve all floors directly from the basement which, in the case of a 1,000m building, would not in any event be possible. Pallet automation techniques are also being studied to "robotise" the solution and automate goods in and waste out movements enabling 24/7 use of the goods lift resource in the building. It is also envisaged that the vast majority of service personnel will use the MMLS system for their "back of house" movements around the building.

8. CONCLUSIONS

This paper has provided a simplistic broad brush overview of what the author believes are some of the essential considerations for the future deployment of MMLS within super and mega tall buildings.

Work is already underway with building traffic simulation capabilities for MMLS to emulate what we can do today for conventional lift systems and traffic analysis.

The author has concluded that MMLS will enable the building of highly efficient multi-use towers within the coming years that are, at last, economically viable.

This is an exciting proposition as building designers search for more sustainable high rise solutions for the buildings of tomorrow.

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BIOGRAPHICAL DETAILS

Adrian Godwin BSc DMS MCIM CEng MIET Chairman, Movvéo Lift Consultants, Woking, UK. adrian.godwin@movveo.com

After graduating with honours in Electrical Engineering & Electronics from Salford University and obtaining a Diploma in Management Studies from UMIST in the early 1980's Adrian worked first for General Electric Co., Hirst Research Centre, one of the UK's premier research laboratories and then for Lift Design Partnership founded by his father, Mike Godwin and Dr George Barney.

Upon his father retiring in 1987 he was responsible for merging LDP with Lerch Bates in 1990 and subsequently developed the firm to include five additional offices in Europe.

His particular areas of interest and expertise are in the development of "smart" elevator control systems, planning of elevator systems for tall, super tall and mega tall buildings and the development of lifts capable of running on a curve. Author of numerous papers and holder of a number of patents in the area of lift systems he has been involved in the design of the lift systems for some of the most prestigious tall buildings in the world working with high profile architects including Norman Foster, Rem Koolhaas and Renzo Piano to produce buildings such as the Shard, the Central China TV HQ building in Beijing and the 90 floor Burj Mohammed bin Rashid Tower in Abu Dhabi. All three buildings winning "Best Building" awards from the CTBUH.

In recent years he has been involved with the first ever application of "destination hall call" control to double deck lifts within the Broadgate and Heron Bishopsgate Towers in the City of London as well as the Shard. He has also been working on the application of linear motors to lifts (a family preoccupation) and is actively engaged in looking at the potential of this technology to solve the challenges of mega tall buildings of the future.

After developing a "world leading" expert system for lift design named AdSimulo he is now exploring new techniques to make vertical transportation in high rise buildings more effective and efficient. Finally, after "demerging" with Lerch Bates in 2014 and rebranding as Movvéo, after more than 30 years, he still heads up the award-winning consultancy founded by his father and Dr Barney.

Analysis of New Lift Typology with Visual Stimulation of Passengers

Aleksey A. Gorilovsky[1], Dmitry A. Gorilovsky[2]

[1] Twisden Works, Twisden Road, London
NW5 1DN, UK, ag@LiftEye.co.uk
[2] Twisden Works, Twisden Road, London
NW5 1DN, UK, mit@LiftEye.co.uk

Keywords: lift car position indicator, virtual lift window, augmented reality

Abstract. For years, lift cars were more like closed transportation boxes than elements of architectural experience. The lack of visual stimulation encountered in a conventional lift became an awkward interruption to the otherwise enriching experience offered by the architecture of public buildings. A glass-walled lift car provides an ideal solution to that disruption, but is not feasible in most instances and often entails extra costs. As a result, the lift level indicator, supplemented in some advanced cases with cartoons, has become the standard tool used to inform passengers of their current position. A lifelike virtual lift window system, designed to transform passenger experience, was released four years ago and gradually found a niche in sophisticated lifts for upscale buildings. The technology relies on the precise calculation of every pixel and offers a real-time picture of the outside view combined with augmented reality and contextual information. Modern trends of visualization employed in lift cars, including virtual windows, vary in degrees of image quality, positioning accuracy, and lag. In times when 'architecture at its best is coming up with something that is pure fiction', we have in our possession a tool that is already embedded in the vertical transportation cabin. There is a sound advertising potential, more humanized typology of lift design, and almost universal navigation tool for visitors of public buildings. Further prospects of employing that technology in forthcoming multidimensional lifts as well as in conventional lifts are shown in terms of technical feasibility, costs and outcome.

1 INTRODUCTION

Thanks to recent dramatic progress in design and manufacturing of widescreen displays, we now see widespread implementation of said screens in lift cars. We shall refer to these large flat screens installed inside elevator cars as 'virtual windows'[1]. This type of installation enables visual stimulation of passengers by offering entertainment content, advertisement videos, emergency announcements, news feed and, last but not the least, navigation cues.

Well-known showcase boxes, which still may be found in some hotel lifts, became the early predecessors of virtual windows, while small-size displays built into the operating panels were their immediate precursors.

2 LIFTS WITH VISUAL STIMULATION OF PASSENGERS

As mentioned above, virtual windows have been installed numerous times, and are rapidly spreading across the globe. Fascinating new installations have recently appeared in the UK, US, EU, China, Republic of Korea, Japan, Malaysia and many other countries.

We believe that numerous examples of virtual window-equipped lift cars constitute a new, separate

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[1] Please note, that there is an alternative term *'lifteye'*, introduced by AFAG Messen und Ausstellungen GmbH for the category of products, related to *real time* lift virtual windows [1, 2]

lift typology where the visual stimulation of passengers is a primary distinction.

To compare known cases of virtual windows, see this 3-dimensional diagram (Fig. 1) with the following axes: 'Actual Environment reflection degree' (x), 'Adjustment to the Height Position' (representing adjustment of the viewer or lift car height position to the performed perspective) (y), and 'Time Lag 1/τ' (z). Someone may find out there various cases from still pattern/picture on lift car wall or just painted one to animated cartoon, fictional environment displayed on walls (or ceiling) and up to live, real time virtual window wall / car door.

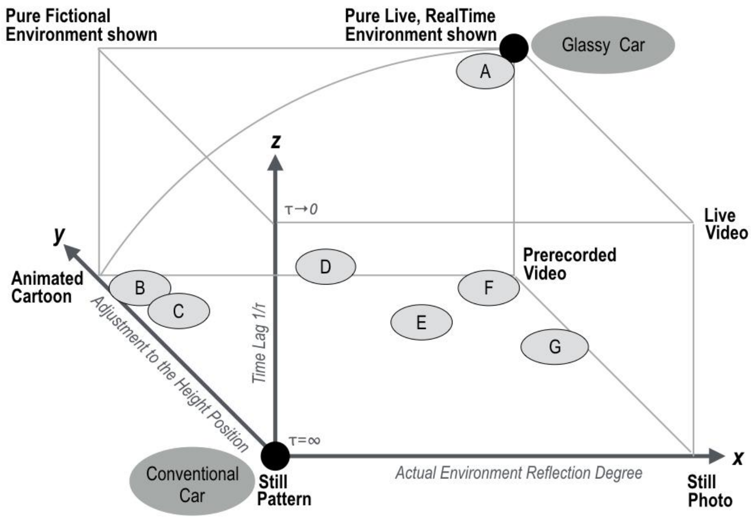

Figure 1. 'Virtual Window Box': 3-dimensional diagram of virtual window utilization cases in lift car.

Prerecorded and fictional movies and mixed cases, released in The Shard, London (C); 1WTC Tower, New York City (D); Lotte World Tower, Seoul (E); Petronas Towers, Kuala Lumpur (F); Tour Montparnasse, Paris (G) [3] and real time virtual window, Augsburg and London (A)

Please note that the location of the Conventional Car with non-transparent walls ('Still Pattern') and the panoramic 'Glassy Car' can be easily found on the diagram - see the gray ovals. The glassy car represents the case, in which a lift passenger can view the actual environment with a correct perspective and in real time ($\tau = 0$). The visual stimulation in the glassy car seems almost perfect.

The obvious disadvantage of panoramic lifts is their limited feasibility due to structural issues and thus relatively high associated costs. Those limitations force the developers to opt for video walls and ceilings in lift cars (Fig. 2, 3) paired with non-real-time content.

The absolute majority of known virtual windows offer zero to little reflection of the outside reality. On the chart, these installations remain close to the x-axis. In most cases, the performance of those virtual windows depends on the actual position of the car (y-axis); therefore, all of these cases tend to belong the horizontal ($\tau = \infty$) surface of the diagram. In other words, the content of those virtual windows (or ceilings) does not reflect the outside world.

We believe that those virtual windows ('B' to 'G') are adequate for one-time visitors, but not for residents. It is hard to believe that someone will enjoy the same content when viewed over and over again. That was our primary challenge.

Figure 2. A case of *fictional content* virtual window installation, New York City.

Nine HD screens installed in lift car (3 displays on each car wall). Content shown corresponds to actual position of lift car. Released in May 2015.

Figure 3. A case of *fictional content* virtual window installation, London.

9 flat displays installed in the lift car ceiling [4]

The natural answer is to offer a live, real-time picture ($\tau \rightarrow 0$). One possible solution is described in US patent 9,571,798 (Fig. 4). The proposed device renders a real-time, live image, with the correct height perspective. A working prototype of that device, with one wide HD display was introduced in October 2013 in Augsburg, Germany (Fig. 5) [5, 6]. To provide the real-time feed, only two HD cameras were utilized. They were mounted on the outer wall of the building with the lift as shown.

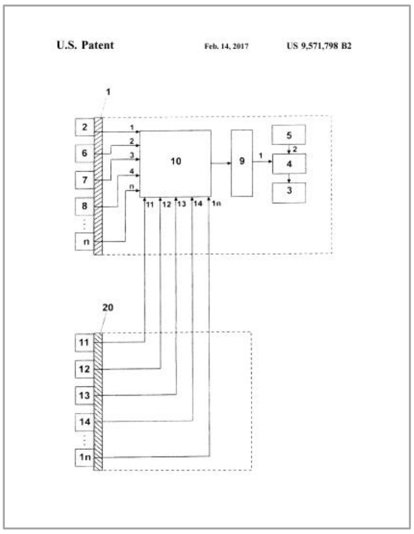

Figure 4. Device for displaying the situation outside a building with a lift.
US Patent 9,571,798

1- outer wall of building with lift; 2, … n - cameras; 5 - precise lift car height sensor; 3 - display, installed in lift car; 20 - outer wall of distant building.

Figure 5. Case of live, real time virtual window: one of two HD cameras mounted on building façade (left) and HD LED display mounted on rear wall of lift (right). Augsburg, 2013

When a real-time feed becomes available from cameras set in other locations, it becomes possible to switch the image to that feed. This feature might be attractive for hotel chain operators, office building of large international corporations and in some other cases.

On the diagram (Fig. 1), a live, real-time virtual window is marked ‘A’. It is very close to the ‘Glassy Car’ point. The proximity of ‘A’ to ‘Glassy Car’ is limited by the time it takes to process the real-time image feed, and may be further affected by the lag in the communication channel between the main building and the distance source.

The basic requirement for the software is to exclude delays in computing the vertical position, especially during accelerations and decelerations, in order to prevent motion sickness.

The ability to render virtual window pictures in high resolution is paramount. The feedback from the 2013 Augsburg installation confirmed that passengers, being so close to the walls, didn't find Full HD / 1080p (1920x1080) displays comfortable due to the relatively large size of the display pixels.

Ultra-high-definition, or UHD-1 / 2160p (3840x2160) displays are preferable in this case. The overall cost of the system is higher due to the higher price of UHD cameras and higher computational requirements (both hardware and software).

The temporary installation of UHD real-time virtual window (Fig. 6, 7) in London (May 2015) became a trial of UHD cameras, software and display as a set [7].

Figure 6. A case of *real time* virtual window installation, London.

The temporary installation of *real time* virtual window in car lift with an outside view of the building (left) and from distant location (right). The displayed view corresponds to the actual position of the lift car, as measured by height sensor. Perspective is smoothly altered as the lift ascends or descends, giving an entirely realistic sense of place and time for passengers.

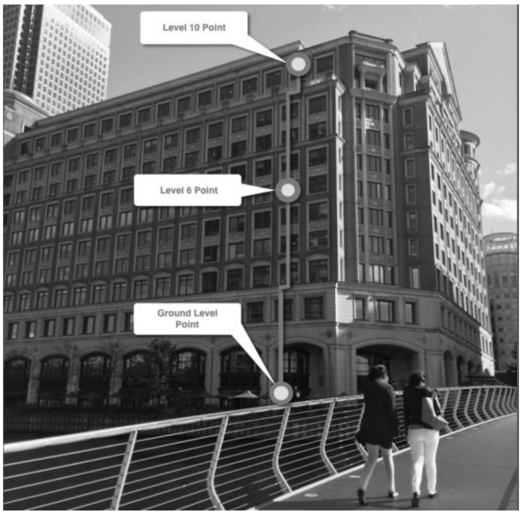

Figure 7. A case of *real time* virtual window installation, London.

Three cameras are mounted (as shown) along a vertical line on the outer wall of the building to provide an ultra-high-definition real time feed for display in the lift car.

The most important specifications of the virtual window are: the thickness of the display, its weight, its power consumption and heat emission, and its ability to withstand impacts and scratches. The latest generation OLED (organic light emitting diode) displays come as thin as 2.57 mm [8], and the weight of the assembly has reduced dramatically as well. These improvements provide more flexibility to cabin designers. Ion exchange-hardened glass has become an industry standard over recent years, and this type of glass finally delivers scratch and crack resistance sufficient for virtual windows. In certain specific cases, an additional translucent protective layer may be required to protect displays in high-traffic areas.

One specific shape of a real-time virtual window is a lift car door (Fig. 8). It is equipped with four wide UHD displays [9]. The door is declared compatible with EN81-20 and suitable for new lifts as well as for replacement of car doors of any brand.

Figure 8. A case of *real time* virtual window as an integral part of car door.

A working prototype of the door with four UHD displays was inaugurated in Augsburg, Germany in October 2015

We believe that a real-time virtual window car door is a good solution for lifts where passengers ride frequently or even daily. It is well known that most of them tend to face the car door, rather than walls, during their trips. This is true even for panoramic lifts.

3 CONSTRAINS

We've learned that privacy issues in many countries may prevent installation of real-time virtual windows in any form, and therefore specific measures as blurring of human faces and car license plates should be taken.

Data channel capacity limitations between the lift and a distant location, from where the real-time feed has to be transmitted, may dramatically reduce the overall performance of real-time virtual windows. Some quasi-real-time solutions are known and may be adequately employed.

4 FURTHER PROSPECTS

We believe that virtual windows and real-time image feeds will prove to be a prime navigation tool for future lifts with linear motors which move people vertically and horizontally.

What will the virtual windows in lifts stream tomorrow? Pure fiction, real-time, or some mixture of both - we'll have to wait and see. In any case, the new lift typology is already becoming an essential part of the architecture, which 'at its best is coming up with something that is pure fiction' [10].

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BIOGRAPHICAL DETAILS

Aleskey Gorilovsky has been CEO of LiftEye Ltd since 2013. An electromechanical engineer by training then specialized in precise torque drives and has extended experience in academic field. He also studied in LSE and got EMBA from SSE. Entered lift business in 1993. He set up his own lift company in 1997 and rapidly run it to the leading position in upscale segment in the territory providing full service for world famous hotel chain operators, retail and offices. He has been granted with patents for tall building lifts.

Dmitry Gorilovsky has been Chief Innovation Officer of LiftEye Ltd since 2013. Dmitry graduated from ITMO University of St. Petersburg. He is a product and solutions innovator with extensive experience in the mobile and IT industry and is currently focused on enabling complex technologies with simple human interfaces. Dmitry has been awarded numerous patents, some of which are for tall building lifts.

Lift Traffic Analysis 1890-1960

Lee E. Gray

College of Arts + Architecture
University of North Carolina at Charlotte
Charlotte, North Carolina USA 28223
Legray@uncc.edu

Keywords: History, Lift Traffic Analysis

Abstract. A survey of recent literature on lift traffic analysis reveals that only one pre-1950 source is referenced in this body of work: "The Probable Number of Stops Made by an Elevator," Bassett Jones, *General Electric Review*, August 1923. Although this investigation included a survey of Elevcon papers from 1986 to 2014, and thus had an international scope, a detailed search for non-English articles was not undertaken as part of this research.

While the number of works that include Jones' 1923 article in their bibliography highlights the significance of this article, the fact that only one source is referenced from the period from 1890 to 1960 prompts the following questions. 1.) What was the intellectual context for Jones' work? And, 2.) Were there others who sought to establish a mathematical basis for determining lift traffic needs?

This paper will examine the history of lift traffic analysis from 1890 to 1960 and will chronicle the initial development and articulation of quantified criteria and mathematical formulas designed for determining the proper number of lifts and required traffic flow. The early history of this subject defines the foundation for contemporary work as well as serving as a reminder that, while many things have changed (often dramatically) since the first half of the 20th century, others appear (perhaps surprisingly) to have remained the same.

1 INTRODUCTION

This investigation uncovered a surprising wealth of material related to this topic. The related subjects of the proper number of lifts for a given building and their associated traffic metrics were common topics of discussion from 1890 to 1960. However, while this subject matter was occasionally the topic of dedicated works, it was more often found imbedded in general works on lift design and engineering. Finding this material required using a variety of searches through various online databases (including Google Books) and surveying lift books from this period. The following paper (in spite of its length) represents an edited view of the material discovered during this investigation. The works discussed below represent an effort to trace the primary ideas developed during this period. However, as with many research efforts, this paper should be considered the foundation upon which a more comprehensive work may be constructed.

2 1890 - 1899

A critical characteristic of the history of lift traffic analysis between 1890 and 1960 is the presence of lift operators and starters. The fact that lift operation, from doors to traffic scheduling, was directly controlled by people – in real time – distinguishes this period from the present day. Thus, the challenge faced by lift engineers included predicting passenger behavior as well as the behavior of lift system operators. The gradual emergence of metrics and formulas that serve as the foundation for modern lift traffic analysis occurred against this human backdrop.

By 1890 architects and engineers, building owners and users, and the lift industry were all well aware of the importance of providing good lift service to commercial buildings. The normative method of operation was to run the lifts on a predetermined schedule or interval of service. The common approach was to have the lifts depart from the ground floor at set intervals, travel to the top of the building – regardless of the need to drop off or acquire passengers at the top floor – and then return to the ground floor. This ensured a consistent flow of lifts throughout the building. Typical intervals in the 1890s ranged from 30 to 45 seconds, depending on the size of the building. Large buildings typically employed “Starters,” who were charged with directing the lift operators’ actions and ensuring that an adequate traffic flow was maintained.

The need for the constant presence of moving lifts was due, in part, to the lack of adequate signaling systems that allowed waiting passengers to summon cars. In the beginning it was not uncommon for passengers to simply stand adjacent to a shaft and call (quite loudly) “up” or “down” to alert the lift operator to the need to stop. The first hall call buttons and in-car indicators alerted the operator of a waiting passenger and their desired direction of travel, however these systems provided this information while the car was moving, such that the alert came – in theory – with just enough warning that the operator could stop their car at the required floor.

While the operation of lifts on a set schedule was believed to offer the best service, it did not constitute a basis for determining how many lifts a given building required. By 1890 the importance of the lift’s “round trip time” was known and was defined as dependent on the “number of stops for receiving and discharging passenger and (the) car speed” [1]. Lift traffic was divided into two categories: local (also referred to as “way” or “accommodation”) and express service. The impact of car size and configuration was also recognized, with a suggested maximum area of 49 sq. ft., with the preferred plan being wide and narrow with the door as wide as possible [1]. Finally, one of the first “rules of thumb” stated that the “number of elevators is proportionate to the cubic contents of a building” [1].

In 1893 engineer George Hill gathered one of the first data sets on lift operation. He surveyed twenty buildings in New York City and collected information on: 1.) the number of stories served, 2.) the number of lifts, 3.) the number of offices, 4.) the interval between trips, 5.) the working speed (recognized as distinct from contract speed), and 6.) the car size and the number of passengers carried [2]. Hill’s examination of the data led him to a series of “independent observations”: 1) that an elevator car travels from one-third to one-eighth of the time, 2.) the time spent in traveling increases with the number of stories served, 3.) the time spent in traveling decreases with the increase in the number of offices on a floor, and 4.) the time that the elevators are not running will thus be seen to fix the number, as well as the size and the speed [2]. Hill claimed that he had attempted to “reduce the results” of his investigation “to some uniform law,” however this proved to be “very difficult, as the service in each building depends upon the class of tenants” [2].

3 1900 - 1909

The first decade of the twentieth century saw the first attempts to derive Hill’s hoped for uniform law for determining lift needs. In 1901 consulting engineer Charles G. Darrach (1846-1927) proposed the first formula to determine lift service where a = car area in sq. ft., A = office area in sq. ft., and T = total trips per hour (Eq. 1) [3]. Darrach had also gathered information from existing

$$a = \frac{A}{T \times 22} \qquad (1)$$

buildings and, in addition to his formula, he published the first lift data tables for existing buildings. These tables included the number of stories, office area above the first floor, number of lift cars, building sq. ft. served per car, car area, trips per hour and average operating speed. Table 1 represents one of Darrach's tables. His formula and data tables were reprinted in two editions of

Table 1 Darrach, Lift Data (1901)

	Stories	Office area above first floor	No. of cars	Building sq. ft. served per car	Area of car sq. ft.
St. Paul Building, New York	25	83,200	6	13,900	23.6
Empire Building, New York	21	150,000	10	15,000	42
North American Building, Philadelphia	18	90,500	5	18,100	27.6
Real Estate Trust Building, Philadelphia	17	155,650	10	15,560	23.7
Bowling Green Building, New York	16	222,000	9	24,700	…
Land Title Trust Building, Philadelphia	15	66,400	5	13,300	29.6
Stephen Girard Building, Philadelphia	13	67,000	4	16,750	29
Drexel Building, Philadelphia	10	180,000	6	21,700	21.4

Frank E. Kidder's *The Architect's and Builder's Pocket* (1904 and 1908) [4]. Interestingly, both editions also included an additional data set provided by Otis engineer Charles H. Kloman (Table 2). Kloman apparently also provided insights into Otis' approach to lift traffic, as Kidder reported

Table 2 Kloman, Lift Data (1904)

Building	No. of Elevators	No. of Floors	Total Floor Area	Floor area per Elevator
Broad Exchange Building	18	20	465,540	25,864
Empire Building	10	20	170,000	17,000
Park Row Building	10	25	315,000	31,500
Bank of Commerce Building	7	19	172,000	24,571
Atlantic Mutual Building	6	18	162,000	27,000
S.E. Cor. Broadway & Maiden Lane	6	18	129,000	21,500
American Exchange Bank Building	3	16	72,000	24,000

that: "the officers of the Otis Elevator Co. have come to the conclusion that the best service is obtained with a large number of small cars having a capacity of not over 15 passengers, rather than with fewer large cars" [4].

The key figure in this decade was engineer Reginald P. Bolton (1856-1942). In addition to publishing numerous articles on lift engineering and traffic design, in 1908 he published the first book devoted to this subject: *Elevator Service: Operating Conditions and Proportions, with diagrams, formulas, and tables for passenger travel, schedule and express operation, with the relation of the elevators to the building, and proportions and loads of cars*. Bolton divided his subject into nine chapters: "The Problem of Vertical Transportation," "Operating Conditions," "Passengers and Operators," "Rating the Work of the Elevator," "Computing the Average Work," "Express Service," "The Shape and Size of the Car," "Load and Speed Combinations," and "The Building and its Proportionate Service." He also provided a glossary of 36 lift terms as well as a variety of charts, tables and diagrams that illustrated his topic. Like his predecessors, Bolton's work was based on an analysis of data collected from existing buildings (Table 3).

Table 3 Reginald P. Bolton, Lift Data (1908)

SCHEDULE INTERVALS			
In existing buildings in New York City			
Expresses			
Floors	Net Area per Floor	Number of Cars	Schedule (seconds)
10 - 19	17,000	9	17
11 - 20	12,000	6	25
10 - 19	8,750	5	30
13 - 25	5,000	4	34
11 - 18	6,800	3	45
Locals Combined With Express			
10	17,000	9	17
10	10,900	6	15
10	8,750	5	24
10	6,850	5	24
13	5,300	4	22.5
14	6,700	3	40
Locals Only			
25	7,600	10	18
24	4,375	6	26.5
19	3,500	5	27.6

The unique aspects of his efforts included a diagram depicting the normative lift traffic pattern found in a typical office building (Fig. 1) and a series of formulas intended for use in traffic analysis. The formulas used a series of variables that addressed a wide range of lift operation attributes (Table 3). His formulas were predicated on a decidedly idiosyncratic constant derived from his observations of lift traffic, which he labeled the "Bolton Rating." This term defined a lift's "mean work," or the typical number passengers carried per trip, as 0.4 of the number floors served by a lift [5]. He also derived a series of constants from his observations of lift traffic (Tables 4 & 5).

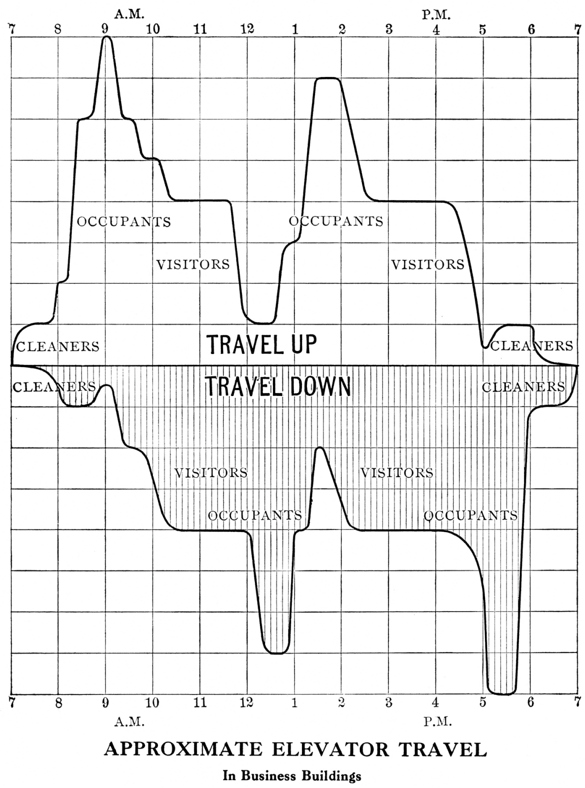

Figure 1 Bolton, Typical Office Building Lift Traffic Pattern (1908)

Table 3 Reginald P. Bolton, Formula Variables (1908)

A	Occupied area per floor of the building in square feet.
a	Occupied area per elevator, in square feet.
c	Occupied area per car per floor in square feet.
o	Occupied area per passenger or occupant in square feet.
n	Number of elevators.
f	Floors served by the elevator, always above the ground floor.
t	Traveling time, or time occupied by the motion of the car, in minutes.
l	Loading and unloading time in minutes.
s	Mean speed between average landings in feet per second.
i	Schedule or interval between starts of the elevator.
r	Round-trip time of a local elevator in minutes.
e	Floors run past by an express elevator.
d	Time of the express distance in minutes.
R	Total round-trip time of an express elevator, in minutes.
p	Passengers per hour, in each direction.
h	Total height of the local floors served, in feet.

Table 4 Bolton, Lift Formula Constants (1908)

Average distance between landings	24 feet
Number of landings	.4(total number of floors up and down)
Time per landing (door handling, etc.)	5 seconds
Time per passenger to enter and exit	2 seconds
Time per visit to top floor & gate handling at ground floor	9 seconds

Table 5 Bolton, Lift Formula Constants (1908)

Nominal Speed (feet/minute)	600	500	400	300
Mean Speed (feet/minute)	440	380	320	260
Mean Speed (feet/second)	7.33	6.33	5.33	4.33

His equation to determine round trip time (calculated for a number of different operating speeds) reveals his general approach to deriving his formulas (Eq. 2). Bolton, however, did not explain the

600 ft./min. $r = (f \times .1345) + .15$ (2)

500 ft./min. $r = (f \times .1432) + .15$ (2)

400 ft./min. $r = (f \times .1550) + .15$ (2)

300 ft./min. $r = (f \times .1723) + .15$ (2)

origin of the constants used in these formulas. An analysis of Bolton's approach reveals that the constant used in the bracket with *f* (the floors served by the elevator) was derived as follows: (Average distance between landings ÷ Mean Speed in feet/second) + .4(Time per landing + Time per passenger to enter and exit) + (Time per passenger to enter and exit at ground floor). This formula, when applied to the various lift speeds produced a constant that expressed the speed per floor in terms of feet per minute (Eq. 3).

600 ft./min. (24 ÷ 7.33) + .4(5 + 2) + 2 = 8.07 ft./sec. or 0.1345 ft./min. (3)

The .15 added to the end Eq. 2 was the 9 seconds, expressed in terms of minutes, allotted for the car's visit to the top floor and gate handling at ground floor. Thus, his formula attempted to account for the fact that most lifts did not operate at their contract speed, that they did not stop at every floor, and that the passengers' and elevator operators' actions were factors in determining the total lift operating speed. The summation of his work was a massive fold-out chart (placed at the back of his book) that allowed users to determine the number of express and local elevators needed for a given building to meet a desired interval of service.[1]

Although Bolton's book was the subject of numerous reviews, it is difficult to gauge its actual influence, particularly because it was self-published and thus it is impossible to determine its distribution or marketing.

4 1910 - 1919

The drive to gather data on lift use and develop formulas to calculate required lift service continued into the next decade. In 1912, commercial engineer Edmund F. Tweedy and electrical engineer Arthur Williams co-authored a book titled *Commercial Engineering for Central Stations*, which included a series of "papers," many of which had been previously published in *Power* and the *Electrical World*. The papers addressed a wide range of topics including coal heating systems, generating electricity, electrical power use, refrigeration and cooling systems, and "The Passenger Elevator in Office Buildings" [6]. Tweedy (1876-1949) authored the chapter of lifts, a fact that was revealed the following year when he published a revised version of his paper titled "Operating Characteristics of the Modern Passenger Elevator" [7].

Tweedy collected an impressive data set on lifts in 26 buildings in New York City that included: 1.) the net rentable area above the ground floor, 2.) the number of floors above the ground floor, 3.) the number of elevators (local and express) and the floors served, 4.) the car dimensions, 5.) the sq. ft. of rentable floor area per sq. ft. of car area, the lift rated capacity in lbs., 5.) the lift type (hydraulic, electric drum or electric traction), 6.) the electric lift motor rating, 7.) the average miles traveled per day (excluding Saturdays, Sundays and Holidays), 8.) the average round trip time in minutes, 9.) the average time interval in seconds, and 10.) the average speed (including stops) in ft. per minute). Tweedy also discovered that, in some cases, the lift system had been predicated on "furnishing transportation for all of the building occupants within a certain specified time of arrival, say within a period of 20 minutes or 30 minutes" [6].

While Tweedy did not use this data to develop lift design formulas, he followed Bolton's lead and developed a chart intended to meet this need: "Chart for determining the number and size of elevators required for office buildings of a given total occupied floor area" (Fig. 2) [6]. The chart allowed the user to select the time period in which to "move all building occupants in one direction" (20 or 30 minutes), the maximum round trip time, and car size. Interestingly, building size was given in terms of occupied floor area (20,000 to 180,00 sq. ft.) rather than building height. The chart could be used to determine local and express lift service, with each considered separately relative to the portion of the building served.

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[1] The chart, due to its size, does not lend itself to reproduction at a small scale. A large reproduction will be available at the symposium.

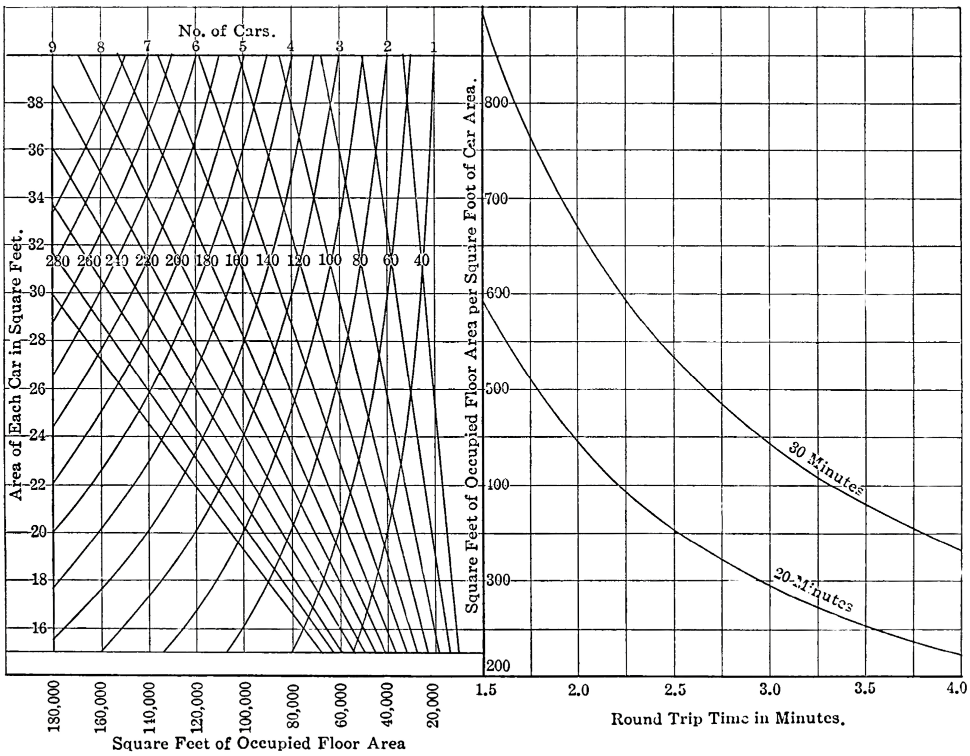

Fig. 2 Tweedy, Chart for determining the number and size of lifts (1913)

In 1914 M. William Ehrlich published a three-part article on lift systems. Although Ehrlich made no mention of Bolton's work, he was either aware of his work or, perhaps, had read a review of the book written by William H. Bryan. Bryan had suggested that the "Bolton Rating" – the mean work or typical passengers carried per trip was 0.4 of the number floors served by a given lift – would be more accurately expressed as 0.5 [8]. Ehrlich used the higher number in his formulas and also assumed that one lift should be allocated per 24,000 gross sq. ft. and, like Bolton, he employed numerous variables (Table 6).

Table 6 Ehrlich, Lift Formula Variables (1914)

E	Number of elevators required
A	Square feet of gross building area served
f	Story at which express run terminates
n	Total number of stories served
s	Speed of elevator in feet per minute
Tl	Local round trip time in minutes
Te	Express round trip time in minutes
Ml	Miles traveled per hour by local
Me	Miles traveled per hour by express
CI	Current consumed per hour by local in kilowatt hours
Ce	Current consumed per hour by express in kilowatt
pl	Passengers carried per hour by local one way up or
pe	Passengers carried per hour by express one way up or

Ehrlich's key formulas addressed round trip times for express and local lifts as well as the number of lifts required (Eq. 4 -6).

$$Te = \left(\frac{25}{s} + \frac{5}{100} \right) n \quad (4)$$

$$Tl = \left(\frac{25}{s} + \frac{1}{10} \right) n \quad (5)$$

$$E = \frac{A}{24,000} \quad (6)$$

He described Eq. 6 has having been "well substantiated" and "based on existing systems in the larger cities of the United States" [9]. He also noted that "the unit area of the elevator car and its traffic limitations have been included in the computation" [9]. Ehrlich offered no explanation for his various constants, however, he did provide a table that "embodied" their "computations" and that facilitated "the ready understanding of the various formulas" (Table 6) [9]. Ehrlich's formulas replaced Charles Darrach's in the 16th edition of Frank Kidder's *Architect's and Builder's Pocket-Book* [10]. However, two new formulas were added that were not included in his original article (Eq. 7 & 8). These were designed to find the number passengers carried one way, per hour by local (*pl*) or express (*pe*) lifts. Interestingly, Ehrlich's formulas were also featured in another general reference book, Gillette and Dana's *Handbook of Mechanical and Electrical Cost Data*, however in this work the passenger formulas were not included [11]. Kidder noted that information on lifts had been "furnished" by the Otis Elevator Company, the H.J. Reedy Company, Reginald P. Bolton, Charles E. Knox, M. William Ehrlich, and "others" [10]. The absence of the additional formulas in

Table 6 Ehrlich, Lift Data (1914)

1	2	3	4	5	6	7	8	9	10	11	12
Building		Number of Elevators Required					Round Trip Time in Minutes				*f*, or express run, in stories
Number of stories	Gross area, sq. ft.	Total car area, sq. ft.	Cars at 25 sq. ft.	Cars at 30 sq. ft.	Cars at 40 sq. ft.	By formula (1)	Tl at 350 ft. per min.	Tl at 500 ft. per min.	Te at 500 ft. per min.	Te at 600 ft. per min.	
8	80000	89	4	…	…	4	1.3	…	…	…	…
10	100000	111	4	…	…	4	1.7	…	…	…	…
12	120000	133	5	…	…	5	2	…	…	…	…
14	210000	262	11	9	…	9	2.4	2.1	…	…	…
16	240000	300	12	10	…	10	2.7	2.4	1.6	…	10
18	270000	337	14	11	…	11	…	2.7	1.8	…	11
20	300000	365	15	13	10	13	…	3	2	1.8	12
25	375000	577	…	19	15	16	…	…	2.5	2.3	15
30	800000	1221	…	40	30	33	…	…	3	2.7	17

$$pe = \frac{300}{Te} \quad (7)$$

$$pl = \frac{300}{Te} \quad (8)$$

Gillette and Dana's book, which was published two years after Kidder, suggests that they were, perhaps, devised by someone other than Ehlich. In spite of the presence of Erhlich's formula, Kidder cautioned readers that: "No iron clad rules can be given for all types of buildings, but the larger office buildings, loft buildings or light manufacturing buildings have been sufficiently regular in design to warrant some general rules, based upon experience; even in these cases, however, the governing conditions vary with the size of the building" [10].

Perhaps the most interesting attempt to devise lift formulas during this decade is found in Hermann Gumpel's 1916 article: "Mathematical Laws Governing Elevator Floor Capacity in Office Buildings From the View Points of Efficiency and Safety" [12]. Gumpel (1876-1929) was born in Lübeck and very likely received his engineering education in Germany. He immigrated to the United States in the early1900s, worked as a consulting mechanical engineer in Philadelphia and Chicago, and patented a double-deck elevator system in 1916. He authored a series of articles on lift traffic design in which he offered several lift formulas, which employed a number of variables, including the first that sought account for the impact of visitor traffic (Table 7).

His work paralleled earlier efforts in that he also failed to explain how he derived numerous constants, such as the allowance for visitors using elevators during rush hour (*b*). Gumpel proposed two primary formulas: the first was designed to estimate the number of lifts required – predicated on the desired interval of service (Eq. 9). He claimed that: "To arrive at satisfactory results in elevator traffic problems we have to consider maximum conditions only, as they occur during rush time in the early morning hours, before and after lunch time and late in the afternoon" [12]. Thus, his second formula (Eq. 10) was used to estimate the number lifts needed to meet a 20 to 30 minute period in which all building occupants could be moved in one direction. He assumed two sq. ft. per passenger, thus the car capacity was $F \div 2$.

Table 7 Gumpel, Lift Formula Variables, 1913

N	Number of cars in a battery of elevators
a	Interval of travel (30 to 50 seconds)
t	Round trip time in seconds during periods of maximum traffic, including time for landing and loading at the main floor
A	Rentable floor area to be served by the elevator battery
o	Rental area occupied by one person in a building expressed in sq. ft. (about 80 to 140 sq. ft.)
b	Allowance for visitors using elevators during rush hours (10 to 40)
F	Ground space of one car expressed in sq. ft.
T	Time in seconds during which all occupants of a building have to be moved either direction to or from their place of business (about 20 to 30 minutes).

$$N = \frac{t}{a} \tag{9}$$

$$T = \frac{F \times T}{2 \times t} \tag{10}$$

He then determined the total number of passengers (including visitors) to be served (Eq. 11), which allowed him to arrive at a formula that gave the number of cars required to move a building's occupants in a set time period (Eq. 12). Gumpel was equally interested in the use of lifts during

$$\frac{A}{o - b} \tag{11}$$

$$N = 2\frac{t \times A}{(o-b) \times T \times F} \tag{12}$$

emergencies, and imagined an evacuation plan whereby lifts would “ascend to a certain floor without stop, accept there as many passengers as possible, descend to the main floor and discharge there their human load. This will repeat, till all occupants of the building are removed” [12]. He devised a series of formulas, based on his primary formulas, to determine the number of lifts required to empty a building in a set time period. The various formulas addressed the number of occupants per floor (Eq. 13), the number passengers per car (in an emergency situation he assumed 1.75 sq. ft. per person) (Eq. 14), the number of trips required (Eq. 15), and the time required to remove all occupants from a given floor (Eq. 16). From these he derived a formula that allowed him to determine the total time required to empty all the floors served by a group of lifts (Eq. 17).

$$\text{Occupants per floor} = \frac{A_n}{o-b} \tag{13}$$

$$\text{Number of passengers per car in one trip} = \frac{F \times N}{1.75} \tag{14}$$

$$\text{Number of trips to remove all occupants from one floor} = \frac{A_n}{o-b} \div \frac{F \times N}{1.75} = \frac{1.75A_n}{(o-b) \times F \times N} \tag{15}$$

$$\text{Time required to remove all occupants from one floor} = \frac{1.75A_n}{(o-b) \times F \times N} \times t_n \tag{16}$$

Time required to empty all the floors served by a group of lifts =

$$\frac{1.75}{(o-b) \times F \times N}\left(A_n t_n + A_{n-1} t_{n-1} + A_{n-2} t_{n-2} + - - - - - - A_2 t_2 + A_1 t_1\right) \tag{17}$$

It is difficult to assess the impact of Gumpel’s efforts as they were not published in an engineering journal or the proceedings of an engineering society – they were published in *Buildings and Building Management*, which described itself as “the only magazine in existence dealing with building construction, building operation and management from the owners’ standpoint.” However, as will be seen, one of the most important early works on lift traffic also appeared in this publication.

5 1920 - 1929

At the 1920 annual meeting of the Elevator Manufacturers’ Association, Howard B. Cook (1888-1971), a young engineer associated with the Warner Elevator Company of Cincinnati, presented a paper titled “Passenger Elevator Service” [13]. This paper marked the first time a member of the lift industry offered a mathematical means of determining lift service. Cook used a number of constants that addressed a typical range of lift operation characteristics (Table 7). He also used a surprisingly small number of variables (Table 8). His formula to determine single trip time (Eq. 18) served as the basis for his formula to determine round trip time, in which Cook doubled the single trip time and added 10 seconds to account for the lift starting and stopping at the first floor (Eq. 19).

Table 7 Cook, Lift Formula Constants (1920)

Distance between floors	12 feet
Elevator speed	400 feet per minute (6.66 ft. per sec.)
Rate of acceleration and retardation	4 ft. per second per second
Average speed during period of acceleration or	3.33 feet per second
Time required for lift acceleration or	1.67 seconds
Time required to travel one floor at full speed	1.8 seconds
Number of stops	Equal to the number of passengers unless the number of passengers per trip exceeds the number of floors above the first floor
Upper floors: time required to open and close the car/shaft doors	3 seconds
First floor: time required to stop/start, open and close car/shaft doors, and to equalize the schedule between lifts due to traffic fluctuation	7 seconds
Time required for one passenger to enter or exit the car	3 seconds
Average total first floor time (passengers + start/stop time)	10 seconds

Table 8 Howard, Lift Formula Variables (1920)

R	Round Trip Time
F	Number of floors above first floor
P	Number of Passengers
T	Number of passengers carried per
E	Number of elevators

$$1.8F + 1.67P + 3P + 3P \quad \text{simplified to} \quad 1.8F + 7.67P \tag{18}$$

$$R = 2(1.8F + 7.67P) + 10 \quad \text{simplified to} \quad R = 3.6F + 15.34P + 10 \tag{19}$$

However, Cook stated that his round trip formula would not provide accurate results if the number of passengers per trip exceeded the number of floors above the first floor. To adjust for this situation Cook added 4 seconds to the round trip time for each additional passenger exceeding the number of floors. He did not, however, explain how he determined that 4 seconds was an appropriate adjustment nor did he explain how he derived the formula to determine the round trip time for this situation (Eq. 20).

$$R = 3.6F + 15.34F + 4(P - F) + 10 \quad \text{simplified to} \quad R = 14.94F + 4P + 10 \tag{20}$$

Cook apparently began with a baseline where the number of passengers equaled the number of floors ($P = F$), then he substituted F for P in Equation 19 and he expressed the need to account for additional passengers and their associated additional time as $4(P - F)$.

He next sought to determine the number of passengers carried per hour, which he stated was “equal to the number of round trips per hour multiplied by the number of passengers per trip” (Eq. 21) [13]. Cook then derived the value of P in terms of F and R from the round trip formula (Eq. 22), which allowed him to determine number of passengers carried per hour in each direction, in terms

$$T = \left(\frac{3600}{R}\right)P \quad (21)$$

$$P = \frac{R - 3.6F - 10}{15.34} \quad (22)$$

of the round trip time and the number of floors above the first floor when the passengers per trip did not exceed the number of floors (Eq. 23). He also generated a formula that accounted for when the number of passengers per trip exceeded the number of floors above the first floor (Eq. 24).

$$T = \frac{3600}{R} \times \frac{R - 3.6F - 10}{15.34} \quad \text{simplified to} \quad T = \frac{235(R - 3.6F - 10)}{R} \quad (23)$$

$$T = \frac{900(R - 14.94F - 10)}{R} \quad (24)$$

Cook stated that: "Good elevator service demands that the round trip time shall not be excessively long and there are rather well defined limits which should not be exceeded. The time spent by a passenger waiting for a car usually causes as much if not more uneasiness than the same time spent in reaching the top floor" [13]. He assumed a maximum round trip time of two minutes, which set a design limit for *R* (Eq. 25). In his final formulas Cook employed the maximum round trip time and

$$\frac{R}{2} + \frac{R}{E} = 120 \quad \text{modified as} \quad R = \frac{240E}{E + 2} \quad (25)$$

used the value of *R* from Equation 25 to provide a means of solving for *T* in both passenger load scenarios (Eq. 26 & 27). Cook also claimed that the maximum traffic volume occurred early in the morning, at noon, and in the evening, was generated solely by the building's occupants, and was "never" due to visitors [16].

$$T = 235 - \frac{235(3.6F + 10)(E + 2)}{240E} \quad (26)$$

$$T = 900 - \frac{900(14.94F + 10)(E + 2)}{240E} \quad (27)$$

Cook's paper was published by the Warner Elevator Company and also appeared as a three-part series in *Buildings and Building Management* [13 & 14]. He published an additional paper, on express lift service, in *Buildings and Building Management* in 1922, and published an article titled "Rates of Starting and Stopping Elevators and Their Effect on Service" in *Power* in 1926 [15, 16]. The latter article offered an interesting discussion of lift acceleration and deceleration speeds and their impact on passengers and service. He also addressed the challenges of accurately calculating these rates, noting that the "necessary assumptions render the results of doubtful value" [16]. Perhaps his most interesting observation regarding this subject was his statement that the traction lift "is, in fact, just a large example of an Atwood machine, widely used in physics for demonstrating the laws of motion" [16].

He concluded the article with a discussion of a "simple way to compute traveling time" [16]. Cook claimed that: "The space required for acceleration and retardation is multiplied by the number of stops and this result is added to the length of travel. The sum of these quantities is divided by the normal speed in feet per second. The result will be the traveling time, in seconds, required to make the trip" [16]. Cook stated that this method was "true because the average speed during acceleration and retardation is one-half of the normal speed, and by adding this distance to the actual distance and dividing by the normal speed, the true traveling time is obtained" [16].

Cook's 1920 effort was followed by an article that is referenced in almost all post-1960 works on lift traffic analysis: Bassett Jones' "The Probable Number of Stops Made by an Elevator," published in the August 1923 issue of the *General Electric Review*. This article is, in fact, the only pre-1960 work referenced in contemporary works on lift traffic analysis. Jones' basic assumptions about lift operation paralleled those of earlier authors. He noted that the round trip time was determined by the distance the lift traveled, the number of passengers carried, and the number of stops made [17]. A key factor was the interval of travel, which determined the available loading time at the ground floor, which in turn set the maximum number of passengers carried, and thus fixed the car's size. Jones further defined the round trip in terms of: "(1) *running time*, or the total time the car is normally in motion between stops and is a direct function of the velocity-time data for the type of equipment adopted, (2) *standing time*, or the total time the car is standing at floors including the interval, and (3) *lost time*, or the time consumed by false stops if any, the time consumed by limit slow-downs, and the synchronizing time, or the time allowed for maintaining the schedule when an abnormal number of stops occur, or for other reasons" [17].

Jones stated that the "object" of his article was "to explain a method based on the theory of probabilities, for determining the number of stops" [17]. He described the theory of probability as "the only known intelligent method of guessing" [17]. His formulas relied on only three variables: *N* – the number of passengers that will enter the car on the ground floor, *n* – the number of floors the car served, and *S* – the probable number of stops. Jones first established formulas for the probability that a single passenger will exit at a particular floor (Eq. 28) and for the probability that she will not wish to exit at that floor (Eq. 29). He then modified the formulas to account for *N* passengers (Eq. 30 & 31), which led him to his formula for the probable number of stops (Eq. 32).

$$\frac{1}{n} \qquad (28)$$

$$\frac{n-1}{n} \qquad (29)$$

$$\left(\frac{1}{n}\right)^N \qquad (30)$$

$$\left(\frac{n-1}{n}\right)^N \qquad (31)$$

$$S = n\left\{1-\left(\frac{n-1}{n}\right)^N\right\} \qquad (32)$$

Jones demonstrated the efficacy of his formula via a "dice analogy" and illustrated a means of determining the odds of a given dice face turning up when the dice was thrown. He also noted that the "only criterion of legitimacy" for the theory of probability "is the test of experience, and in this regard, it has proved to be quite satisfactory" [17]. In this instance, "experience" was defined as follows: "For a long period it has been the custom, based on observed stops, to assume that during the morning arrival traffic peak the cars would stop at 0.8 of the floors on the up motion while delivering the passengers loaded on the ground floor" [17]. Jones provided a chart that illustrated the results of the application of his formula and he observed that "It is interesting to note how much of the data presented … averages $S = 0.8n$" [17].

Jones' decision to use 0.8 is intriguing in that it connects to Reginald Bolton's 1908 work. In his review of *Elevator Service*, William Bryan offered the following explanation of Bolton's theory: "Having placed the average number of passengers per trip each way at 0.4 the number of floors served, *f*, the provision that this number may be increased 80% when all are carried one way, together with a margin of 10% for emergencies, fixes the number of people to be provided for per trip at 0.8 the number of floors served" [9]. Thus, Jones' key assumption used to verify his theory relied on "custom" and the "Bolton rating," which was derived primarily from observation.

Jones formula for determining the probable number of stops does not, however, represent the first such attempt. In a 1932 article Howard Cook offered the following definition of probable stops and a formula for their calculation: "The probable number of stops made by an elevator is less than the number of passengers taken on at the first floor. If the number of persons per floor is the same for all the floors at which stops may be made and of the car always stops at the top floor then the probable number of stops made on the trip is found from the equation where *S* equals the number of possible stops above the first floor and *P* equals the number of passengers taken at the first floor. *This equation was developed by S. Margles in 1922*" (Eq. 33) [18].[2]

$$\text{Probable stops} = S - (S-1) \times \left(\frac{S-1}{S}\right)^{P} \tag{33}$$

Unfortunately, Cook offers no further explanation of this formula or its origins. "S. Margles" was Samuel G. Margles (1889-1978), an engineer with the Otis Elevator Company. He joined Otis following his graduation from Cooper Union and, in 1959, he described his career at Otis as follows: "I entered the employ of the Otis Elevator Company late in in 1911 as a structural draftsman in the construction department. In 1918, I was transferred to the engineering department, where I have been ever since; that is, until the date of my retirement in August 1954. I began work on escalators in 1919 and, subsequently, I have been in charge of complete design, invention, and construction of escalators"[19]. This brief autobiography only raises more questions: Why would an engineer focused on escalators devise a formula for the probable number of lift stops? When and where would Cook have encountered Margles and his formula? And, finally: If Cook's dating of Margles' effort is accurate, was Jones aware of his work? This event also marks another, albeit very limited, glimpse into the approach that Otis was taking toward solving this problem.

In 1924 British engineer Howard Marryat (1871-1944), co-founder of Marryat & Scott, presented a paper to the Institution of Electrical Engineers that included a more substantive glimpse into the lift industry's approach to traffic analysis – from the British perspective. He claimed that "given the necessary particulars of a building, the lift engineer will be able to calculate the probable traffic" [20]. However, Marryat also noted: "It must be admitted … that the lift engineer himself does not usually employ any scientific method in arriving at the number of passengers per minute which will require lift service on each particular floor during the busy part of the day" [20]. Instead of relying on a "scientific method" the typical lift engineer drew "upon his own experience and home-made formulae" [20]. At this point Marryat opined that, if the various "home-made formulae" used by British lift manufacturers "could be collated, the general advantage would be served and many mistakes avoided" [20].

[2] Italics added by author.

In his paper Marryat reported that the "only English pronouncement" he could find on lift traffic was found in "a paper read recently by Mr. C.H.J. Day before the Association of Engineers-in-Charge, in which he says … that in buildings where tests have been made, the rate of traffic flow at the busiest time of the day has been found to be such as to include the equivalent of the entire population of the building in 45 minutes, and that the passenger traffic can be predetermined by allowing for a period of rush from 15 to 20 minutes, during which time a number equal to one-third of the population of the building is dealt with" [20]. While Marryat stated that his observations did not align with Day's, he also noted that "although I have been investigating the subject for some considerable time I have not yet amassed sufficient data to permit of my making an authoritative pronouncement" [20]. None-the-less he offered two formulas designed to calculate a building's lift capacity and round trip time, which used five basic constants (Table 9). Marryat provided a detailed

Table 9 Howard Marryat Lift Formula Constants (1924)

A	Rental floor area above the first floor (in thousands of sq. ft.)
N	Number of circular trips, including stoppages, per lift per hour
L	Number of lifts
R	Running speed of lift (in ft. per min.)
T	Total travel of lift in feet in one direction

description of his data gathering strategy, which included using different approaches for different types of buildings and reflected differences in use patterns. He reported that: "In taking this census of traffic in existing occupied buildings, I have at the outset been faced with the fact that existing lift accommodation is, in almost every instance, insufficient. It has been necessary, therefore, to count not only persons using the lifts but also those using the staircases" [20]. He provided several data tables, one of which addressed the issue of insufficient service in London office buildings (Table 10). From this he determined that an average lift capacity of 9.6 passengers per 1,000 sq. ft. of rental floor area above the first floor was a reasonable figure, which allowed him to propose a formula to find the lift capacity required in an office building (Eq. 34).

Table 10 Howard Marryat Lift Service in London Office Buildings (1924)

Lift capacity in persons per hour per 1,000 sq. ft. rental floor area above first floor	Number of minutes during the day when lift capacity will be insufficient
7	84
7.5	56
8	33
8.5	14
9	5
9.5	1

$$\text{Lift Capacity} = \frac{9.6\text{A}}{\text{NL}} \tag{34}$$

Because the round trip time was, in large part, dependent on the interval of service, Marryat felt it necessary to define this key factor: "As about 30 seconds represents the limit of patience to be expected of the average city man waiting for a lift, a building cannot be considered to be adequately served when the occupants or visitors are asked to wait longer" [20]. He also recognized that he needed to known the overall lift speed – "allowing for all stoppages" [20]. While he found that "the number of stoppages a lift may be required to make in the course of a return journey from the ground floor and back again varies considerably," in most London office buildings the number of stops was "found to average about one stop for every 42 ft. of running" [20]. Marryat also allowed

“12 seconds per stop for loss in acceleration, deceleration, opening and closing of gates and for the time taken by the passengers in entering and leaving the car” (Eq. 35) [20]. In addition to lift traffic

$$\text{Round Trip Time} = \frac{60 \times 2T}{R} + \frac{2T \times 12}{42} \tag{35}$$

Marryat’s paper (the first draft was completed in July 1923), addressed a wide range of topics concerning electric lifts and in his introduction he noted that it was “remarkable that so little has been written or published upon the subject in this country, although there are a large number of works dealing with cranes, conveyers, etc.” [20].

In 1923 British engineer Ronald Grierson (1886-1955) published *Electrical Lift Equipment for Modern Buildings*. Marryat’s comment on lift publications reflected his lack of awareness of Grierson’s forthcoming book. However, had he known, he might have questioned the decidedly American bias reflected in much of the book’s content (it was published in the United States in 1924 as *Electrical Elevator Equipment for Modern Buildings*). In fact, the book’s bibliography lists only nine sources and it includes only American publications. Grierson addressed lift traffic in Chapter II: “Estimating Service Requirements” [21]. The chapter presented information gleaned from several sources (including Bolton), contained no formulas, and offered readers only a general introduction to this important topic. However, this was, in fact, more information than Fred A. Annett provided in the first edition of *Electric Elevators: Their Design, Construction, Operation and Maintenance*, published in 1927, where he made no mention of lift traffic analysis.

6 1930 - 1939

By the early 1930s the methodology used for gathering data needed to substantiate the development of lift traffic formulas and related metrics appeared to have been well defined. In a 1930 article Luther J. Kinnard discussed a traffic study worksheet that included 29 data points (Table 11). Kinnard’s worksheet appears to represent a comprehensive list of the factors associated with lift traffic design. While he provided a few basic formulas and charts that followed the pattern of prior work, he also noted that: “There has been a general demand among architects for a *Rule of Thumb* by which one could determine in a few seconds how many elevators were needed in a prospective building” [22]. Kinnard observed that a reliable rule of thumb depended on an accepted definition of satisfactory lift service, however, because there was no universal agreement on a definition due to variations in service required by different building types as well as differing expectations in similar buildings in different parts of the country, such a rule was impossible.

Howard Cook continued his work on traffic analysis in the 1930s, contributing additional articles to *Power* magazine and serving as a consultant to the second edition of Annett’s *Electric Elevators: Their Design, Construction, Operation and Maintenance*, which appeared in 1935 [23 & 24]. Whereas Annett’s first edition had ignored this subject, the second edition included a chapter devoted to lift traffic: “Selecting Elevators for Office Buildings” [24]. In a footnote Annett acknowledged that: “Howard B. Cook supplied a large part of the material in this chapter, and ” the majority of the chapter’s text and illustrations came directly from Cook’s articles [24]. Annett’s book thus served as means of disseminating Cook’s work and, perhaps most importantly, given its publication and distribution by a major publishing firm (McGraw Hill), attempted to set an American standard for lift traffic analysis.

Lift traffic was described as dependent on morning and evening traffic peaks, with the “five-minute morning peak of traffic as the controlling factor” in lift design “unless some peculiar conditions exist” [24]. According to Cook and Annett “the morning traffic peak is used as the basis for calculating elevator requirements even though the evening peak is higher, because passengers congregating in the evening on the upper floors is not so objectionable as crowding at the first floor" [24]. They also stated that: "in a well-diversified office building the five-minute traffic peak

Table 11 Luther J. Kinnard, Traffic Study Worksheet

Traffic Study	
Name of Building:	Location:
1. Number of floors served including main floor)	
2. Travel, Round Trip (Ft.)	
3. Rentable Area, per floor (Sq. Ft.)	
4. Rentable Area, above Main floor (Sq. Ft.)	
5. Population, above Main floor	
6. Service (local or Express)	
7. Number of Elevators in Bank	
8. Full speed of cars (F.P.M.)	
9. Capacity (Pounds)	
10. Capacity (Passengers)	
11. Type of control	
12. Type of Door Operators	
13. Time to open and close doors, each stop (Seconds)	
14. Extra time to Accelerate & Decelerate, each stop (Seconds)	
15. Standing time, Main floor (Seconds)	
16. Standing time, Top Floor (Seconds)	
17. Passengers carried per round trip, each car	
18. Stops per round trip, each car	
19. Loading time per passenger (Seconds)	
20. Standing and loading time, each car (Seconds)	
21. Door operations, round trip, each car (Seconds)	
22. Full speed Time, round trip (Seconds)	
23. Extra Time, Accelerate & Decelerate, round trip (Seconds)	
24. Extra Time, slowdown in limits (Seconds)	
25. Time for False Stops, round trip (Seconds)	
26. Total time of round trip (Seconds)	
27. Interval of Departure (Seconds)	
28. People Handled in One Hour	
29. Time to Empty Building (Minutes)	

will usually not exceed one-ninth of the building's population" [24]. The chapter included discussions of well-known topics such as round trip time, time for passengers to enter and leave the car, and the probable number of stops. Cook once again discussed Margles' 1922 formula and it is interesting to note that he made no reference to Jones' 1923 article. Cook did address a few additional areas of lift traffic and provided a means (Eq. 36) to calculate the rate of acceleration, where *t* is the time per stop in seconds, *S* is the average distance in feet between stops and *a* the rate of acceleration. The steady increase in the development of automatic door operating systems led to the development of a formula to calculate hoistway door operation time, which was described as dependent on the "weight of the door, the width of the opening and the forces applied." [24]. Thus, the formula (Eq. 37) included: *T* the time required for operating any sliding door, *W* is the weight of the door in pounds, *D* the door movement in inches, and *F* the force in pounds [24].

$$t = \sqrt{\frac{4S}{a}} \qquad (36)$$

$$T = \sqrt{\frac{WD}{96.6F}} \qquad (37)$$

Annett also published a detailed chart Cook had devised that illustrated four possible traffic scenarios during the morning 5-minute peak. The chart depicted "the round-trip time and the number of passengers carried per car in 5 min. … for 10, 12, 15, and 18 passengers per trip … to be carried during the morning peak of traffic by cars having capacities of 2,000, 2,500, 3,000, and 3,500 lb., respectively" [24]. Cook and Annett agreed that: "no definite standard has been formulated to measure the quality of elevator service" [24]. This did not, however, stop them from attempting to establish such standards: "After considerable investigation of this subject, it has been determined that when one-half of the interval between cars plus one-fourth of the round-trip time is equal to 45 sec. the service may be classed as excellent. When the sum of these quantities is 52.5 sec. the service may be called good. When the sum is 60 sec. the service is only fair" [25]. Cook provided a chart (first published in 1931) that gave "values for determining the quality of elevator service" (Fig. 3) [23 & 24].

The 1930s closed with the publication of the first edition of Reginald S. Phillips' *Electric Lifts*. Unlike Ronald Grierson's *Electrical Lift Equipment for Modern Buildings*, which had a decidedly American bias, Phillips' book relied almost exclusively on British sources. He offered his readers a brief introduction to the subject of lift traffic, which was included in his first chapter titled "Provision" [25]. He provided a broad definition of round trip time, noting that it was composed of several "varying factors" including: the car's maximum running speed, the rates of acceleration and retardation, the average number of stops made per journey, the average distance between stops, and the time required of passengers to enter and leave the car. Phillips provided definitions for each these factors as well as three basic formulas (Eq. 38, 39 and 40).

Number of passengers carried during the peak period = (Number of passengers carried per journey) x (Number of journeys made during the peak period) (38)

$$\text{Number of cars in the bank} = \frac{\text{Number of passengers carried}}{\text{Number of passengers per car}} \tag{39}$$

$$\text{Number of cars} = \frac{\text{Round trip time}}{\text{Waiting Interval}} \tag{40}$$

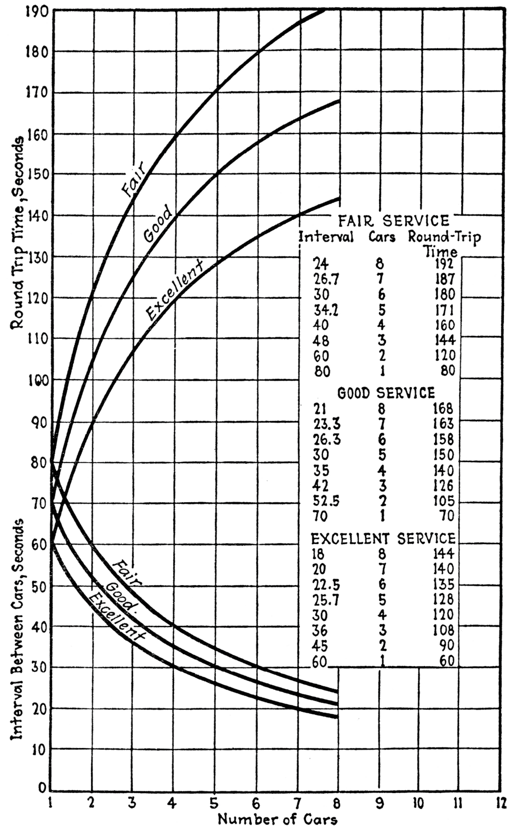

Figure 3 Cook, Values for Determining the Quality of Lift Service (1931)

Phillips claimed that his formula for determining the number of cars was accurate "irrespective of the capacity of each car" [25]. And, he concluded that: "The quality of service given by an installation is measured by the time of the waiting interval together with the time for the car to arrive at an average floor, the latter being a function of the round trip time. Waiting intervals of say, 20, 30, and 40 sec. may be considered, but a passenger should never be expected to wait more than 40 sec. before the arrival of a lift" [25].

7 1940 - 1960

The third British book on electric lifts appeared in 1941: *Electric Lifts: A Practical Treatise on their Construction, Operation and Maintenance* [26]. The author of the book, somewhat vaguely, was simply identified as "Contractor," with Edward Molloy listed as the General Editor. Molloy was also listed as the editor of the *Electrical Engineer*, and he served as the editor for a wide range of engineering books published by George Newnes Limited of London. Thus, the actual author (or authors) of this book are unknown. This is unfortunate as the book holds a partial answer to the mystery of Samuel Margles' 1922 formula for probable stops.

Chapter one includes a section titled "Traffic Analysis" which, as expected, includes a disclaimer that the "exact determination of lift requirements is extremely difficult, because so many variables have to be taken into account and it is almost impossible to estimate what conditions may be encountered in the future" [26]. Variability in service was illustrated by a description of lift traffic conditions: "In office buildings the peak traffic occurs in the morning, at lunch time, and in the evening, and the heaviest peak will depend upon the class of business, luncheon facilities, discipline, and similar factors, which vary with each building. Generally the morning peak is the heaviest, and in some buildings the lifts may have to handle as much as one-third of the population in five minutes when filling the building, whilst in others the lifts need not carry more than from one-tenth to one-twelfth of the population in the same time. The peaks vary between these values, depending upon the specific conditions of the building" [26]. The various factors discussed included the "suitable time-interval between car arrivals, determining the most satisfactory car size, methods of operation for car and landing doors, time-allowance for attendants' faults, time required for passengers to move in and out of cars, and probable stops" [26].

The section's unknown author states that: "by resorting to the *mathematics of probability* a formula can be evolved to determine the average number of stops that will be made to discharge passengers in the peak period of filling the building" [26].[3] The proposed formula relied on a discrete number of variables (Table 12). The constant *n* was defined as the total number of persons going into the building, thus equal to the number of people occupying the building (Eq. 41). The number of probable stops was defined relative to the occupancy of each floor (Eq. 42) with "the total number of minus terms being equal to *s*" [26]. If we assume that each floor has the same number of occupants, then a = *b* = *c* = *d*, which means that *sa* = *n*, thus, according to our unknown author,

Table 12 Probable Number of Stops Formula Variables (1941)

n	Total number of persons going into the building
a	Number of persons on one floor
b	Number of persons on another floor
c	Number of persons on another floor, etc.
p	Number of passengers in the car at loading floor
s	Total number of possible stops to discharge passengers

$$n = a + b + c \text{ ... etc.} \quad (41)$$

$$s-\left(\frac{n-a}{n}\right)^{p}-\left(\frac{n-b}{n}\right)^{p}-\left(\frac{n-c}{n}\right)^{p}\ldots \text{ etc.} \quad (42)$$

Eq. 42 may be simplified (Eq. 43) and, when one of the stops "is a fixed stop" the final formula matches the one Cook attributed to Margles (Eq. 44). It should be remembered that standard practice during peak service times required the car to travel to the top floor regardless of need (a "fixed stop") in order to maintain the interval of travel.

$$s-s\left(\frac{s-1}{s}\right)^{p} \quad (43)$$

$$s-(s-1)\left(\frac{s-1}{s}\right)^{p} \quad (44)$$

The book includes a chart that illustrates the "number of probable stops in the peak period of filling a building, assuming that the same number of persons is on each floor served by the lift" (Fig. 4) [26]. The unknown author claims that: "the results from the above formula compare favourably with those found in actual practice, and the formula has the advantage of giving a definite basis for comparison of different types of lifts" [26].

[3] Italics added by author.

The appearance of Margles' formula prompts several questions: Are the text and chart the work of Samuel Margles? And, if it is Margles, how was Molloy able to access this material? Molloy (and "Contractor") expressed in the introduction their "indebtedness to the leading lift manufacturers for having assisted us by supplying illustrations of the most modern types of lift equipment" [26]. These companies doubtless included Waygood-Otis and thus, if the companies provided more than images, it is possible that Waygood-Otis supplied Margles' work to Molloy, book's editor. This would, perhaps, imply that Margles wrote a paper on this topic in 1922, perhaps for internal consumption at Otis. The search for answers to this mystery will continue as it may shift our understanding of the origins the probable stop formula as well as how the lift industry was approaching this problem in the 1920s.

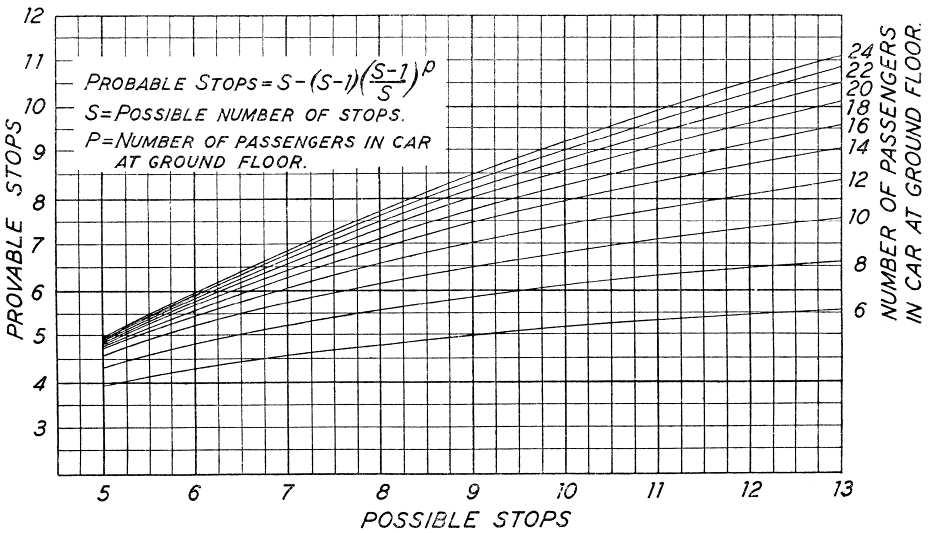

Figure 4 Number of probable stops in the peak period of filling a building (1941)

The second edition of Reginald Phillips' *Electric Lifts* appeared in 1947. It included a bibliography (a feature missing in the first edition) that was composed almost exclusively of British sources (the exceptions were the America A17 code and an associated Inspectors' Manual). Phillips made no reference to Molloy's book and, perhaps surprisingly, also made no changes to the lift traffic material that had appeared in the first edition. The book's third edition (1951) had an expanded bibliography that included two articles by Howard Cook ("A Measuring Stick for Elevator Service" and "Selecting Elevators for an Office Building") and two articles by Bassett Jones ("Time-velocity Characteristics of the High-speed Passenger Elevator" and "Note on Probable Number of Stops Made by an Elevator"). It is important to note that the Jones' article was not his 1923 article on probable stops, but a follow up article written in 1926 [27]. The reason why Phillips chose this article instead of the original is unknown. It is also curious that he references Cook but ignores Annett's work; likewise Molloy's book remained absent.

Phillips did, however, use these new sources to update the book's first chapter, which was renamed "Design and Traffic Analysis" [28]. He added a new section addressing "grade of service" in which he provided several formulas designed to determine the quality of lift service [29]. These formulas used three variables (Table 13). Phillips first established an initial formula for the grade of service

Table 13 Phillips, Graded Lift Service Formula Variables (1951)

W.I	Waiting Interval (maximum time a person may have to wait for a lift)
R.T.T.	Round Trip Time
N	Number of Lifts

in terms of the waiting interval and round trip time (Eq. 45). He then determined the waiting interval for *N* lifts in a bank (Eq. 46), which he used to derive his final formula (Eq. 47).

$$\text{Grade of Service} = \frac{\text{W.I.}}{2} + \frac{\text{R.T.T.}}{4} \tag{45}$$

$$\text{W.I.} = \frac{\text{R.T.T.}}{\text{N}} \tag{46}$$

$$\frac{\text{W.I.}}{2} + \frac{\text{N} \times \text{W.I.}}{4} \quad \text{simplified to} \quad \frac{\text{W.I.}}{4}(2 + \text{N}) \tag{47}$$

Phillips defined four grades of service in terms of the total traveling and waiting time (in seconds) (Table 14). He also characterized the passenger's experience as follows: "A lift service which has a small *W.I.* and a large travelling time always appears to the user to be better than an equivalent service with a larger *W.I.* and a smaller travelling time, as a long wait tends to make a person impatient" [29].

Table 14 Phillips, Graded Lift Service (1951)

Excellent	45
Good	45-55
Fair	55-65
Casual	>65

As noted above, Phillips' bibliography referenced a 1926 Basset Jones' article, "Note on Probable Number of Stops Made by an Elevator," rather the original 1923 article. Phillips recreated the essential aspects of Jones' 1926 argument and published a set of formulas that lead to the original conclusion expressed in Eq. 29. However, Phillips failed to mention what prompted Jones to write a "note" to his original article. Jones reported that, following the publication of his 1923 article: "the formulas and charts therein presented have been generally accepted and have come into general use. They have been checked over and over again by observation, and have been found to give results quite as close to practice as was originally claimed for them" [27]. However, by the mid 1920s, the literal shape of skyscrapers had changed: "the increasing number of zoned or set-back buildings that are being built introduces cases where the wide variation in floor area and in distribution of population is beyond the applicability of the (original) formulas that were given" [27]. Jones therefore proposed a new set of variables (Table 5) and a new series of formulas aimed at solving this new problem.

Table 15 Jones, Variables for Probable Stop Formula (1926)

N	Total number of passengers entering the car at the ground floor for each trip during the peak period.
P	Total population served during the peak period.
n	Number of floors served above the ground floor.
P_a, P_b, P_c, etc.	Population on the first, second, third, etc. floor.

He worked through a series of steps that leaded him to a revised formula (Eq. 48), which he noted was "first developed by David Lindquist" [27]. This statement adds to the mystery surrounding the origins of the formula to determine probable stops. Lindquist (1874-1944), was one of Otis' chief engineers, and presumably would have aware of Margles work from 1922. Jones also gives no hint as to when Lindquist proposed this formula. Thus, Jones offers yet another clue that Otis was also working on solving this problem.

$$S = n - \left\{ \left(\frac{P - P_a}{P} \right)^N + \left(\frac{P - P_b}{P} \right)^N + \ldots + \left(\frac{P - P_n}{P} \right)^N \right\} \quad (48)$$

Phillips also included a new section on travel time that featured formulas derived, in part, from Jones' examination of lift time-velocity characteristics [27]. His primary focus was a formula, which used four basic variables (Table 16), which could be used to determine a lift's total travel time. He derived a series of formulas to determine the distance traveled and the time period required

Table 16 Reginald Phillips Travel Time Formula Variables (1951)

S	Number of stops made between the ground floor and the uppermost floor at which
D	Distance in feet between ground floor and this top floor
V	Contract speed in feet per second
d	Distance in feet required for acceleration from rest to contract speed (assumed to

during a lift's acceleration and retardation period (he assumed that the average speed during these periods was half the contract speed) (Eq. 49, 50, 51, & 52). He also devised formulas for the distance traveled and the time period the lift was running at contract speed (Eq. 53 & 54).

Upward distance travelled during acceleration and retardation period = 2dS (49)

Downward distance travelled during acceleration and retardation period = 2d (50)

Total acceleration and retardation periods = 2d(S + 1) (51)

Total Time during acceleration and retardation periods = $\frac{2d(S+1)}{\frac{V}{2}}$ or $\frac{4d(S+1)}{V}$ (52)

Total distance traveled at contract speed = 2D - 2d(S + 1) (53)

Time for running at contract speed = $\frac{2d - 2d(S+1)}{V}$ (54)

From these he proposed a formula to find the total traveling time (Eq. 55). He also offered a formula to find the traveling time if the distance (d_1) between any two stops was less than the distance needed to reach contract speed (where *f* is the average acceleration) (Eq. 56)

Total traveling time = $\frac{2}{V}(dS + D + d)$ (55)

$$2\sqrt{\frac{d_1}{f}} \quad (56)$$

Although Phillips expanded his bibliography in the book's fourth edition (1958), he did not edit or add to the content on lift traffic design and analysis found in the third edition.

The third edition of Fred Annett's *Electric Elevators* appeared in 1960 with a substantially revised title – *Elevators: Electric and Electrohydraulic elevators, Escalators, Moving Sidewalks, and Ramps* – and a revised chapter on lift traffic, which also featured a new title: "Automatic Dispatching of Passenger Elevators and Attendantless Operation" [29]. There is an intriguing symmetry between this publication and the first works examined in this paper in that, after 70 years of pursuing the development of lift traffic formulas, Annett's book contains no such formulas: in their place we given the "magic" of automated lift supervisory systems. These new systems were marketed under a variety of names intended to highlight the mathematical acumen hidden within the technology: Autotronic (Otis), Selectomatic (Westinghouse), Auto-Signamatic (Haughton) and Measured Demand (Montgomery).

The language of past lift traffic analysis efforts was also updated with terms such as up-peak, off-peak, down-peak, forgotten-man pickup, and zone operation now used to describe and define this topic. Annett illustrated ongoing efforts to understand lift traffic patterns in a diagram that depicted typical service demands as occurring in "waves" throughout the day (Fig. 5). He illustrated the efficiency of the new automatic systems is diagrams depicting their operation during off and up peak periods (Fig. 6). However, Annett's descriptions of these systems are also filled with references to the roles of lift supervisors and operators. These serve as important reminders that in 1960, the lift industry was effectively poised between two worlds: the "old" world where the starter and operator played key roles in lift traffic management, and the "new" world where traffic management was vested in controllers driven by hidden algorithms. The continued importance of the starter was illustrated by a diagram of a typical supervisors control unit, where the starter interacted with and directed the automatic system (Fig. 7). The hidden logic that drove a typical automatic system was illustrated by a series of definitions describing it operational parameters (Table 16). Although these definitions are clear, there is, perhaps, a certain irony in that their simplistic tone is reminiscent of the general description of lift operation from the early 20th century.

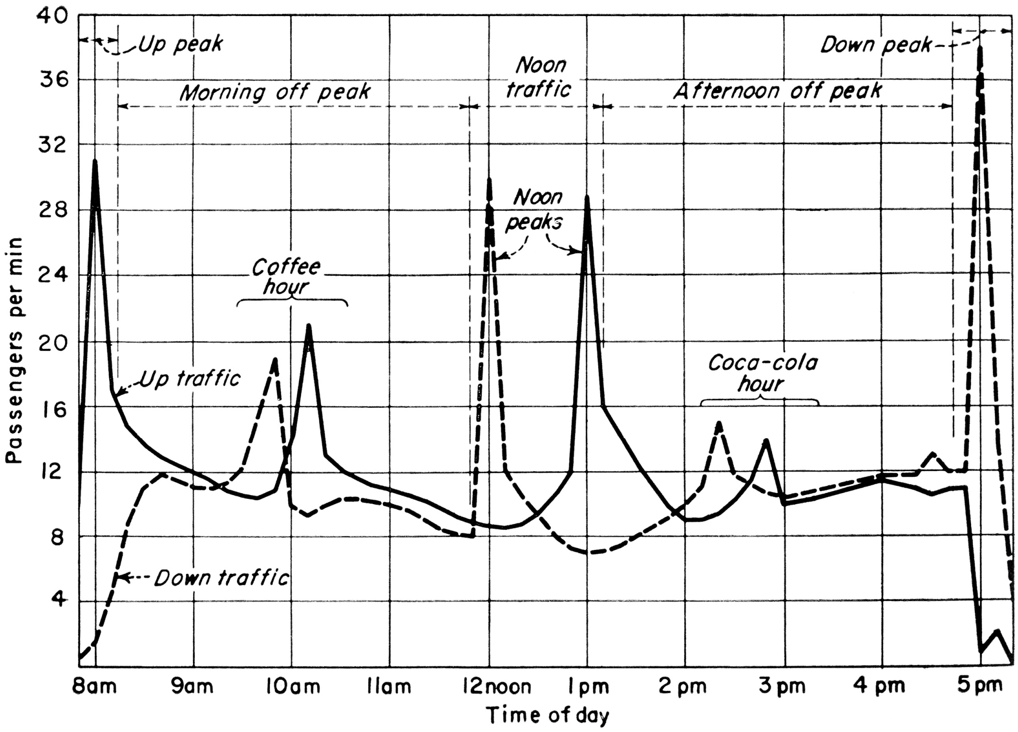

Figure 5 Annett, Typical Lift Travel Peaks in an Office Building (1960).

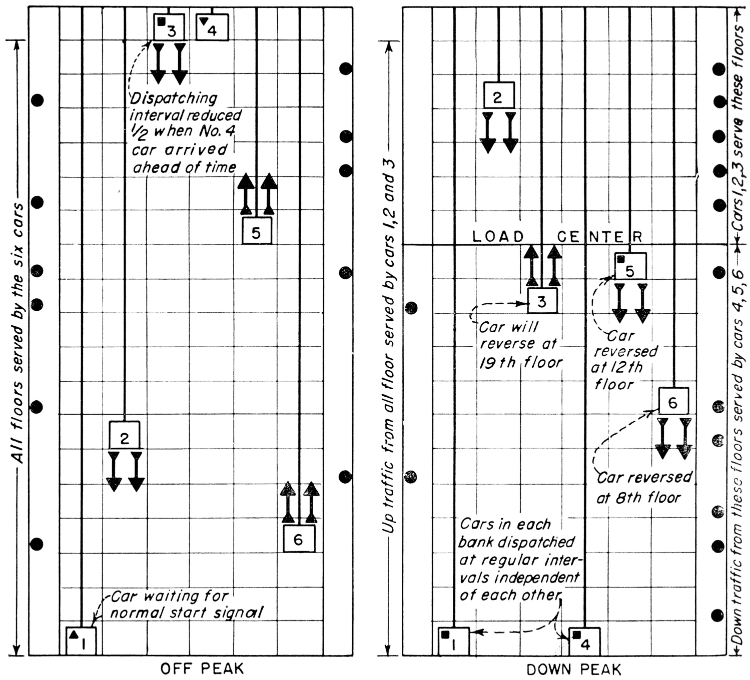

Figure 6 Annett, Off-Peak and Down-Peak Travel (1960).

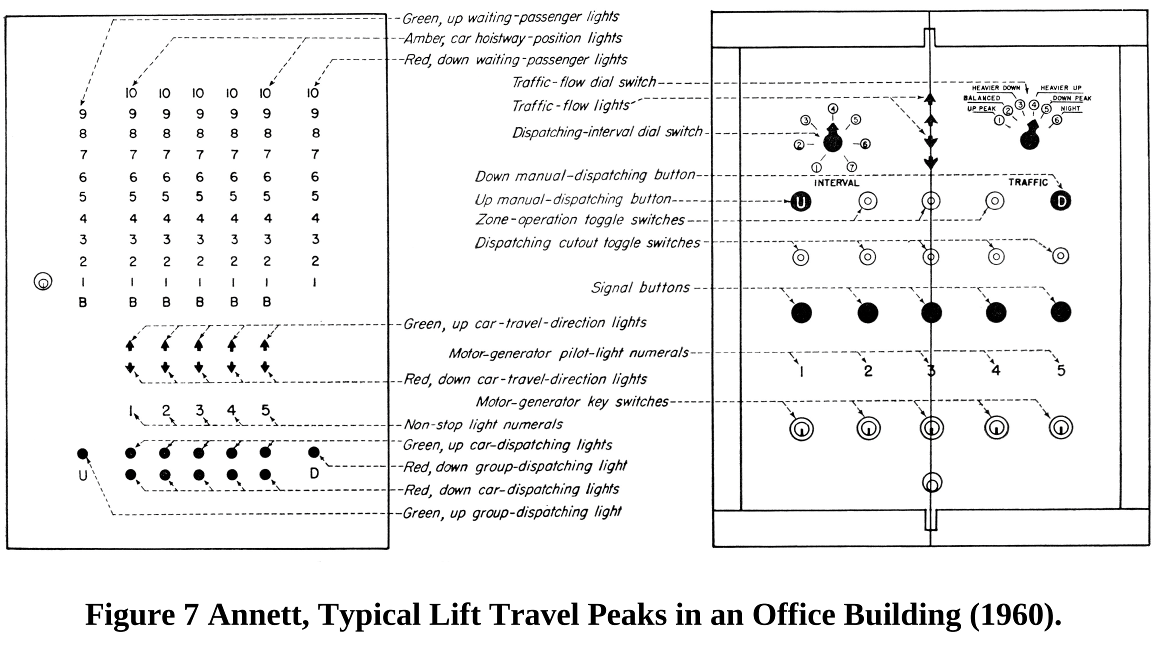

Figure 7 Annett, Typical Lift Travel Peaks in an Office Building (1960).

Table 16 Annett, Typical Lift-operating Program Definitions (1960)

Up Peak	Heavy up-traffic from the main floor with little or no interfloor or down traffic, as
Heavier Up	Heavy up-traffic plus appreciable down traffic, as during the late noon peak.
Down Peak	Heavy down-traffic with little or no interfloor or up traffic, as during the evening
Heavier Down	Heavy down-traffic plus appreciable up traffic, as during the early noon peak.
Balanced	Traffic about equal in up and down directions.
Night	Light and intermittent traffic, as during nights, Sundays and Holidays.

8 CONCLUSION

This investigation revealed two streams of development regarding lift traffic analysis that might be termed public and private (or perhaps, proprietary). While the topic was clearly recognized as important, the majority of published works on these topics were written by individuals who were either outside the lift industry or who operated as lift consultants. While evidence of the lift industry's approach to this subject was discovered during this investigation, this material, because of its proprietary nature, remained largely hidden from view. The results of industry efforts were evident in the automated traffic control system referenced above, however the mathematical concepts that underlay this work were "hidden" from pubic view.

This bifurcated approach continued after 1960 with one critical difference: the addition, beginning with the work of Dr. Gina Barney in the late 1960s (assisted by colleagues and students at the University of Manchester Institute of Science and Technology), of what may be termed the academic pursuit of lift traffic formulas and criteria. While this work has a strong connection to the lift industry and to the work of lift consultants, it represents, perhaps, a "third" parallel path of investigation.

As the history of this important topic continues to unfold it is to be hoped that industry members might be willing to share material with researchers that is "outdated" and no longer considered proprietary. This additional material will make it possible to tell the full story of the development of lift traffic analysis.

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BIOGRAPHICAL DETAILS

Dr. Lee E. Gray is the Senior Associate Dean in the College of Arts + Architecture at the University of North Carolina at Charlotte and a Professor of Architectural History in the School of Architecture. He received his Ph.D. in architectural history from Cornell University, his Masters in architectural history from the University of Virginia, and undergraduate degrees in architecture from Iowa State University. He is the author of *From Ascending Rooms to Express Elevators: A History of the Passenger Elevator in the 19th Century*. Since 2003 he has written monthly articles on the history of vertical transportation for *Elevator World* magazine. Current projects include a book on the history of escalators and moving sidewalks.

Lift Modernisation Challenges

Roger Howkins

ARUP
13 Fitzroy Street, London. W1T 4BQ. UK.
roger.howkins@arup.com.uk

Keywords: Modernisation, Codes, Standards, Guides, Structures, Professional Advice, Skill base.

Abstract. Question – What are the lift modernisation challenges? Currently there are no published definitive codes, standards and not many guidelines what constitutes a lift modernisation. Based on this fact how could we have confidence that the planned lift modernisation will be safe mechanically, structurally and electrically? Also, how could we make sure that the appointed lift contractors will have the required skill sets to design and sign off the completed works?

For new lift installations, the code BS 5655-6:2011 is very specific what type of design information needs to be provided. According to this code the client's representative needs to provide various documents and information including but not limited to structural loading, vertical shaft alignments and requirements for fixing guide brackets. Unfortunately, this information exchange is not required for a lift modernisation.

For lift modernisations the successful lift contractor will also have to comply with many relevant statutory regulations. In the UK many important requirements are stated in Health and Safety at Work Act, Construction (Design and Management) Regulations and Lifting Operations and Lifting Equipment Regulations (LOLER). For every country specific and local regulations will apply.

1 AVAILABLE INFORMATION

The biggest challenge is the pressure on lift companies and lift consultants to replace older lifts with new lifts without detailed examination that this approach is absolutely necessary. CIBSE Guide D (2015) in Section 16 states "a refurbishment is usually less expensive than a full replacement but may not extend the life of a lift by more than a few years. In the long term it could be more expensive". It is not clear how this statement is justified but in the last decade we can witness reduced skill of lift modernisation labour and engineers. Nowadays, it is not easy to find lift companies who are able to engineer a lift modernisation and provide a long term life expectancy.

The Vertical Transportation Handbook by George R Strakosch states the opposite *"building management expects from elevator modernization is a major reduction in elevator downtime. This is accomplished through greater reliability of new components"*

The Lift Modernisation Design Guide (2nd edition 2017) by Roger E Howkins gives a comprehensive list of life expectances of the majority of lift components and a systematic approach to modernisation and the people who should be involved from the preplanning stage to the award of the contract and these people and professionals include but are not limited to the structural, mechanical, electrical and fire engineers.

The objective of BS EN 81-80:2003 is to try to improve the safety of existing lifts by risk assessment but does not go as far referring to modernisation – in essence it's a shopping list for minor repair to a lift which tries to bring the lift up to the minimum requirements of EN81-1 and EN81-2, however without the electrical, structural and environmental requirements detailed in BS 5655-6: 2011.

The European Lift Association (ELA) document "Safety of Existing Lifts" (March 2013) provides advise based on BS EN81-80: 2003, details of 74 risks associated with lifts in service which makes no reference to modernisation but this is more applicable as a sales tool for maintenance companies as it tries to improve the overall safety of the lift installation but not the life expectancy.

The Lift and Escalator Industry Association (LEIA) in its 2016 Focus publication states *"The complex challenge of lift modernisation was clearly identified as a hot topic"* also *"our industry has many technical roles from design and engineering to troubleshooting and testing. All these roles are of equal importance"*. There is an underlying theme in this publication for commercial considerations, CE marked components and reference to BS EN 81-20:2014, yet this is not a relevant standard for Lift Modernisations.

The Lift and Escalator Industry Association (LEIA) publication "Lift Safety in the modern built environment" – April 2017, in section "Modernisation and sustainability" references sustainability and concentrates on energy performance but not on the safety of a lift modernisation. It gives the wrong impression of what a lift modernisation should focus on. It does not increase the life expectancy of the lift installation when modernised.

2 FUNDAMENTAL QUESTIONS

What should be done with lifts installed prior to the adoption of codes or standards such as BS 2655-1: 1957? Who would be responsible for actions such as checking and verifying the structural design to withstand the loadings on the machine room slab, guide rails and fixings?

As it is very unlikely that any original design information will be available from the original lift manufacturer, architects or structural engineers therefore who would be responsible to verify the original design and check if the site is suitable for the new lift equipment?

Should the building owner accept, without further investigation, that the existing building structure, electrical supplies and the retained lift equipment are suitable for the modernised lift?

3 HOW MUCH INFORMATION IS REQUIRED AND WHEN?

With lift contractors' sales teams under pressure to maintain sales targets, it is apparent that tenders for lift modernisations are also based upon a percentage success strike rate determined by number of tenders submitted. This has resulted that the competitive bids are submitted on limited or basic surveys. When the lift company is successful, a full survey is then undertaken but with a very high risk to the client of the additional costs and programme delays due to the tender original surveys being incomplete or poorly executed.

The major risks that could be identified are, but not limited to the following:

- Corrosion of equipment.
- Guide fixings and machine slab loadings.
- Tolerance and verticality of lift shaft.
- Electrical supply loadings.
- Air conditioning refrigerants in cars and lift motor rooms.

Generally, as the design issues are not covered by any guidelines, codes or standards, many issues are usually identified during lift modernisations process. Majority of them could be addressed during the pre-tender surveys and prior to the bid submittal or being included in the project as a contingency sum.

With more lift modernisation contracts being "turnkey" the lift companies need to have more comprehensive skill sets. LEIA have stated *"our industry has many technical roles from design and engineering"* but how quickly can lift modernisation companies respond to these complex and new objectives and increase their overall skill base in the field of lift modernisations.

4 CORROSION OF LIFT EQUIPMENT

Corrosion is the adverse impact on the features of a metallic material due to the chemical or electromechanical reaction of that material with the surrounding medium.

For a potential lift modernisation the appointed lift contractor should understand the main corrosion groups: general corrosion, paint corrosion and corrosion cracks and beware during pre-bid surveys to allow for remedial works.

Ideally the designers of the original lift installation should have considered the potential areas of corrosion risk especially if the lift is an industrial, open environment or humid conditions. The lift company should also maintain the material correctly by the application of the correct additional surface coating to the component or sub assembly if corrosion is discovered.

Within the published guides, codes and standards there is no guidance on how lift components corrosion should be inspected and whose responsibility it is to treat of repair corroded components and subsystems. It is a misleading concept that the component has worked correctly since the original lift was installed, therefore there is no requirement to inspect for corrosion.

Corrosion degrades the materials surface, colour and strength but can be easily treated by the correct surface preparation and re-painting. In areas where corrosion is widespread the area should be inspected by specialist methods such as ultrasonic tests, or magnetic particle inspection. Then, the results should be compared with the original component structural characteristics. It is the lift modernisation contractor's responsibility to undertaken this works prior to commencing the job on site by inspecting the works primarily via non-destructive testing (NDT) without destroying the serviceability of any part and, if needed, employing a specialist structural engineer who specialises in corrosion.

Another area of a critical and safety risk is bi-metallic corrosion (Galvanic corrosion). This is an electrochemical process in which one metal corrodes preferentially when it is in electrical contact with another, in the presence of an electrolyte. It is most common when a steel door frame (goal post) is fitted directly on to an aluminium cill without a barrier between the steel section, fixing bolts, and the aluminium cill. This type corrosion is difficult to notice but, if existing, it would affect the overall strength of the door set. This inspection, should be the lift companies responsibly and if there is any doubt on the integrity of the sub system assembly, a specialist corrosion engineer should be engaged.

5 GUIDES FIXINGS, MACHINE BEAMS AND SLAB LOADINGS

Lift modernisation contractors need to determine when the lift was originally installed as a manufacturing data plate is not always fitted.

If the lift has Tee Guides installed it may not have been designed to the minimum safety standard but to code BS 2655-1:1957 which in terms of calculations for safety components is very basic.

It is a misleading concept that due to the fact that the guide rails have worked correctly since the original lift was installed they could be re-used without any examinations. The lift modernisation contractor should carry out a guide rail calculation as described in BS EN 81-20:2014. This is very important, especially if new car/counterweight safety gears are being fitted as the existing guide rails may have an unacceptable deflection when the safety gear operates. When new bi-directional safety gears are considered on existing lifts, possibility of lifting guides when operates in up direction should be also analysed.

If the lift contractor carries out a detailed lift survey at the tender stage with the subsequent calculations they will be able to decide if the guide rails are suitable for reuse. In extreme cases where the guide rails are not suitable for a lift modernisation a new lift in the existing shaft will be required.

The car and the counterweight guide rails are fixed into the lift shaft wall by fixings such as “rag bolts”, welded studs or built in inserts which have unknown pull out qualities. When carrying out dynamic tests on a new “type tested” safety gear these fixings could fail and the building owner would have to pay substantial additional costs for new fixings and programme delays. This could be avoided if these concerns were identified during the pre-tender survey.

The original design assumption and calculations may not be applicable for the lift modernisation therefore many design aspects need to be investigated prior the commencement of work. Queries such as if a new drive would be required due to the lift speed increase or if a more energy efficient type of machine could be used need to be investigated at the beginning of the project.

It is very dangerous to assume that the structure and machine beams have worked correctly since the original lift installation and therefore they are correct. The possibility that there may have been calculation errors originally needs to be assumed. It is very important that a structural engineer comments on the new dynamic and static loadings and compare these with the original design.

It is common to see lift modernisation contractors fixing new lift machines to the original machine beams (bed plates) without any consideration to the design of the original machine beams in terms of deflections, twisting moments and condition of the bolted or welded fixings.

Also quite common is keeping the original machine isolation as the removal and renewal will require the existing machine beams or bed plates to be lifted. As a result keeping the existing machine isolation which may have lost a high proportion of its isolation characteristics, would not improve the noise and vibration characteristics of a modernised lift.

6 TOLERANCE AND VERTICALITY OF LIFT SHAFT

It is an assumption that the original lift shaft was constructed with tight tolerances and verticality requirements typical for new installations. For modernisation projects it is the responsibility of the lift contractor to establish the tolerances and verticality of the lift shaft during the tender process to avoid for any concerns being raised during the installation process.

As a general practice, the lift company surveyor will only dimensionally measure the lift shaft in one location and then assumes that this is a correct dimension throughout the lift shaft and only on rare occasions check the verticality of the lift shaft.

This approach doesn’t highlight the defects of the original lift shaft construction such as bowing due to concrete shuttering slipping or building settlement, shaft floor beams not aligned or other none lift related services within the lift shaft. These issues may have been permitted during the original installation and due to restraints of the building cannot be removed or repositioned. These original defects often occur when larger lift platforms are being installed or when manual car and landing doors are being replaced by automatic designs.

A “point cloud survey” replaces the traditional limited 2D survey carried out by the lift contractors. It generates a very accurate 3D model through laser technology which enables defects in the existing lift shafts by providing geometrical points. It should be required by all lift contractors to employ a professional surveyor to carry out a “point cloud survey” prior to starting any lift modernisation projects. This would eliminate many of the risks related to the lift shafts being “out of plumb” such as delays for new materials to be ordered or possible financial consequences due to programme creep.

7 ELECTRICAL SUPPLY LOADINGS

A lift modernisation will always require analysing of the electrical power supplies to the lift motors, lighting and socket outlets in the lift shaft, motor room and cars. The original lift installation electrical supply could be very old and not comply with the requirements of the proposed lift modernisation.

The lift modernisation contractor must employ a qualified electrical contractor or consultant to survey the existing electrical installation and report on its suitably for the new equipment being supplied.

This survey should include the information how the new electrical supply cable can be re-routed to comply with the current requirements and if run within the lift shaft how this will affect the safety clearances.

For safety the electrical installation isolation switches and distribution boards in the lift motor rooms may have to be repositioned to enable authorised personnel to work on them. Also, the new rubber mats, electric shock notices and danger notices need to be replaced as good practice, to not put lives at risk by having non-compliant equipment and incorrect notices fitted.

The lift modernisation companies’ responsibility is to include technical advice from a competent person to the building owner on the nominal voltage, phases, full load current and any other relevant details that may be required for lifts etc.

It is the responsibility of the lift modernisation contractor during the tender stage of the project to seek professional advice and provide the building owner with sufficient information to enable them to budget for any additional works and not be informed during the installation or testing that the electrical supply is not sufficient.

8 AIR CONDITIONING REFRIGERANTS IN CARS AND LIFT MOTOR ROOMS

The use of air conditioning in panoramic lift cars and within lift motor rooms is very common.

The air-conditioning units in lift motor rooms are normally self-contained free standing and not connected to the building air-conditioning system due to the smell of the lift drive. This can be noticeable especially when hot hydraulic oil smells are being circulated within the building air conditioning system. The self contained air-conditioning systems fitted to lift cars do not have these problems as the exhaust is vented directly to atmosphere either outside or within the lift shaft.

Within a “turnkey” lift modernisation it will be required for the successful lift contractor to overhaul or replace the self-contained air-conditioning systems. During the initial pre tender survey it is essential that a professional mechanical or refrigeration engineer is employed by the lift company to provide advice and a report on the fitted air-conditioning units.

The early involvement of a professional mechanical or refrigeration engineer not only will clarify the suitability of the existing air-condition unit but also could advise on the possible repositioning of the air flow ducting within the lift car. Within the lift motor room the air-conditioning unit may have to be repositioned due to the new equipment being installed and the existing heat generators are being replaced with new equipment.

9 CONCLUSIONS

It is apparent that for any lift modernisation the lift companies are required to adapted and increase their skill sets by employing more professional qualified engineers. The complex design issues such as original structural design, corrosion, refrigeration, electrical and mechanical design would need to be addressed at the beginning of the project. It is not acceptable to have the mindset that the lift structure, fixing and loadings have been satisfactory for 20 or more years and therefore will be fit for purpose after the modernisation.

The lift industry needs to understand the building as a whole entity and not be focused on the element which is the lift installation.

The limited publications produced by the lift industry trade bodies, guides, codes and safety standards need to reflect the complex nature of lift modernisation. They cannot be only presented as sales tools for minor repairs or upgrade due to sustainability. As the lift modernisations declare high percentage of the overall number of the lift projects they should be treated as an equal with new lift installations and become more frequently recommended as a viable option to establish long life expectancy of the lifts.

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BIOGRAPHICAL DETAILS

Roger Howkins is an Associate within the Arup Vertical Transportation team, providing advice to Arup both in the UK and overseas on the use of lifts, escalators and passenger conveyors in new and upgraded buildings. He is an authority on modernisation of lifts, escalators and external lift installations. He has experience in giving expert witness testimony in the UK and abroad.

A Study on Seismic Response Analysis in Consideration of Non-linear Restoring Force Characteristics of Escalator Truss Structure

Asami Ishii[1] and Satoshi Fujita[2]

[1]Graduate school of Advanced Science and Technology, Graduate school of Tokyo Denki University
Senju Asahicyo, Adachi-ku, Tokyo 120-8551, Japan, 15udq91@ms.dendai.ac.jp
[2]Professor, Department of Mechanical Engineering, Tokyo Denki University
Senju Asahicyo, Adachi-ku, Tokyo 120-8551, Japan, sfujita@cck.dendai.ac.jp

Keywords: Escalator, Escalator Truss, Non-linear Restoring Force Characteristics, Analytical Model, Seismic Response Analysis, Slide Friction

Abstract. In the Great East Japan Earthquake, fall accidents of four escalators occurred. In one of these accidents, the escalator that linked the third floor from second floor dropped. This occurred in the commercial facilities of the low-rise, steel-frame building. In general, escalators are usually installed in buildings with one side of them in fixed connection and the other side in free condition. In contrast, they might be installed both sides in the non-fixed style in order to mitigate undesirable excessive deflections induced in the truss-like structures of escalators. However, an escalator truss might break off from the building beams, due to excessive lateral deformations induced in the storey-layers. In a new public notice about the reinforcement of the falling off prevention structure of the escalator after these accidents, a new and improved structure was determined: 1, The structure must include enough overlap allowance, 2, The structure must take backup measures to ensure enough overlap allowance for the escalator truss to not come off from the beam of building, and so it is less likely to drop. During these accidents, it was also considered that a non-fixed part might collide with the beam of building by larger deflections than expected; this collision might cause excessive compressive force and residual displacement. It is necessary to clarify the seismic behavior of the escalator to prevent such an accident. From the above-mentioned background, the object of this research is to construct an analytical model to clarify the seismic response behavior using the non-linear restoring force characteristic of the escalator truss model. In this paper, the multi-linear model is built based on the load-displacement. In addition, the seismic response analysis of an escalator installed in the building is performed using the multi-linear model and the bi-linear model. As result, the bi-linear model is acceptable to evaluate the seismic response.

1 INTRODUCTION

Escalators are one of the most important vertical transportation measures to connect storey-layers in buildings. During severe earthquakes, escalators are not only shaken by themselves, but withstand lateral relative deflections induced in the structures or buildings installing them. Therefore, escalators are usually installed in the buildings with one side of them in fixed connection and the other side in free condition or utilized both sides in the non-fixed style in order to mitigate undesirable excessive deflections induced in the truss-like structures of escalators. However, in the Great East Japan Earthquake, fall accidents of four escalators occurred in the three locations [1] [2]. Escalator truss might come off from the building beams, because excessive lateral deformations were induced in the storey-layers with more than assumption where the accidents happened.

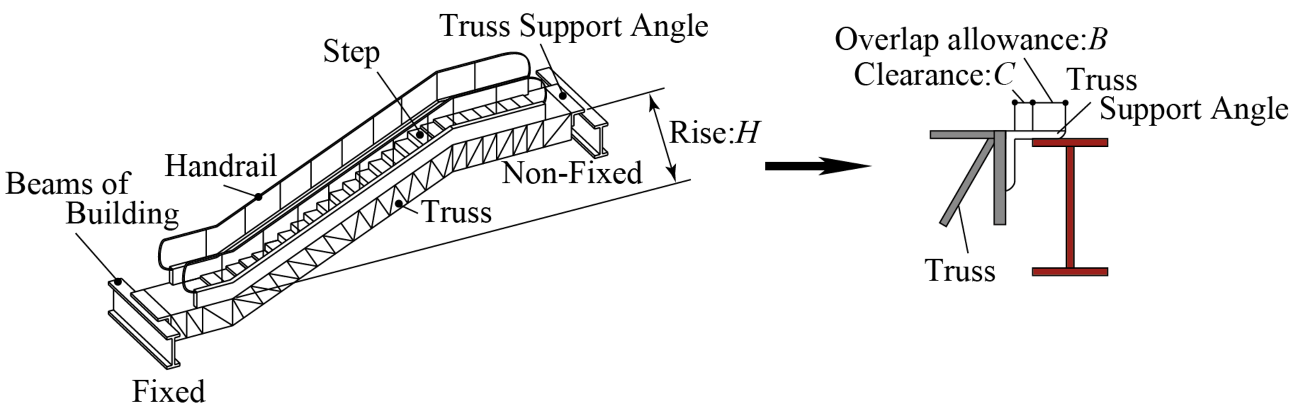
During these accidents, it was also considered that a non-fixed part might collide with the beam of building by larger deflections than expected occurred in the sliding parts; this collision might cause excessive compressive force and residual displacement in the escalator truss might be caused. It is necessary to clarify the seismic behavior of the escalator to prevent such an accident. From the above-mentioned background, the object of this research is to construct an analytical model to clarify the seismic response behavior using the non-linear restoring force characteristic of the escalator truss model. In this paper, the restoring force characteristic model is built based on the load-displacement. In addition, the seismic response analysis of an escalator installed in the building is performed using the restoring force characteristic and the Bi linear model.

2 STRUCTURE OF ESCALATOR

The general view of the escalator and the enlarged picture of the non-fixed side are shown in (a) and (b) of Figure 1. Escalators are comprised of steps, handrails and electric motors, with the escalator truss supporting them. An escalator truss is a structural element supporting live load and its own weight. Angle steels are used mainly. The frame combined by angle steels is coupled by welding. Therefore, each element receives the axial force of compression or tensile. Escalators are usually installed in the buildings with one side of them in fixed connection and the other side in free condition or utilized both sides in the non-fixed style in order to mitigate undesirable excessive deflections induced in the truss like structures of escalators. The length of that escalator truss hangs to the building beams is called overlap allowance. As shown in equation (1) and (2), the length of the overlap allowance is determined by escalator technology standard in Japan [3]. Where C is the gap between the beam of the building and the escalator, H is the rise, γ is the layer deformation angle of building, and 20 [mm] is margin of the overlap allowance.

$$B \geq \sum \gamma \cdot H + 20 \qquad (C > \gamma \cdot H) \tag{1}$$

$$B \geq 2\sum \gamma \cdot H + 20 \qquad (C \leq \gamma \cdot H) \tag{2}$$



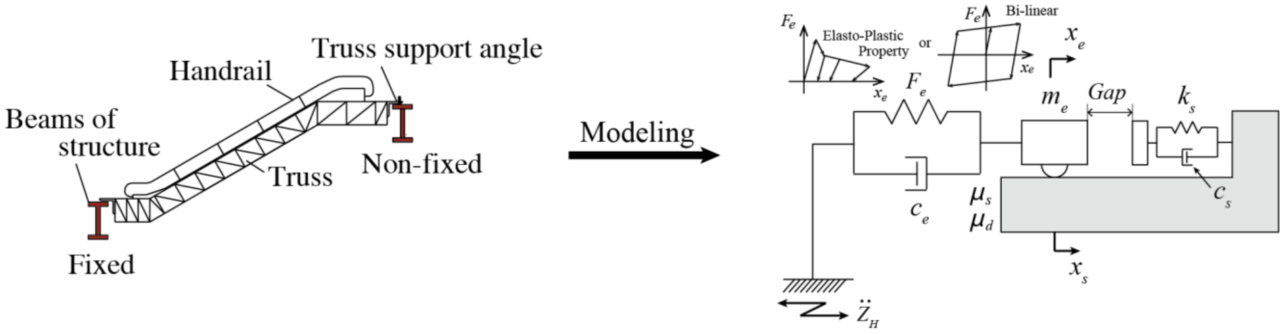
(a) Escalator System (b) Enlarged Picture

Figure 1 Escalator system and the non-fixed side of the escalator

3 ANALYTICAL MODEL

3.1 Analytical model of escalator

In this study, the target escalator is a bottom end fixation - upper and non-fixation type escalator. Focus on the slide friction that is caused between the building beams and the escalator, the simple escalator model of one mass system was built [5]. The dynamic behavior of the escalator truss members is regarded as a spring element, and the damping of the support member is considered. Therefore, the damping force, the friction force, the inertial force and the restoring force act on the escalator. Figure 2 shows the escalator analytical model. In Figure 2: m_e is the mass of the escalator, F_e is the stiffness escalator truss, c_e is the damping coefficient of the escalator truss, μ_s is the static friction coefficient of the escalator truss, μ_d is the dynamic friction coefficient of the escalator truss, x_e is the displacement of the escalator, k_s is the stiffness of the building beam, c_s is the damping coefficient of the building beam, x_s is the displacement of the building, $\ddot{z}_H$ is the acceleration of the bottom end fixation department floor of the escalator. Table 1 shows parameter of escalator. The escalator used in this analysis shall have a mass of 8000[kg] and a head of 6.0[m]. The 1st stiffness k_1 of the escalator truss is calculated using FEM analysis, and the damping ratio ζ_e is 1[%]. In this study, a general escalator installed in the commercial facilities is intended for. In addition, the dynamic friction coefficient and the static friction coefficient is equal in this analysis, and their values are set to 0.25 as the friction coefficient of the typical steel. The behavior of the escalator shall not come under an influence of a building.



(a) Escalator System (b) Escalator Analysis Model

Figure 2 Analytical model of escalator

Table 1 Parameter of escalator

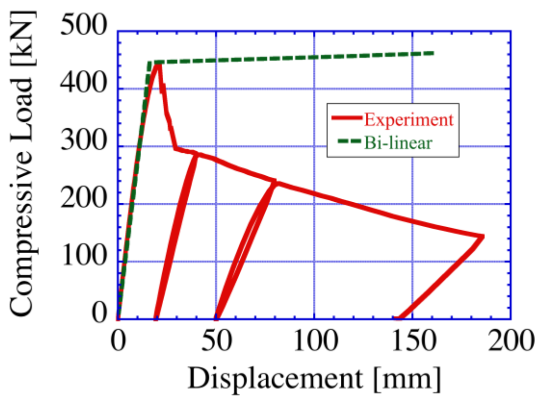
Mass of Escalator m_e [kg]	1st stiffness k_1 [N/m]	Damping ratio ζ_e [%]	Friction Coefficient μ_s , μ_d	*Gap* [m]
8000	2.75×10^7	1	0.25	0.03

3.2 Restoring force characteristics of escalator

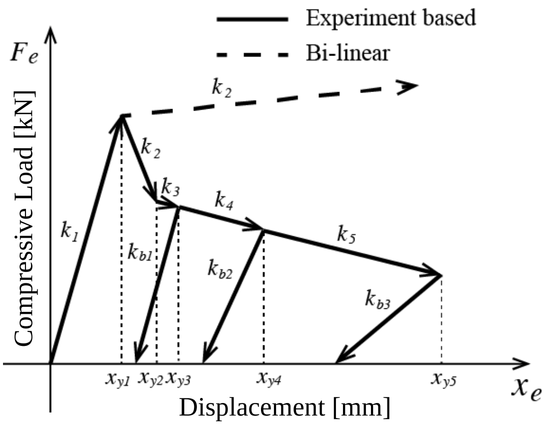
In the past this study, bi-linear model has been used as the restoring force characteristics of the escalator truss. The compression experiment using the size of the original escalator truss was conducted in 2014, so the restoring force characteristics of the escalator truss were provided.

Figure 3 (a) shows the load-displacement curve obtained in the experiment, and (b) shows the result of linear approximation.

It is necessary to revise an escalator analysis model to consider the restoring force characteristics obtained the experiment. Therefore, the restoring force characteristics model of the escalator truss is built by being similar by plural straight lines with the load-displacement curve that the experiment provided. In this paper, the restoring force characteristic obtained from experimental values is called "multi-linear model".



(a) Load-displacement curve of the experiment value and bi-linear model



(b) Linear approximation of the experiment value and bi-linear model

Figure 3 Elasto-plastic properties of the escalator truss in the compression experiment using the size of the original escalator and Bi-linear model

Table 2 Parameter of Escalator Truss Stiffness

	Bi-linear	Experiment based
1st stiffness k_1 [N/m]	2.75×10^7	2.75×10^7
2nd stiffness k_2 [N/m]	1.10×10^5	-2.70×10^7
3rd stiffness k_3 [N/m]	-	-9.70×10^5
4th stiffness k_4 [N/m]	-	-9.70×10^5
5th stiffness k_5 [N/m]	-	-9.70×10^5

3.3 Equation of motion in analytical model of escalator

The three equations of motion are devised, in consideration of influence by the slide friction and the collision to occur between an escalator and the building beams. Equation (3) shows the case that sliding does not occur. Equation (4) shows the case that sliding occurs. Equation (5) shows the case that collision with the construction beams occurs. In addition, Equation (6)~(9) show the switching condition of Case 1, Case 2, and Case 3.

(Case 1) when sliding does not occur

$$\ddot{x}_e = \ddot{x}_s \qquad \dot{x}_e = \dot{x}_s \qquad x_e - x_s = const \tag{3}$$

(Case 2) when sliding occurs

$$m_e\ddot{x}_e + c_e\dot{x}_e + F_e + \mu_d \frac{1}{2} m_e g \cdot \mathrm{sgn}(\dot{x}_e - \dot{x}_s) = -m_e\ddot{z}_H \tag{4}$$

(Case 3) when collision with construction beams occurs

$$m_e\ddot{x}_e + c_e\dot{x}_e + F_e + \mu_d \frac{1}{2} m_e g \cdot \mathrm{sgn}(\dot{x}_e - \dot{x}_s) + k_s\{(x_e - x_s) - Gap\} + c_s(\dot{x}_e - \dot{x}_s) = -m_e\ddot{z}_H \quad (5)$$

Switching condition

Case 1→Case 2

$$\left|m_e(\ddot{x}_e + \ddot{z}_H) + c_e\dot{x}_e + F_e\right| > \mu_s \frac{1}{2} m_e g \quad (6)$$

Case 1→Case 3

$$\left|m_e(\ddot{x}_e + \ddot{z}_H) + c_e\dot{x}_e + F_e\right| > \mu_s \frac{1}{2} m_e g \ \text{ and } \ x_e - x_s \geq Gap \quad (7)$$

Case 2→Case 1

$$\left|m_e(\ddot{x}_e + \ddot{z}_H) + c_e\dot{x}_e + F_e\right| \leq \mu_d \frac{1}{2} m_e g \ \text{ and } \ \dot{x}_e = \dot{x}_s \quad (8)$$

Case 2→Case 3

$$x_e - x_s \geq Gap \quad (9)$$

Case 3→Case 1

$$\left|m_e(\ddot{x}_e + \ddot{z}_H) + c_e\dot{x}_e + F_e\right| \leq \mu_d \frac{1}{2} m_e g \ \text{ and } \ \dot{x}_e = \dot{x}_s \ \text{ and } \ x_e - x_s < Gap \quad (10)$$

Case 3→Case 2

$$x_e - x_s < Gap \quad (11)$$

3.4 Analytical model of building

In this study, it is assumed that the escalator is installed in the three-story steel-frame building, the response of each layer is input into an escalator analysis model. In addition, it is assumed that the restoring force characteristic of the building is tri-linear in consideration of the elastic-plastic deformation. The primary natural period is 0.74[s], and the structural damping of the building is 2[%].

Figure 4 shows the modeling building. In Figure 4, m_{si} is the mass, c_{si} is the damping coefficient, k_{si} is the 1st stiffness, Q_{si1} is the 1st yield load, Q_{si2} is the 2nd yield load, α_{si1} is 2nd stiffness degradation ratio, α_{si2} is 3rd stiffness degradation ratio, $\ddot{z}_H$ is the horizontal seismic acceleration.

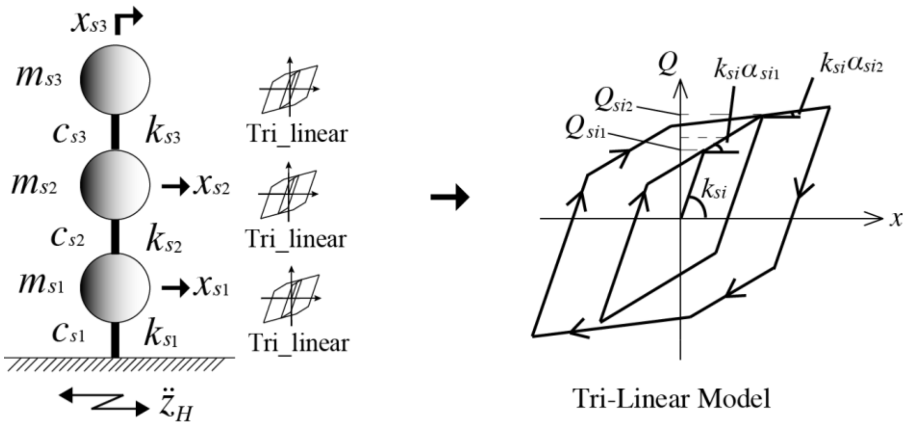


Figure 4 Analytical model of building

Table 3 Parameter of building

Layer	Height [m]	Mass m_{s1} [kg]	1st Stiffness k_{s1} [m]	1st Yield Disp. x_{s1} [m]	1st Stiffness Degradation Ratio α_{si1}	2nd Yield Disp. x_{s2} [m]	2nd Stiffness Degradation Ratio α_{si2}
3	5.5	11.22×10^6	3.48×10^9	1.20×10^{-2}	0.130	5.0×10^{-2}	0.020
2	5.5	9.20×10^6	3.68×10^9	1.55×10^{-2}	0.145	6.4×10^{-2}	0.042
1	6.5	9.70×10^6	3.83×10^9	1.80×10^{-2}	0.212	6.0×10^{-2}	0.056

4 SEISMIC RESPONSE ANALYSIS

4.1 Input seismic wave

In this analysis, the seismic wave is inputted into the analysis model of the building. The seismic response analysis of the escalator is performed by inputting the analysis results of each layer into the analytical model of the escalator. By the seismic response analysis, the changes of the seismic behavior are confirmed by the difference in the restoring force characteristics of the escalator.

Figure 5 shows the response spectrum and the time history wave of the input seismic wave. In this paper, the K-NET Sendai NS Original wave observed at Sendai in the Grate East Japan Earthquake was used. This seismic wave was obtained from Strong-motion Seismograph Network of National Research Institute for Earth Science and Disaster Prevention (K-NET); the observation point is MYG013 [4]. From the response spectrum of Figure 5, a natural period excels in the amplitude of the seismic wave near 0.6~0.7 seconds.

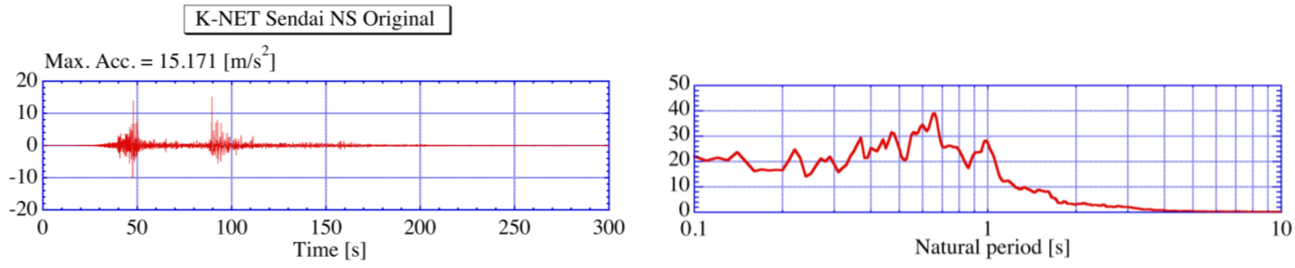


Figure 5 Input seismic waves, and response spectrum (damping ratio 5[%])

4.2 Results of seismic response analysis of building

Figure 6 shows the results of the seismic response of analysis of the building; they are the vibration mode, the maximum acceleration of each floor, the maximum layer displacement, and the maximum layer deformation angle from the left. Focus on the maximum acceleration of each floor, it is clear that the acceleration of the building does not greatly amplify, for increase of acceleration of the seismic wave. It is considered that the seismic energy is absorbed for the elastic-plastic deformation of the building. In addition, it is clear that the floor of the largest layer deformation angle was between the second floor and the third floor. Therefore, there is the high risk that the escalator is installed between the second floor and the third floor falls down.

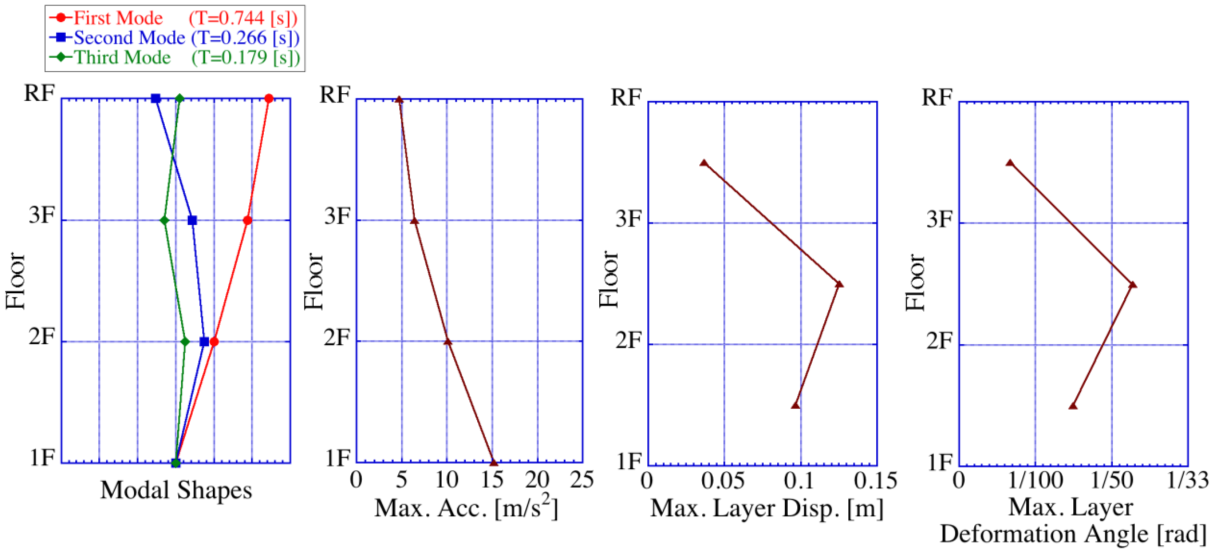


Figure 6 Vibration mode and response values of each floor

4.3 Results of seismic response analysis of escalator

Figure 7 shows the results of the seismic response analysis of the escalators; they are installed on the 2nd through 3rd floors, in case of bi-linear model and multi-linear model obtained from experiment results. Figure 7 expresses the acceleration, the slide displacement, the displacement, the restoring force, and the case (state of the escalator in the sliding and the collision). When the condition of the escalator shifted to Case 3, the acceleration of the escalator shows a big value, it expresses that the escalator replied intensely when the escalator and the building beams collide.

Figure 8 shows the maximum response values of the displacement and the slide displacement of the escalator in such floor. As a result, the response of the escalator installed between the second floor and the third floor showed the biggest value. It is thought that this is because the residual displacement that a building gives to an escalator grows big so that the displacement of the building is big.

As shown in the restoring force of the escalator, plastic deformation occurs to the escalator, and it is able to confirm that that residual displacement is remained. In the bi-linear model and the multi-linear model obtained from experiment results, the big difference by the difference in restoring force characteristics was not seen in the maximum deformation. Therefore, it is supposed that there is little influence to give the seismic behavior of the escalator. When the seismic behavior of the escalator is considered, it is able to be supposed to be bi-linear model.

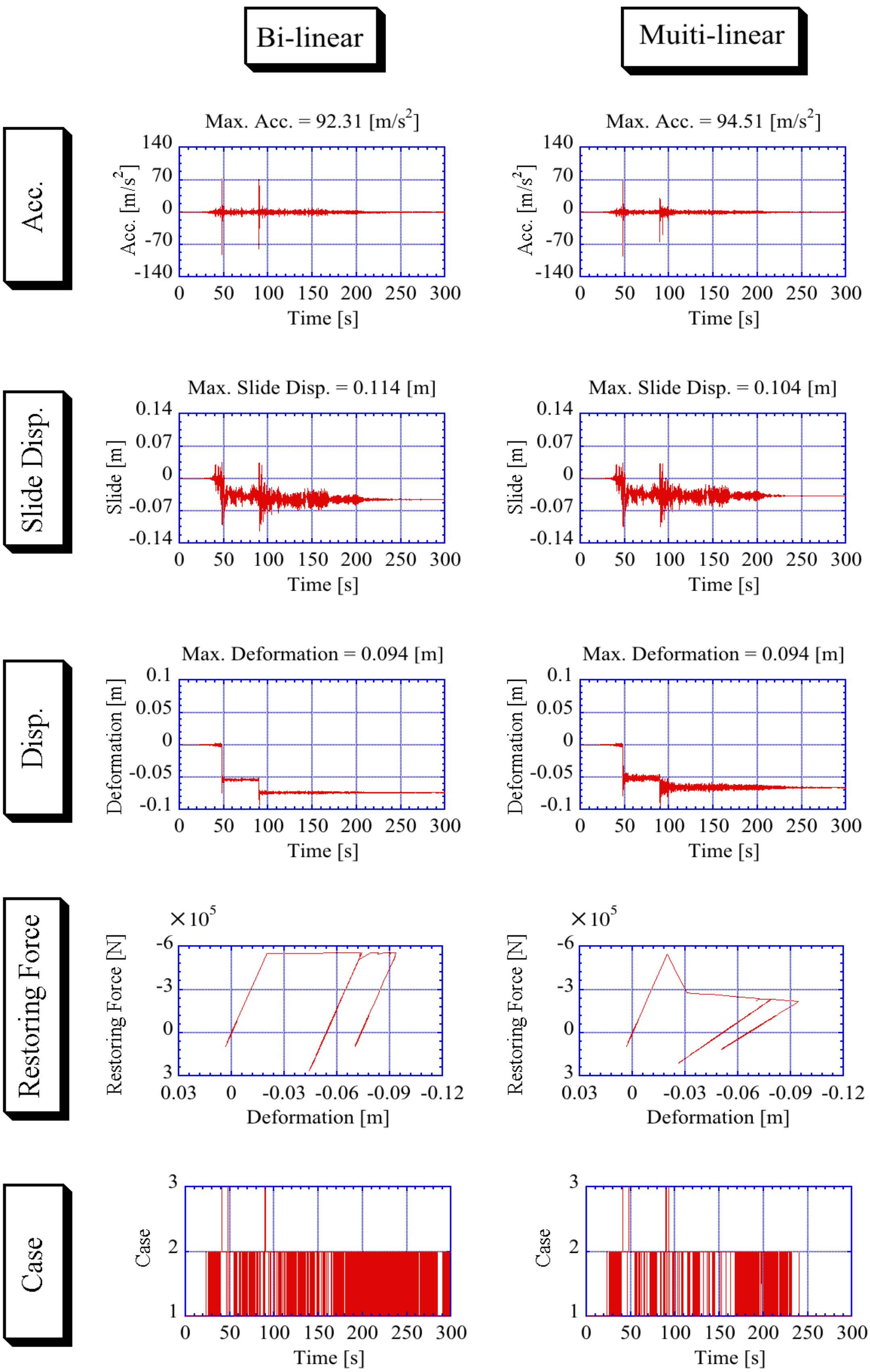


Figure 7 Seismic Response Analysis of Escalator installed between 2nd floor and 3rd floor

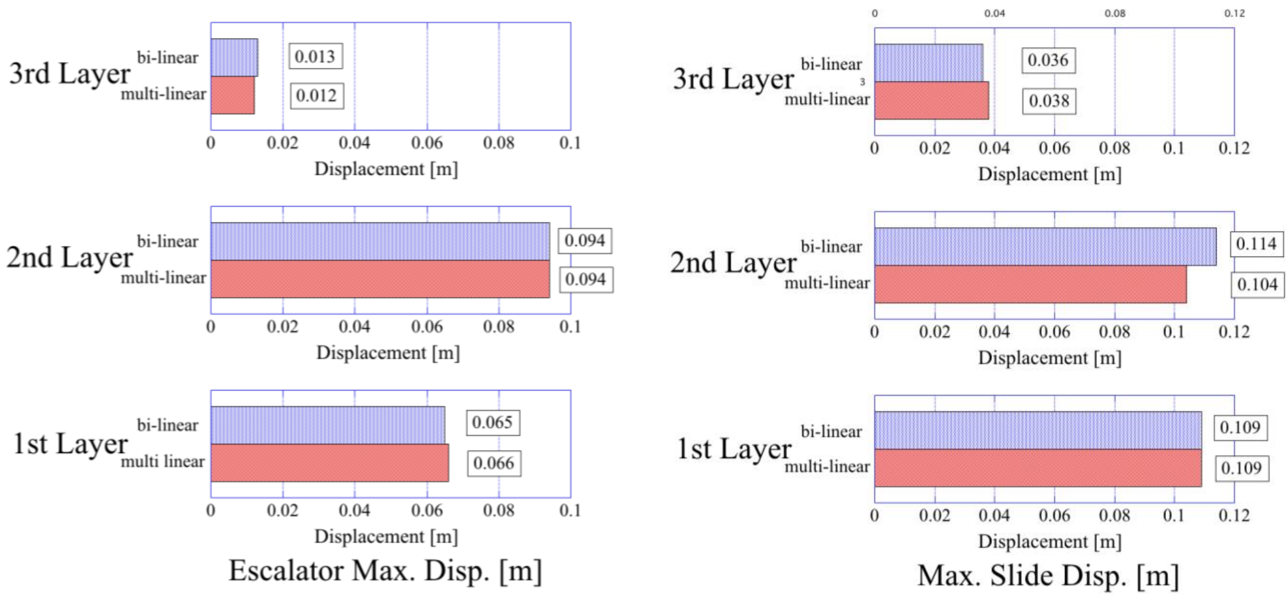


Figure 8 Max. Response values of displacement and slide displacement

5 CONCLUSION

In this paper, the analytical model of escalator was built, that was considered that slide friction and collision caused between escalators and building beams, and elasto-plastic property of the escalator truss obtained by the compression experiment. In addition, the analytical model of building was built, that was similar to the building that fall accidents of escalators occurred in the 2011 Great East Japan Earthquake. Seismic response analysis was performed using 2 kinds of the restoring force characteristics, and the seismic behavior of the escalator was examined. In Bi-linear model and the restoring force characteristics obtained by the experiment, the big difference by the difference in restoring force characteristic was not seen. Therefore, it is thought that the seismic behavior of escalator is evaluated integrally with restoring force characteristics of Bi-linear model in consideration of material properties. In both restoring force characteristics, it is thought that the maximum displacement of the escalator is more likely to depend on forced displacement to receive from a building.

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BIOGRAPHICAL DETAILS

Miss Asami Ishii received a master's degree in mechanical engineering from Tokyo Denki University, Tokyo Japan, 2006. She is now a doctoral course student of Tokyo Denki University. Her research interest includes seismic behavior of escalator and seismic behavior of lift ropes.

Prof. Satoshi Fujita, a JSME (Japan Society of Mechanical Engineers) Fellow, has ten years of management experience as a director, a dean of school of engineering and currently a vice-president of Tokyo Denki University. He has been engaged in engineering research and development of seismic isolation systems and vibration control systems for buildings or key industrial facilities for over 35 years at both University of Tokyo and Tokyo Denki University. In recent ten years, he has been a committee member of the Panel on Infrastructure Development of Japanese ministry of land, infrastructure and transport (MILIT), and a chair of the Special Committee on Analysis and Evaluation of Lifts, Escalators and Amusement Facilities Accidents and Failures held in MILIT. In addition, he has been a chair of the ISO TC178 Japanese committee.

Lift Guide Rail – Counterweight/Car - Suspension Systems under Seismic Excitations: the Dynamic Behaviour and Protection Measures

Stefan Kaczmarczyk

Faculty of Arts, Science and Technology, University of Northampton, UK

Keywords: Guide Rail, Counterweight/ Car, Seismic Excitation, Dynamic Response, Tuned Mass Damper

Abstract. Lift systems are susceptible to damage when buildings are subjected to strong earthquake motions. The counterweight - guide rail and car guide rail systems suffer from earthquake-induced vibrations. The most common mode of failure is the counterweight derailment. This paper reviews that dynamic phenomena and presents a model to study, to predict and to mitigate the effects of the seismic responses of guide rail – counterweight/ car – suspension systems. The application of a Tuned Mass Damper (TMD) is a convenient method to reduce the guide rail-counterweight/ car response and to control the system operating under seismic conditions. In the TMD arrangement vibrations of the counterweight/ car can be suppressed and the stresses in the guide rails reduced by the application of an auxiliary spring – damper - mass system attached to the main structure. In the counterweight system a part of the counterweight mass can be used as the auxiliary mass. The performance of the TMD can be improved by the application of an actuator force determined by a suitable feedback control algorithm.

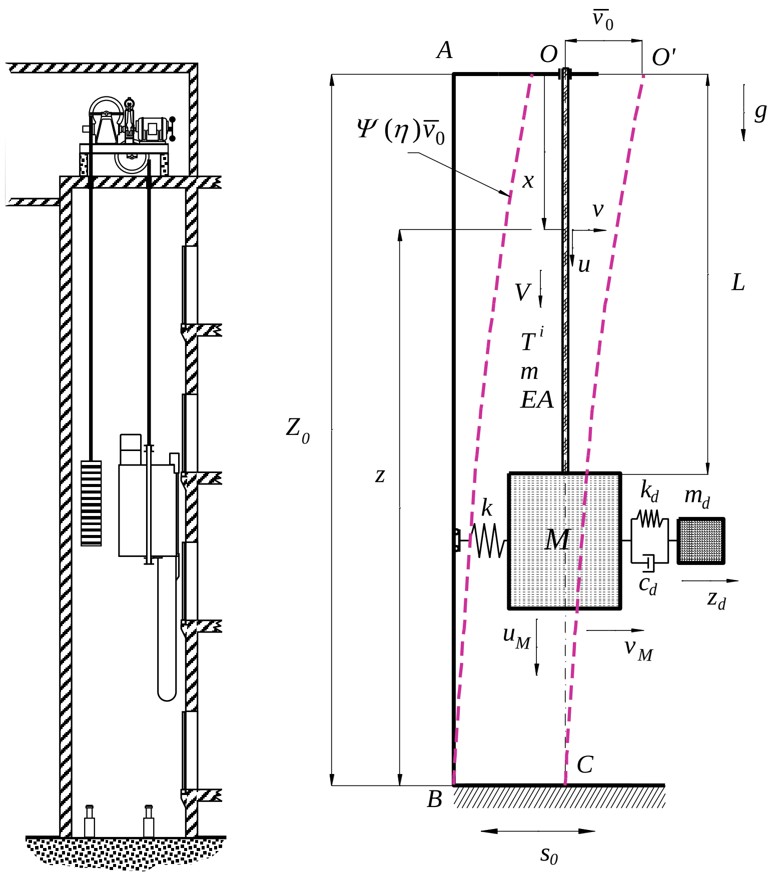
1 INTRODUCTION

Lift installations subject to seismic conditions suffer from service disruption and damage. Various surveys have been conducted and the performance of lifts during strong earthquakes has been documented and analyzed [1-2]. For example, the statistics from the analysis of an earthquake which took place in San Fernando, California, on 9th February 1971, caused significant damage to vertical transportation systems in affected buildings, and provided a base for development of safety requirements for lifts operating in seismic risk zones [3,4]. The available statistics show that the counterweight - guide rail as well as the car guide rail systems suffer from earthquake-induced vibrations. The counterweight is the heaviest component of a lift system and the most common mode of failure is the counterweight derailment and its collision with the car. Other damage and modes of failure include bent guide rails, broken guide rail brackets, loose/ broken roller guides, moved/ damaged machine room equipment, suspension ropes/ compensating ropes damaged/ jumped out of the traction sheave/ diverter pulleys and broken/ tangled travelling cables.

A good understanding and prediction of dynamic phenomena occurring in lift installations subject to excitation forces due to earthquake ground motions is essential for developing mitigation and control strategies. The national and international safety codes [4,5] provide specific design guidance and safety measures to be applied for lift installations that operate in seismic zones. Those include the application of seismic switches / detection systems, counterweight displacement detectors, position restrainers to the car and counterweight frames, rope guards to prevent ropes jumping from the sheaves /pulleys and reinforced guide rails. Additional mitigating measures might involve damping devices and the use of a part of the counterweight as a tuned mass damper (TMD) [6]. In this paper, a dynamic model of a lift guide rail – counterweight/car - suspension system subject to seismic excitations is developed in order to analyse and assess the effectiveness of application a TMD to suppress the dynamic response of the lift system.

2 BUILDING STRUCTURE AND LIFT GUIDE RAIL – COUNTERWEIGHT/CAR - SUSPENSION SYSTEM INTERACTION MODEL

The diagram presented in Fig. 1(a) shows a typical configuration of a traction lift installation, and Fig. 1(b) illustrates a simplified model of a building (host) structure - lift guide rail – counterweight/car - suspension system subjected to seismic excitation. A mass – vertical rope system is mounted within the hoistway (well) structure. The larger (primary) mass shown on the diagram as M, represents the lift car or counteweight which is attached to the lower end of the rope (equivalent to the multi-roping arrangement in the lift suspension system) of length L and is constrained horizontally within the host structure by a spring of effective coefficient of stiffness k. This spring represents a combined flexibility of the roller guide - guide rail – guide rail bracket system. The auxiliary (secondary) mass m_d is attached to the primary mass via a spring – damper element of coefficient of stiffness k_d and coefficient of viscous damping c_d. The upper end of the rope is passing through O at the top of the well of height AB = Z_0. The system moves vertically in the hoistway at transport speed V and acceleration a. The mean quasi-static tension, mass per unit length, modulus of elasticity and cross-sectional metallic area of the rope are denoted as $T^i = \left[M + m_d + m(L-x)\right](g-a)$, m, E and A, respectively. The Eulerian spatial coordinate x is measured from the upper end downwards as shown. The lateral dynamic displacements of the rope are denoted as $v(x,t)$. They are coupled with the longitudinal displacements denoted as $u(x,t)$. The lateral and longitudinal motions of mass M are denoted as $v_M(t)$ and $u_M(t)$, respectively. The auxilliary mass m_d is constrained to move horizontally with its motion denoted as z_d. The structure is subject to ground motion $s_0(t)$ and that the structure undergoes bending deformations with displacements $v_0(t)$ at the top of the well.



(a) (b)

Figure 1 (a) Traction lift system; (b) simplified model of the car/ counterweight mass – suspension rope system with TMD

2.1 Equations of Motion

The equations of motion can be developed by the applications of the Hamilton's principle [7] and are formulated as follows

$$m\frac{D^2u}{Dt^2}-EA\varepsilon_x=0,\ \ m\frac{D^2v}{Dt^2}-T_{ML}v_{xx}+m(g-a)(xv_{xx}+v_x)-EA(\varepsilon v_x)_x=0$$
$$M\ddot{v}_M+T^i(L)v_x\big|_{x=L}+k\Delta_s-k_d(z_d-v_M)-c_d(\dot{z}_d-\dot{v}_M)+EA\,\varepsilon\big|_{x=L}v_x\big|_{x=L}=0$$
$$m_d\ddot{z}_d+k_d(z_d-v_M)+c_d(\dot{z}_d-\dot{v}_M)=0,\ \ (M+m_d)\ddot{u}_M+EA\,\varepsilon\big|_{x=L}=0 \tag{1}$$

where $\varepsilon=u_x+v_x^2/2$ represents the axial strain, $D(\ )/Dt=(\ )_t+V(\ )_x$ $(\ )_t$ and $(\ )_x$ represent partial derivatives with respect to time t and x, respectively, $T_{ML}=(M+m_d+mL)(g-a)$ and Δ_s is the deformation of the equivalent spring k. For tensioned members such as steel wire ropes (SWR) the lateral frequencies are much lower than the longitudinal frequencies. Thus, considering that the excitations frequencies are much lower than the fundamental longitudinal frequencies the longitudinal inertia of the ropes can be neglected in the first equation in (1). This equation can be integrated to give $u_x=e(t)-v_x^2/2$ where $e(t)$ represents the quasi-static axial strain in the rope.

2.2 Resonance response to ground excitation

During the earthquake activity buildings are subject to ground (base) excitation motion. Very often the fundamental frequencies of the buildings fall within the frequency range of the ground motion [2]. Thus, in the scenario considered in this paper it is assumed that the ground motion $s_0(t)$ corresponding to the harmonic of frequency Ω_0 is exciting the fundamental mode of the building structure of the same frequency. This excitation results in bending deformations of the well structure described by the polynomial shape function $\Psi(\eta)=3\eta^2-2\eta^3$ (see Fig. 1), where $\eta=z/Z_0$ with z denoting a coordinate measured from ground level. At the top of the well ($z = Z_0$) the bending deformations lead to harmonic motions / displacements v_0 of frequency Ω_0 and of amplitude v_{0max}. In order to accommodate the base excitation in the equations of motion (1) the overall lateral displacements of the rope – mass system are expressed as

$$v(x,t)=\bar{v}(x,t)+s_0(t)+\left(1+\frac{\Psi_L-1}{L}x\right)\bar{v}_0(t),\ \ \Psi_L=\Psi\left(\frac{Z_0-L}{Z_0}\right) \tag{2}$$

where $s_0(t)$ is harmonic motion of frequency Ω_0 and $\bar{v}_0(t)=v_0(t)-s_0(t)$. The relative lateral displacements $\bar{v}(x,t)$ can then be expressed using the finite series given by

$$\bar{v}(x,t)=\sum_{n=1}^{N}\Phi_n\left[x;L(\tau)\right]q_n(t) \tag{3}$$

where $q_n(t)$ represent the generalised coordinates and $\Phi_n\left[x;L(\tau)\right]$ are orthogonal trial functions depending on the spatial coordinate and the length of the ropes. In this formulation it is assumed that the lift is moving at reduced speed under the seismic conditions. Thus, the length of the rope varying slowly with time meaning that the change of L over a period corresponding to the fundamental frequency of the system is small compared to L [7]. In order to represent this fact a slow time scale defined as $\tau=\epsilon t$, where $\epsilon = 1$ is a small parameter, is introduced.

The trial functions satisfy the homogenous boundary conditions and are defined as $\Phi_n\left[x;L(\tau)\right]=\sin\left[\lambda_n(L(\tau))x\right],\ n=1,2,\ldots,N$, with N denoting the number of terms/ modes taken in (3).

The eigenvalues $\lambda_n\left(L(\tau)\right)$ that vary with the length of the rope are determined from the frequency equation given as

$$\left(k-\frac{M}{m}T_{Md}\lambda_n^2\right)\sin\left(\lambda_n L\right)+T_{Md}\lambda_n\cos\left(\lambda_n L\right)=0,\ T_{Md}\equiv T^i\left(L\right)=\left(M+m_d\right)\left(g-a\right) \tag{4}$$

It should be noted the stiffness coefficient *k* would vary with vertical motion of the mass. However, an assumption is made that this variation is small and *k* is considered to have a constant value [8]. As stated above *k* represents a combined flexibility of the roller guide and the guide rail – guide rail/ bracket system. In the analysis to follow the guide rail is modelled as multi-span beam. The coefficient of stiffness is then calculated according to BS EN81-50:2014 specifications for guide rail deflection (based on a 3-span beam model). The TMD design can then based on the worst case scenario when the system is near the resonance.

The response of the system when rth mode is subject to resonance can then be determined by considering a single-mode approximation with the relative displacements expressed as $\bar{v}(x,t)=\Phi_r\left[x;L(\tau)\right]q_r(t)$. The linearized lateral response (uncoupled from the longitudinal mode) of the main mass can then be defined by the following set of two ordinary differential equations

$$\begin{aligned}&m_{re}\ddot{\bar{v}}_M+\tilde{c}_{re}\dot{\bar{v}}_M+\tilde{k}_{re}\bar{v}_M-k_d\left(z_d-\bar{v}_M\right)-c_d\left(\dot{z}_d-\dot{\bar{v}}_M\right)=Q_{re}\left(t;\tau\right),\\&m_d\ddot{z}_d+k_d\left(z_d-\bar{v}_M\right)+c_d\left(\dot{z}_d-\dot{\bar{v}}_M\right)=Z_{re}\left(t;\tau\right),\\&m_{re}=\frac{m_r}{\Phi_r^2\left(L\right)};\ \tilde{c}_{re}=\frac{\tilde{c}_r}{\Phi_r^2\left(L\right)};\ \tilde{k}_{re}=\frac{\tilde{k}_r}{\Phi_r^2\left(L\right)},\ Q_{re}\left(t;\tau\right)=\frac{Q_r\left(t;\tau\right)}{\Phi_r\left(L\right)},\ Z_{re}\left(t;\tau\right)=\frac{Z_r\left(t;\tau\right)}{\Phi_r\left(L\right)}\end{aligned} \tag{5}$$

where modal damping is introduced through the coefficient $\tilde{c}_r=2m_r\zeta_r\tilde{\omega}_r$, where $\tilde{\omega}_r=\sqrt{\tilde{k}_r/m_r}$ and

$$\begin{aligned}&m_r=\int_0^L\Phi_r^2dx+M\Phi_r^2\left(L\right),\ \tilde{k}_r=k_r+K_{rr},\ k_r=m_r\omega_r^2,\ \omega_r=\lambda_r\sqrt{\frac{T_{Md}}{m}},\\&K_{rn}=m\left[g\Psi_{rn}+\left(g-a\right)\left(\Theta_{rn}-L\Upsilon_{rn}\right)\right],\ \Psi_{rn}=\int_0^L x\Phi_n''\Phi_r dx,\Psi_{rn}=\int_0^L\Phi_n'\Phi_r dx,\ \Upsilon_{rn}=\int_0^L\Phi_n''\Phi_r dx,\end{aligned} \tag{6}$$

At the right-hand sides of Eq. 5 Q_r and Z_r represent excitation functions due to the base harmonic motions.

3 COMPUTER SIMULATION TESTS AND RESULTS

The dynamic response of the system to seismic excitation is investigated through a numerical simulation of the linearized equations (5). The 4th-5th order Runge-Kutta algorithm is used in the simulation tests. The fundamental parameters of the system are presented in Table 1. In the scenario considered in the simulation the fundamental frequency of the building is given as Ω_0 = 3.3929 rad/s (0.54 Hz). The primary mass $M = P + 0.5Q$ representing a counterweight (cwt) is fitted with a TMD and travels upwards at reduced speed of 0.75 m/s. During travel the length of the ropes is changing from $L(0) = L_{max}$ = 128.66 m to to L_{min} = 8.66 m. The frequency of excitation is near the 2nd natural frequency (n = 2) and the 1st (fundamental natural frequency, n = 1) of the cwt – suspension system during the lift travel when the length of the ropes are between 120 m – 100 m and 60 m - 40 m , respectively, see Fig. 2. Fig. 3 shows the corresponding mode shapes of the system determined at L = 120 m and 45 m, respectively. The optimal value of damping ratio of the TMD system is determined as $\zeta_d=\sqrt{\frac{3\mu}{8(1+\mu)}}$, where $\mu={m_d}/{m_{re}}$, so that $c_d=2m_d\zeta_d\omega_d$, where

$\omega_d = \sqrt{k_d / m_d}$. By noting that the ratio of natural frequencies is given as $\omega_d / \tilde{\omega}_r = (1+\mu)^{-1}$, the coefficient of stiffness of TMD is determined as $k_d = m_d \left(\frac{\tilde{\omega}_r}{1+\mu} \right)^2$.

Considering that the frequency of base excitation becomes tuned to the fundamental mode of the system when the length of the suspension ropes L is approximately 45 m the parameters of TMD are determined as m_d = 296.913 kg, k_d = 2819.9 N/m and c_d = 337.895 Ns/m. Fig. 4 and Fig. 5 show the lateral response $\bar{v}_M$ of the primary mass vs. time, and the corresponding forces acting upon the guide rail vs. time, determined by numerical simulation, with TMD action (red solid lines) and without TMD action (dashed blue lines). The plots presented in Fig. 4 correspond to the region where the frequency of excitation is near and the fundamental natural frequency and the plots in Fig. 5 correspond to the region where the frequency of excitation is near to the 2nd natural frequency of the system, respectively. Within those regions both modes are associated with the motion of cwt. It is evident that the resonance oscillations and forces are becoming attenuated by the TMD action by about 30%. In addition, Fig. 6 demonstrates that the application of TMD at the cwt results in attenuation of the rope vibrations that are associated with the 2nd mode of the system.

Table 1 Fundamental parameters of the system

Parameter	**Value**	**Unit**
Car mass P	2000	kg
Rated load mass Q	1600	kg
Rope mass per unit length m_r	0.872	kg/m
Number of ropes n_r	6	
Travel height H	120	m
Young's modulus of guide rail E_g	2.07×10^5	N/mm^2
Guide rail 2nd moment of area	947×10^4	mm^4
Guide rail bracket spacing L_g	2.5	m
Roller guide coefficient of stiffness k_{rg}	1.6674×10^5	N/m
Damping ratio ζ_r	0.25	
Fundamental frequency of the building Ω_0	0.52	Hz
Peak amplitude displacements of the building v_{0max} at $z = Z_0$	75	mm
Mass ratio μ	0.1	

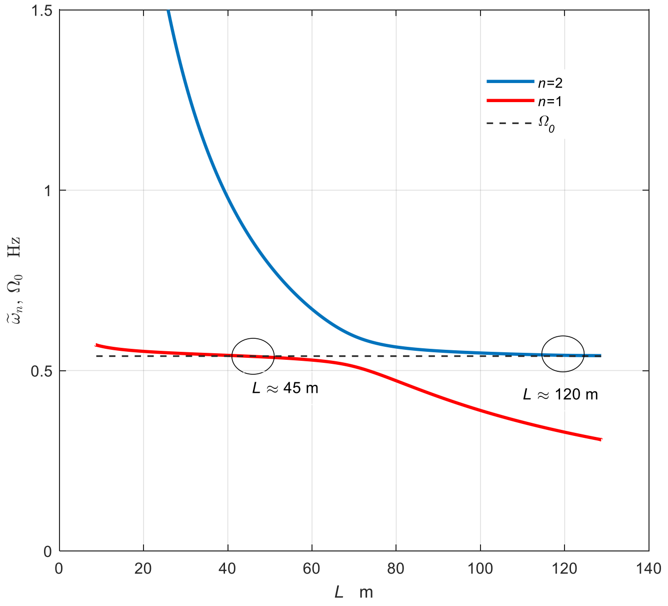
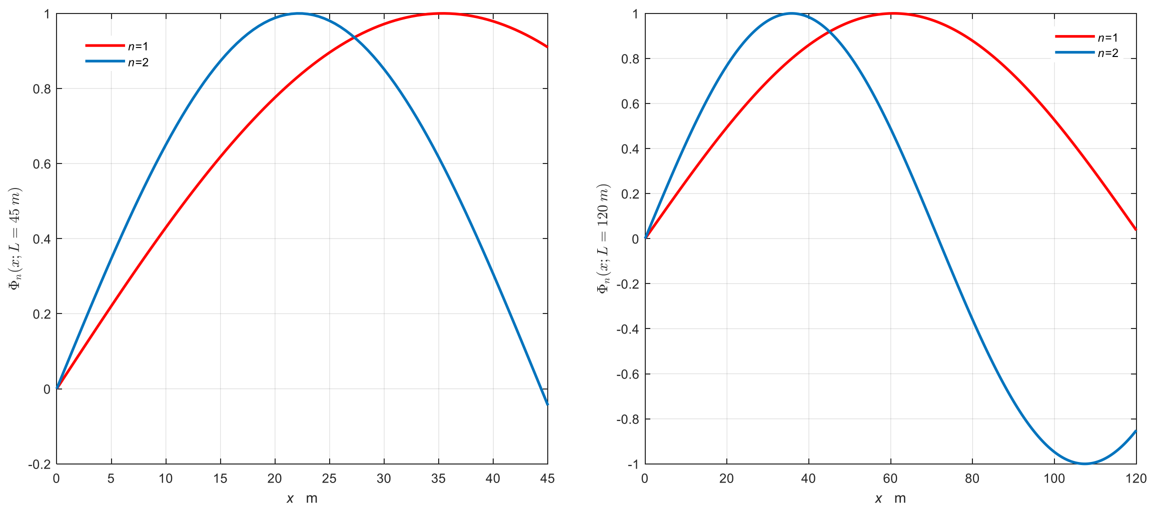
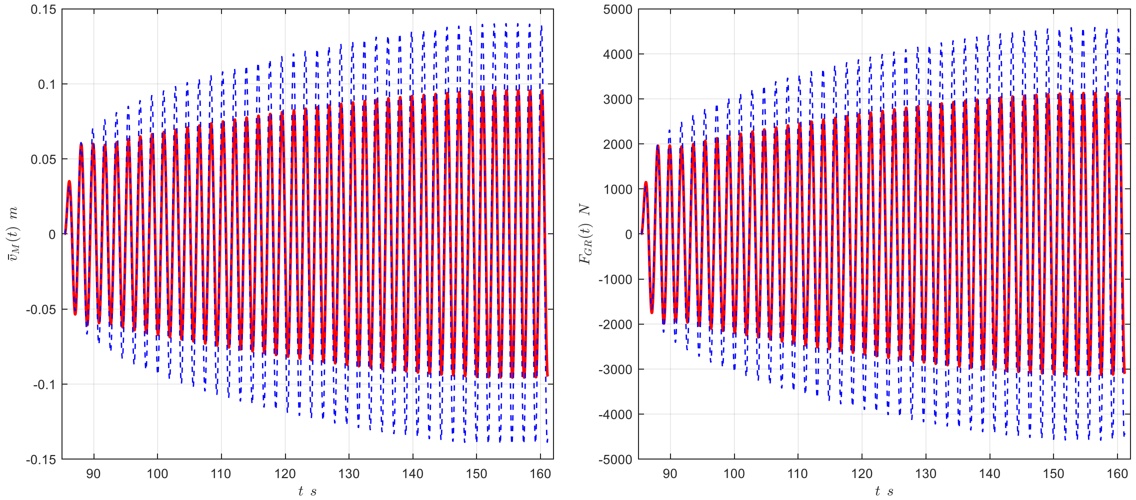


Figure 2 The 1st mode and 2nd mode natural frequencies and resonance regions.



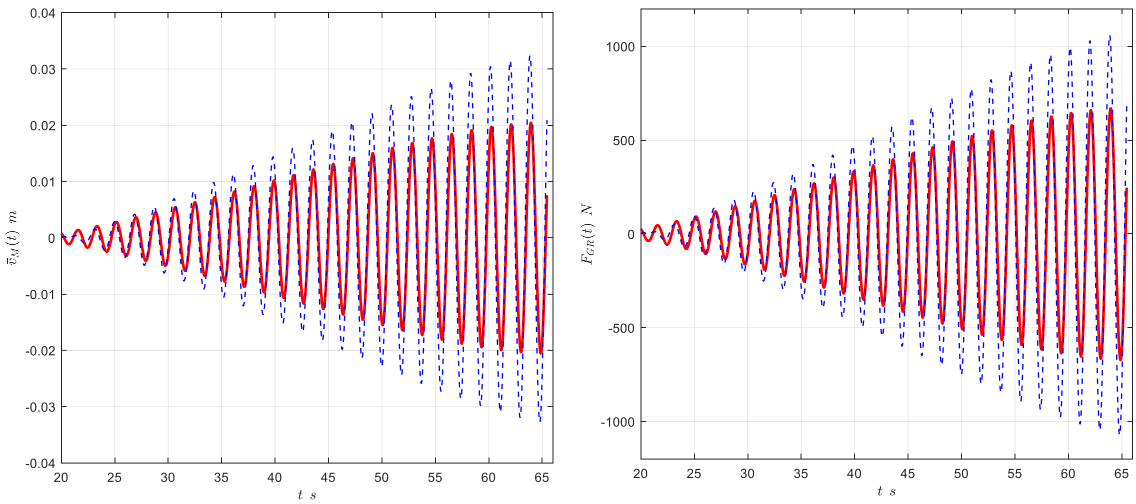
(a) **(b)**

Figure 3 The 1st mode and 2nd mode shapes (a) at *L* = 45 m, (b) at *L* = 120 m.



(a) (b)

Figure 4 (a) Displacements of the primary mass; (b) guide rail forces at the 1st mode resonance (blue dashed line without TMD and red solid line with TMD action)



(a) (b)

Figure 5 Displacements of the primary mass (a) and guide rail forces (b) at the 2nd mode resonance (blue dashed line without TMD and red solid line with TMD action)

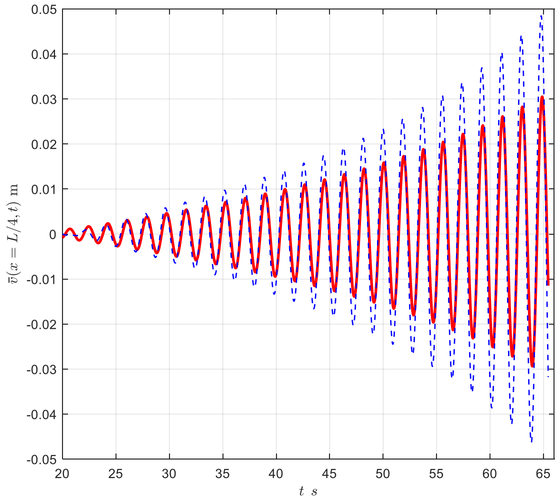


Figure 6 Displacements of the rope at $x = L/4$ at the 2nd mode resonance (blue dashed line without TMD and red solid line with TMD action)

4 CONCLUDING REMARKS

Seismic-induced ground motions have adverse influence on the performance of lift installations. Dynamic models and computer simulation techniques facilitate the prediction of responses to, and mitigate the effects of, those excitations. The analysis and results presented in this paper show that under resonance conditions the application of a passive TMD system forming a part of the counterweight (or the car – frame assembly) is effective in reducing the dynamic responses and dynamic forces acting upon the lift system components. The level of reduction predicted in the case study discussed above is about 30%. In order to achieve higher performance of the system an active TMD (ATMD) can be introduced. The ATMD system is equipped with a controller, sensors and an actuator providing a control force [9].

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EN 81:20/50 as a Key Driver for Technological Innovation in the Next Generation of Lifts

Dennis Major

Lift Technology Product Consultant

Keywords: Lift, Innovation, EN81:20/50, Mechatronic safety system

Abstract. The current EN 81-1 Norm is going to be replaced by EN 81-20 / 50: 2014 on August 31st, 2017. This paper covers some topics to be considered in the implementation of the new standard. In addition, innovative approaches for alternative suspension system and safety devices can also be taken by means of risk analysis, according to the Lift Directive 2014/33 / EU: the introduction of mechatronic systems opens up entirely new ways to dispense with conventional speed limiters in the near future.

To implement such systems, fails-safe electromechanical brakes must also be developed. This is part of a trend in the lift business to reduce the number of required components and integrate them to optimise the use of available shaft space. The challenges to master this technology in the context of a complete lifts, and how to cope with the increasing complexity for installation, testing and maintenance by developing complete 3D models for each project are also discussed in this article.

1 INTRODUCTION

Introduced in August 2014, the new European standards EN 81-20 and EN 81-50 bring considerable benefits in terms of accessibility and safety for both passengers and service engineers.

The familiar EN 81-1 is no longer valid since 31.08.2017 when it was permanently replaced by the new standards. This document covers some of the topics to be considered in the implementation of the new directive in a new lift project.

Where designs diverge from EN 81-20/50:2014, the Lifts Directive 2014/33/EU allow taking innovative approaches by means of risk analysis, specifically concerning the use of innovative safety solutions.

Furthermore, mechatronic systems open up brand new ways to avoid conventional speed limiters in the future, reducing the number of components inside the shaft and allowing bigger cars in the same shaft area. Likewise, we should consider the use of electromechanical safety gear. At the end of the document, we outline the challenges we need to overcome for the successful introduction of the next generation of lifts.

2 SCHEDULE OF LATEST UPDATES OF NORMS AND CODES

- Lifts Directive: 20.04.2016
- EN 81-20/50:2014 31.08.2017
- Draft EN 81-20/50 A1 expected to be released early 2018

3 SIGNIFICANT CHANGES IN EN 81-20 FROM EN 81-1/2

The new EN 81-20 introduces a set of significant changes from the previous standards, which aims to improve safety for passengers and for service engineers as well as clarify and improve the current building interface requirements introducing changes that may affect the building design.

This section gives an overview of the main changes to the safety requirements introduced in EN 81-20 that have to be carefully considered and may have a direct impact on the introduction of PESSRAL (Programmable Electronic Systems in Safety Related Applications for Lifts) system.

3.1 Lift Car Safety Zones

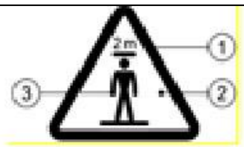
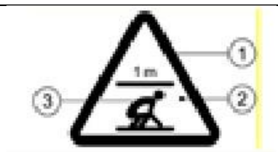
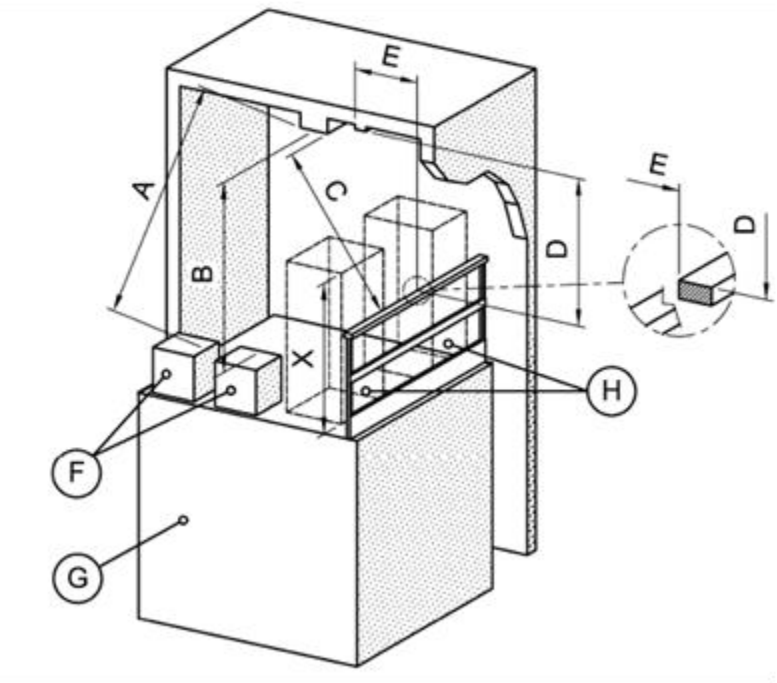
Model	**Position**	**Warning sign**	**Horizontal dimensions of the safety zone** m x m	**Height of safety zone** m
1	Upright		0.40 x 0.50	2.00
2	Crouching		0.50 x 0.70	1.00
Legend for warning signs 1- black 2- yellow 3- black				

Figure 1: Dimensions of the safety zones in the shaft head [Source: DIN EN 81-20, Table 3]

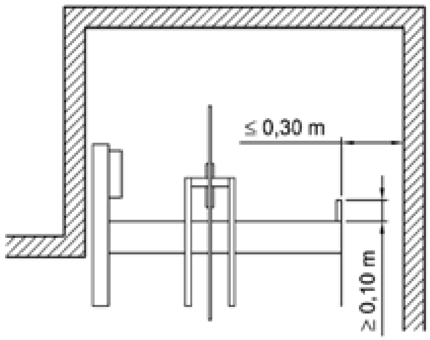


Legend

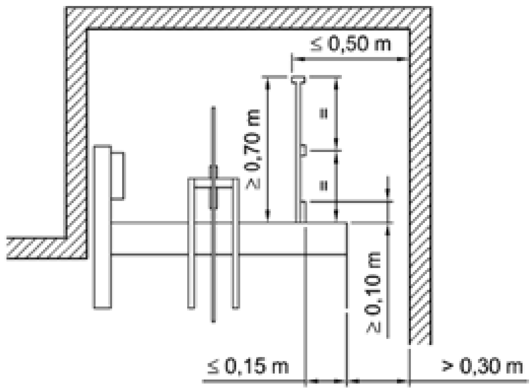
A	Clearance ≥ 0.50 m (5.2.5.7.2 a))
B	Clearance ≥ 0.50 m (5.2.5.7.2 a))
C	Clearance ≥ 0.50 m (5.2.5.7.2 c) 2))
D	Clearance ≥ 0.30 m (5.2.5.7.2 c) 1))
E	Clearance ≤ 0.40 m (5.2.5.7.2 c) 1))
F	Highest parts installed on the lift car roof
G	Lift car
H	Safety zone

Figure 2: Minimum distances between the parts mounted on the lift car roof and the lowest parts mounted on the shaft ceiling [Source: DIN EN 81-20]

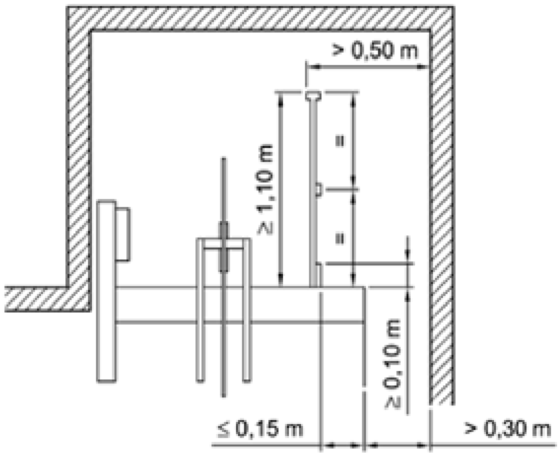
3.2 Balustrades



No railings required
but baseboard required with a min. height of 100 mm



Railings required, min. height 700 mm
and a baseboard, min. height 100 mm



Railings required, min. height 100 mm
and a baseboard, min. height 100 mm

Figure 3: Balustrades on the lift car roof – height [Source: DIN EN 81-20]

3.3 Device for Bridging the Shaft and Lift Car Door Contacts

Electrical bridging option on the control panel or the emergency and test panel:

- Protected against unintentional actuation
- Labelled "Bypass" or with an icon
- Clear identification of activation state

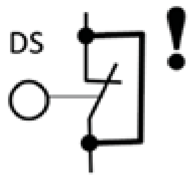


Figure 4: Bridging switch sign [Source: DIN EN 81-20]

Functional requirements:

- Eliminates normal control
- Must be a way to bridge the door and latch contacts from the shaft hatch and lift car doors
- No simultaneous bridging of lift car and shaft hatch contacts
- Driving operation only with service or recall control
- Audible alarm [55 dB (A) at a distance of 1m] in the lift car and flashing light under the lift car

Figure 5: Flashing light with audible alarm

3.4 Second Service Control Device for Shaft Pit

There must be a service control system in the shaft pit.

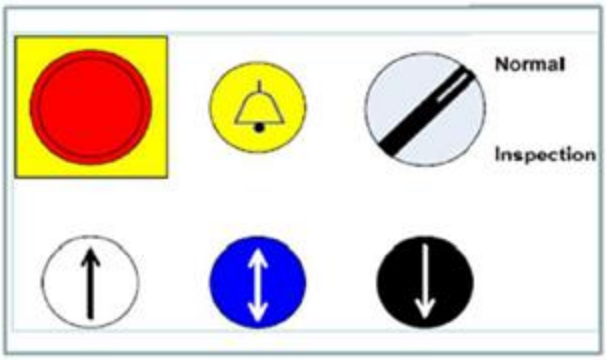


Figure 6: Service control device

Control elements:

- Switch
- Directional buttons "UP" (white) and "DOWN" (black)
- Control button: BLUE, protected against unintentional actuation
- Simultaneous, one-handed actuation of direction and travel buttons
- Emergency stop switch
- Device to prevent the stationary part of dials from twisting

3.5 Lighting (Shaft – Lift Car / Emergency Lighting)

Shaft:

- Min. 50 lux at a height of 1 m above the lift car roof and above the shaft pit
- 20 lux in the rest of shaft
- Sufficient number of lighting fixtures in the shaft and, if necessary, additional lighting on the lift car roof
- Additional (mobile) lighting for any special tasks required

Lift car:

- Normal 100 lux (on controls + 1 m above ground)
- Emergency lighting 5 lux (on alarm trigger device + centre of lift car and lift car roof at a height of 1 m)

3.6 Ladder

Ladder requirements:

- Maximum weight of moveable ladders 15 kg
- Movable ladders must be secured in the threshold and pit to prevent slipping and tipping over
- Distance from rungs to the wall min. 200 mm for vertical ladders
- Distance from threshold to movable ladder in storage position max. 800 mm

- Distance from threshold to rung centre max. 600 mm to disembark
- Electrical monitoring of the storage position for movable ladders that protrude into the lift shaft

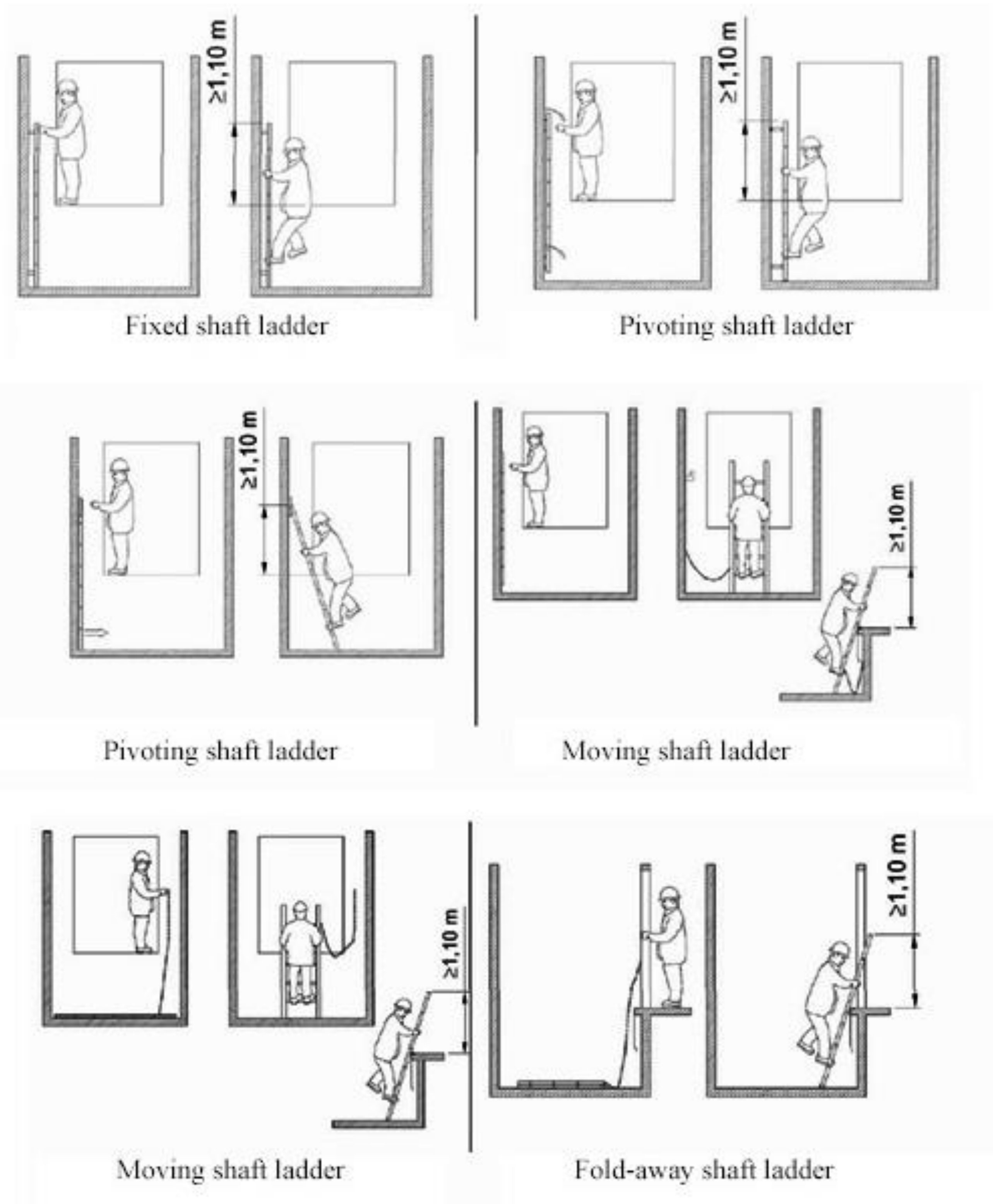


Figure 7: Types of shaft pit ladders [Source: DIN EN 81-20]

4 IMPLEMENTING INNOVATIVE LIFT SYSTEMS BY MEANS OF RISK ASSESSMENT

4.1 Drivers of Lift Design Innovations

In the last 30 years, innovation in lift design was driven by some key targets:

1. Maximising safety of users during lift standard operation safety of technicians and during installation and maintenance activities
2. Reducing pit depth
3. Reducing headroom height
4. Maximising car surface vs shaft dimensions by reducing dimensions of shaft components or eliminate them altogether
5. Combining existing components into logical modules that can perform differently according to different system status (i.e. UCM solutions – Unintended Car Movement)

4.2 Depicting Innovation

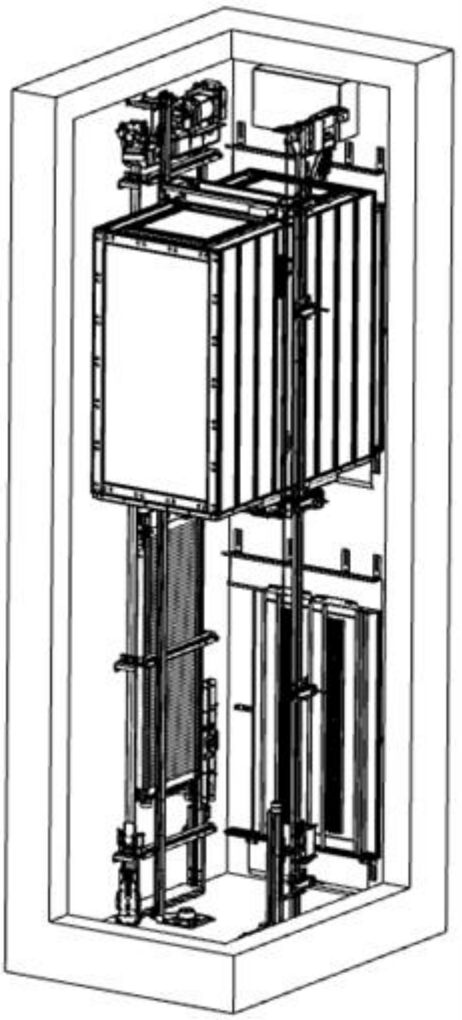


Figure 8: 3D view of a lift implementing innovative solutions in line with EN81-20/50 requirements

Figure 8 shows a lift system incorporating some innovative solutions in line with market requirements. In particular, it features:

- Introduction of a PESSRAL system
  - → No mechanical limit switches
  - → No mechanical service limit switches
  - → Integrated door zone bridging
  - → Integrated UCM solution
- Use of a magnetic strip-based absolute positioning system
- Use of mechatronic safety gear

4.3 Introduction of PESSRAL System

PESSRAL

Programmable Electronic Systems in Safety Related Applications for Lifts

In the elevator industry, today more and more systems are comprised out of electrical and/or electronic elements, which are used to perform safety functions in lifts (see operating modes below). The new EN 81-20 standard contributes by defining SIL (Safety Integrity Level) requirements for safety functions. These kinds of systems require a totally different approach compared to the development for a conventional safety system.

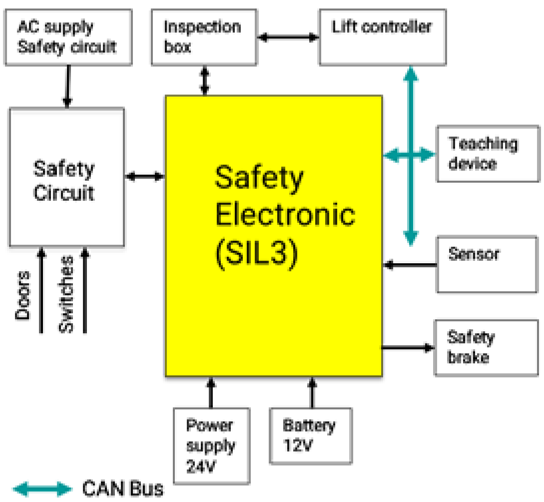


Figure 9: Safety electronics

Examples of safety functions/operating modes performed by electronic elements

- Pre-commissioning
  → Open safety circuit
  → Drive only with call-back control

- Teach-in
  → Door zones
  → Calculation of end positions

- Normal mode

→ Excessive speed detection
→ Open safety circuit
→ Activating the Safety Gear

4.4 Magnetic Strip-Based Absolute System: Main Characteristics

Magnetic tape technology has significant advantages over alternative measuring methods of the car position in the shaft. Contaminations that typically occur in the lift shaft, like dirt, moisture and even smoke do not affect the measurement result - a significant safety advantage over optical systems.

- Impervious to dirt, smoke, moisture and high temperatures
- High transport speeds of up to 10 m/s
- High accuracy and reproducibility
- Absolute location always available
  → No teach-in trips or reference procedures even after long power outages

- Practically wear-free – almost zero mechanical stress
- Significantly reduced number of parts in the shaft
- Savings in assembly and maintenance

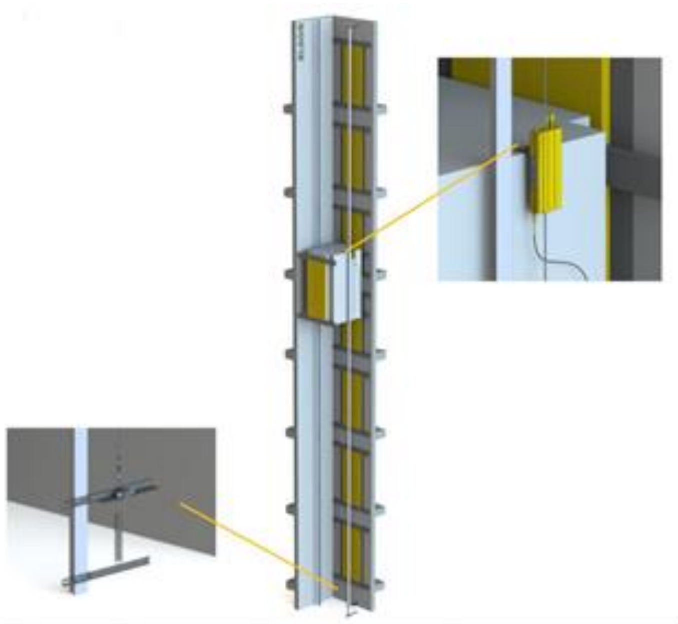


Figure 10: Magnetic strip-based absolute position system [1]

Future-oriented

- Conventional overspeed governor and tension weights can be replaced
- Option for automated trigger of electro mechanical safety gear
- Remote monitoring of safety components via the lift control system

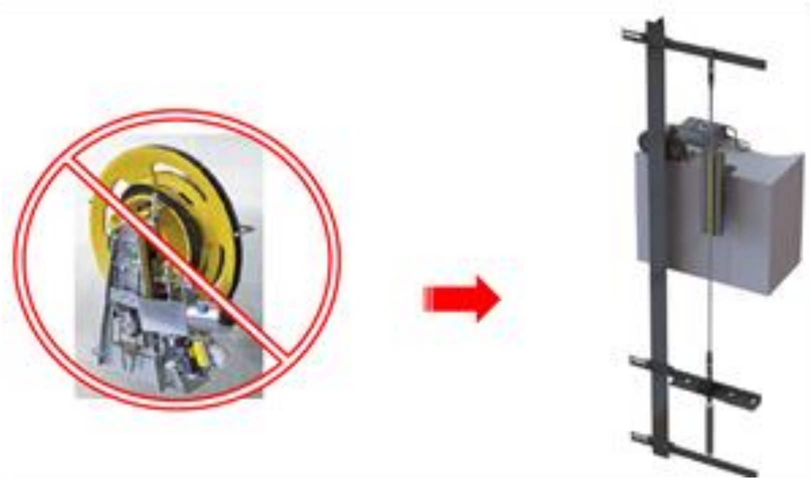


Figure 11: Mechanical Overspeed Governor replaced with electromechanical trigger system [1]

5 FROM CURRENT IMPLEMENTATIONS TO INNOVATIVE MECHATRONIC SAFETY GEAR

5.1 Current Typical Lift Model Implementation

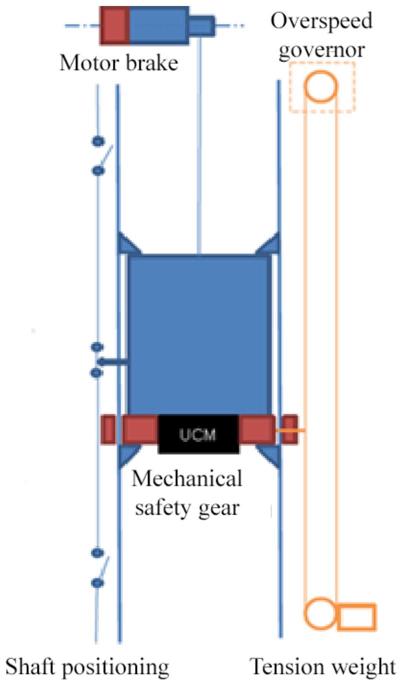


Figure 12: Typical safety gear system

The current typical market implementation of the safety system in a lift, although highly reliable, relies on a quantity of sub-components that take valuable shaft space and are subject to wear and tear:

- Safety gear assemblies
- Mechanical synchronisation of safety gear
- Overspeed Governor

- Tension weight
- Overspeed governor rope
- ... and its connection to the safety gear synchronisation on the lift car

Disadvantages

- Several components used to provide the safety solution, all must function as a compatible system to ensure correct activation
- Sub-optimal shaft utilization
- Reliability (many components, more potential for malfunction, mechanical interfaces are prone to wear and contamination from debris, lubrication build up etc.)
- Accuracy (tripping can happen at potentially dangerous speeds due to mechanical activation in pre-determined points of the over-speed governor wheel)

5.2 Mechatronic Safety Gear System

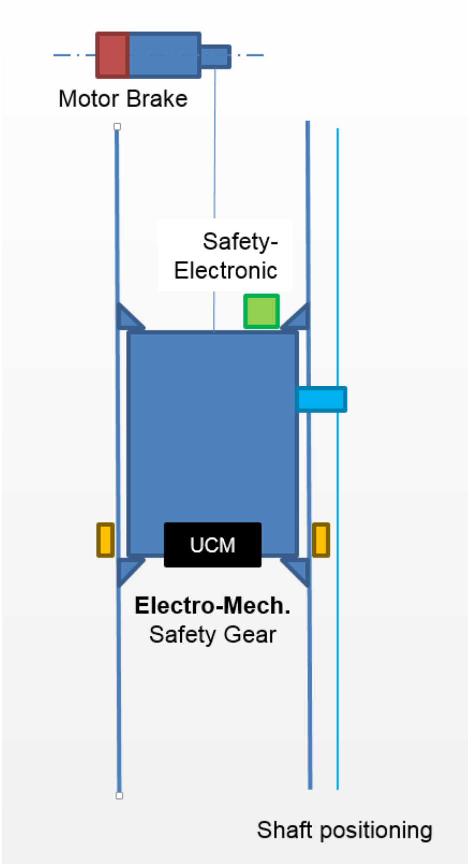


Figure 13: Mechatronic safety gear system

The use of an absolute positioning system opens the way to the adoption of a new type of electromechanical safety gear. A mechatronic safety gear is kept in standby mode by a retention electromagnet. Tripping is deployed by an electrical signal that turns the electromagnet off, thereby freeing an activation spring that performs a mechanical activation of the safety gear.

Synchronisation among additional braking components is electrically performed.

Fewer components

- Mechanical synchronisation of safety gear
- Overspeed Governor
- Tension weight
- Overspeed governor rope
- … and its connection to synchronization

New components

- Sensors (SILx) – shaft positioning
- Safety electronics
- UPS (Uninterruptable Power Supply)

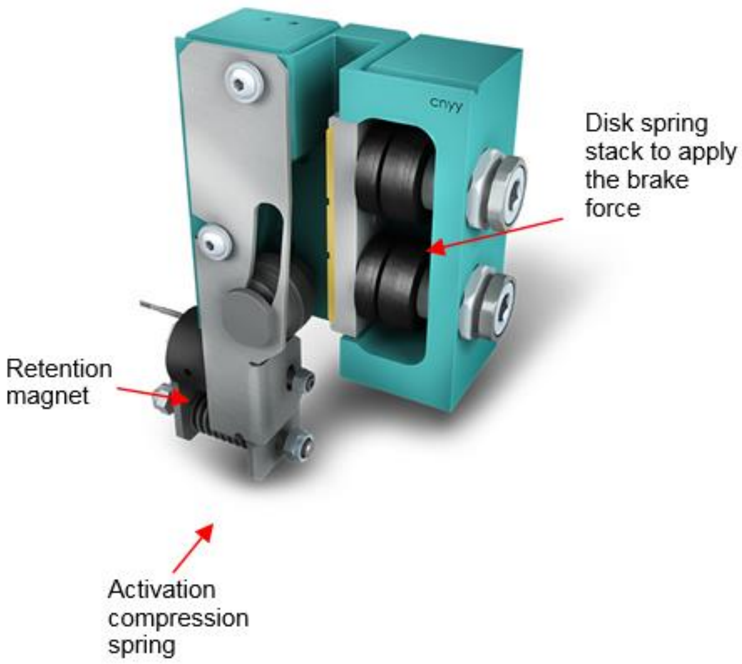


Figure 14: Mechatronic safety gear

Advantages

- Less components in the shaft
- More space for the cabin inside the same shaft
- Faster activation can be achieved compared to mechanical activation, overspeed conditions could even be detected before they reached critical activation.
- Easy synchronisation between multiple units open the way to new and optimised design for car slings
- Easy integration in a complete UCM solution against uncontrolled car movement when open at a landing, no additional control modules or electronic monitors on overspeed governors required.
- Easy connection to remote cloud-based monitoring systems for smart maintenance and general speed monitoring (acceleration/deceleration rates)

To be considered

- UPS must be installed and periodically inspected for efficiency to guarantee the correct operations in case of power failure.
- Correct installation and testing of this innovative sub-system required, more demanding on installation technical resources.

6 CHALLENGES TO COPE WITH INCREASING LIFT COMPLEXITY

New requirements introduced by EN81-20/50 as shown in the first part of this paper are increasing the complexity of the design stage of a new lift, as new measurements must be taken into account and choices of equipment are driven by the actual measurements of each shaft.

The best way to cope with the increasing complexity is to deploy a full 3D design workflow. Although this might draw some extra resources in the planning stage, experience documented by design manufacturers proves that the extra effort is more than rewarded in the long run. For example, production of required documentation and extra documentation for the installation becomes straightforward. Moreover, experience in designing EN81-20/50 systems in 3D will progressively become a company asset in form of re-usable 3D drawing templates.

Moreover, working with 3D models of the complete lift is the easiest way to take the most advantage from the new arrangement of mechatronic safety gears and reclaim the extra space for the car. 3D design makes it easier to work out solutions to accommodate larger cars that could not possibly be inserted in a traditional system with mechanical activation and synchronisation of safety gears. The availability of standard models for the next generation of safety gears and car slings is surely going to make the redesign easier in the near future.

7 CONCLUSIONS

The enforcement of EN 81-20/50:2014 is another step in the process of continuous improvement of safety and comfort in the standard use of lifts and in the installation and maintenance activities involved in its lifecycle.

New possibilities arise in the implementation of lift design, mostly connected to the use of sophisticated electronics, which have reached a suitable reliability degree for lift implementation. PESSRAL systems simplify approach to a number of safety topics connected to the lift system.

Absolute positioning systems have led the way to the adoption of a new generation of safety gear that, when combined with a magnetic strip-based absolute positioning system including safe electronic actuation, do not require a conventional over-speed governor and its tension weight: easy synchronisation of multiple safety gears, fewer components in the shaft, and more space available for the cabin.

To cope with the added complexity brought about by the introduction of EN81-20/50 and to be able to make the most out of the new possible safety gears arrangement, it is advisable to deploy complete 3D design workflow for each new lift project to reclaim the extra space available and install larger car in a shaft that could not traditionally host them.

Correct deploying of mechatronic safety systems requires an UPS to overcome power failures and demands on the installation technicians. However, it also has the advantage of being ready for the next generation of remote monitoring systems that have recently been introduced on the market.

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BIOGRAPHICAL DETAILS

Dennis Major has worked in the UK Lift industry for 38 years; he has collected a wide range of experience in the UK & European lift industry in a number of different technical and commercial positions before joining Wittur Ltd, a subsidiary of Wittur Group in 2010, becoming Managing Director in 2014. He current works as a freelance technology and business development consultant that he also combines with his specialist field of lift rope application, inspection, training and investigation.

Health Monitoring System for Wire Rope Using Image Processing

Keisuke Minagawa[1] and Satoshi Fujita[2]

[1] Department of Mechanical Engineering, Saitama Institute of Technology,
1690 Fusaiji, Fukaya, Saitama 369-0293, Japan, mina@sit.ac.jp
[2] Department of Mechanical Engineering, Tokyo Denki University,
5 Senju-Asahi-cho, Adachi-ku, Tokyo 120-8551, Japan, sfujita@cck.dendai.ac.jp

Keywords: wire rope, diameter, red rust, monitoring, image processing.

Abstract. Rupture of wire ropes is one of the potential severe accidents in a lift system. Before rupture by aging degradation, diameter of wire ropes decreases and surface of wire ropes is rusted. Thus diameters and red rust of wire ropes should be checked in periodic inspections of lift systems in Japan. The diameters are usually measured by using vernier calipers or scales, and red rust is checked with eyes, so there are errors and differences among inspectors. Therefore development of a new monitoring system for diameters and red rust of wire ropes is required in order to maintain the quality of inspection and efficiently manage inspection data. This paper proposes and constructs a health monitoring system for wire rope using image processing. The system consists of a digital camera and a computer. The digital camera takes a photograph of a wire rope and the photograph is analyzed by the computer. The diameter is calculated from the number of pixels of the rope, and red rust is detected by resolving the colour of the photograph into RGB data. Image processing method and examples of inspection are reported in this paper. As a result, the measurement error was less than 1% by adjusting photographing condition.

1 INTRODUCTION

There are many kinds of wire ropes such as hoist rope and compensating rope in a lift system. Hoist rope is an especially important component because it suspends a car, so rupture of the rope causes severe accidents. In addition, roping of recent lifts has been complicated. The increase in number of bends of the hoist rope heightens the risk of the rope's vulnerability. Therefore maintaining rope safety is very important.

In 2011, a rupture accident of a hoist rope in a lift system occurred in Tokyo. According to the accident analysis report[1], the cause of the accident was aging degradation of the hoist rope and insufficiency of inspections. Decrease in the diameter of the rope and rust were confirmed in the rope, but detection of rupture was difficult because the rupture had started inside the rope. In consequence of the accident, further investigations regarding safety measures of hoist ropes of lift systems and revisions of inspection methods were implemented. The investigation report described the relationship between decrease in diameters of rope and decrease in strength of rope [2]. In addition, wires in strands may break before rupture of a rope. Therefore detection of wire breakage is also important.

In Japan, the diameter of the rope and red rust are checked in periodic inspection of lift systems. Usually the diameters are measured by using vernier calipers or scales, and red rust is checked with eyes, so there are errors and difference among inspectors. However the inspection should be implemented homogenously and accurately from the viewpoint of above-mentioned accidents.

In order to check conditions of ropes homogenously, accurately and speedily, this paper proposes a new health monitoring system for the diameters and red rust by using image processing. A photograph taken by a digital camera of a rope is used in this system, and the digital image is processed by using a computer. The diameter is calculated from the number of pixels of the rope, and red rust is detected by resolving the colour of the photograph into RGB data. A concept of the health monitoring system of wire rope using image processing, methodology used and results of experiments for verification of the system are reported in this paper.

2 CONCEPT OF HEALTH MONITORING SYSTEM USING IMAGE PROCESSING

The health monitoring system of wire rope using image processing proposed in this paper aims at inspection of diameters and red rust of wire ropes. Figure 1 shows a concept diagram of the proposed system. The proposed system consists of a PC and a digital camera, and the camera is able to be set any place near the hoist rope, because the camera is small and is able to be connected with the PC by cable, Wi-Fi and Bluetooth. Digital images taken by the digital camera are transmitted to the PC, and these images are processed using analysis software such as MATLAB. Both the digital camera and the PC are of consumer use, so no special function is equipped. This system will be able to measure diameter of a running rope by using a high-speed video camera instead of the digital still camera.

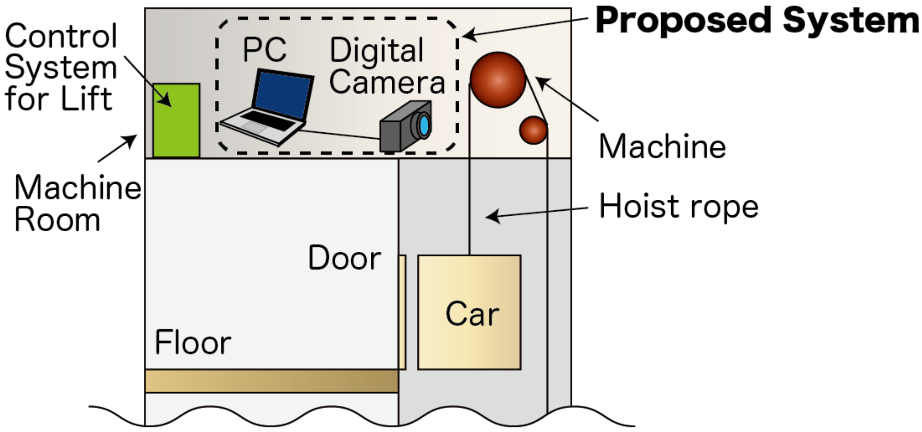


Figure 1 Concept diagram of health monitoring system

3 METHODOLOGY

3.1 Diameter measurement by image processing

This section describes an algorithm of diameter measurement of a rope by using image processing. Figure 2 shows a flowchart of the diameter measurement programme, and Fig. 3 is an example of image processing. The algorithm is as follows:

First of all, a digital image taken by a digital camera is loaded to a computer as shown in Fig. 3 (a).

Next unnecessary part of the image is trimmed, and the image is changed from colour to gray scale as shown in Fig. 3 (b). Generally a colour image consists of three layered two-dimensional arrays that are a red layer, a green layer and a blue layer, and each colour is expressed by 8bit (= 256) data. The gray scale image has only one layer that expresses luminance, and the luminance is also expressed by 8bit (= 256) data. Therefore, the capacity of data of the image is decreased by this process.

Then a low-pass filter is applied as shown in Fig. 3 (c). This process removes noise, dust and unevenness of rope surface, so boundary line will be decreased.

After that, the image is changed from gray scale to monochrome as shown in Fig. 3 (d). A monochrome image is expressed by 1bit (= 2) data. In other words, black is expressed by 0, and white is expressed by 1. In this process, a threshold value that separates gray scale data into black and white is needed, and the threshold value should be adjusted in consideration of photographing condition.

Then boundary lines between white and black are detected as shown in Fig. 3 (e). In this process, value of each pixel is checked, and boundary is judged by comparing it with surrounding pixels. These lines express an outline of the rope.

After that, the Hough transform [3] is applied as shown in Fig. 3 (f). Hough transform is a method that detects linear functions from a digital image. In general, a linear function is expressed by the following equation.

$$y = b_1 + b_2 x \tag{1}$$

However β_2 of perpendicular line will be infinity, so this cannot be expressed in computer programmes. Therefore the line is expressed by distance from the origin ρ and an angle between the horizontal axis θ as shown in Fig. 4. In the Hough transform, candidate values of ρ and θ of each pixel are calculated, then ρ and θ are decided by their coincident values. Difference of ρ is distance between two lines.

Finally the diameter of the rope is calculated. Distance derived by the Hough transform was distance in the digital image, so it should be transformed to length in actual scale. The pixel in the digital image is transformed to actual length by using the sensor size and a ratio of the focal length in the digital camera to distance between the camera and rope as shown in Fig. 5.

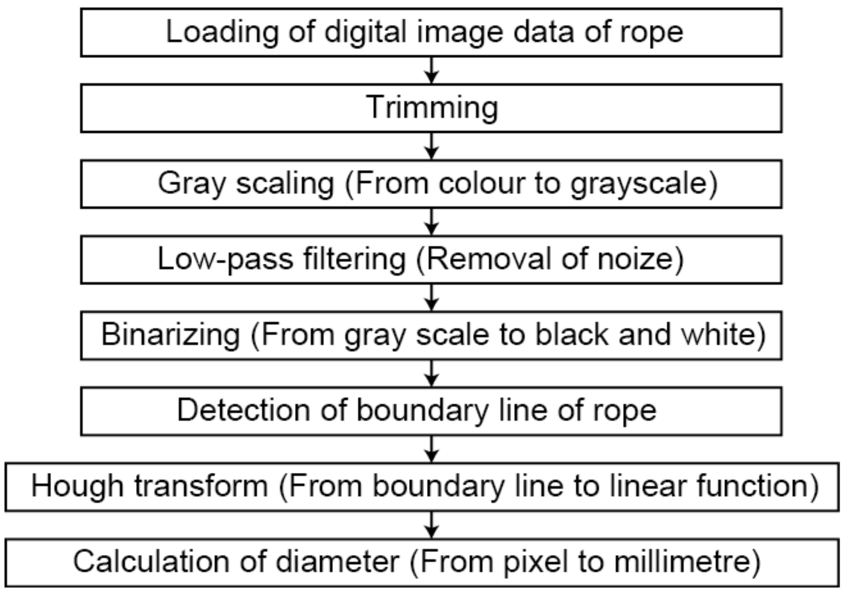
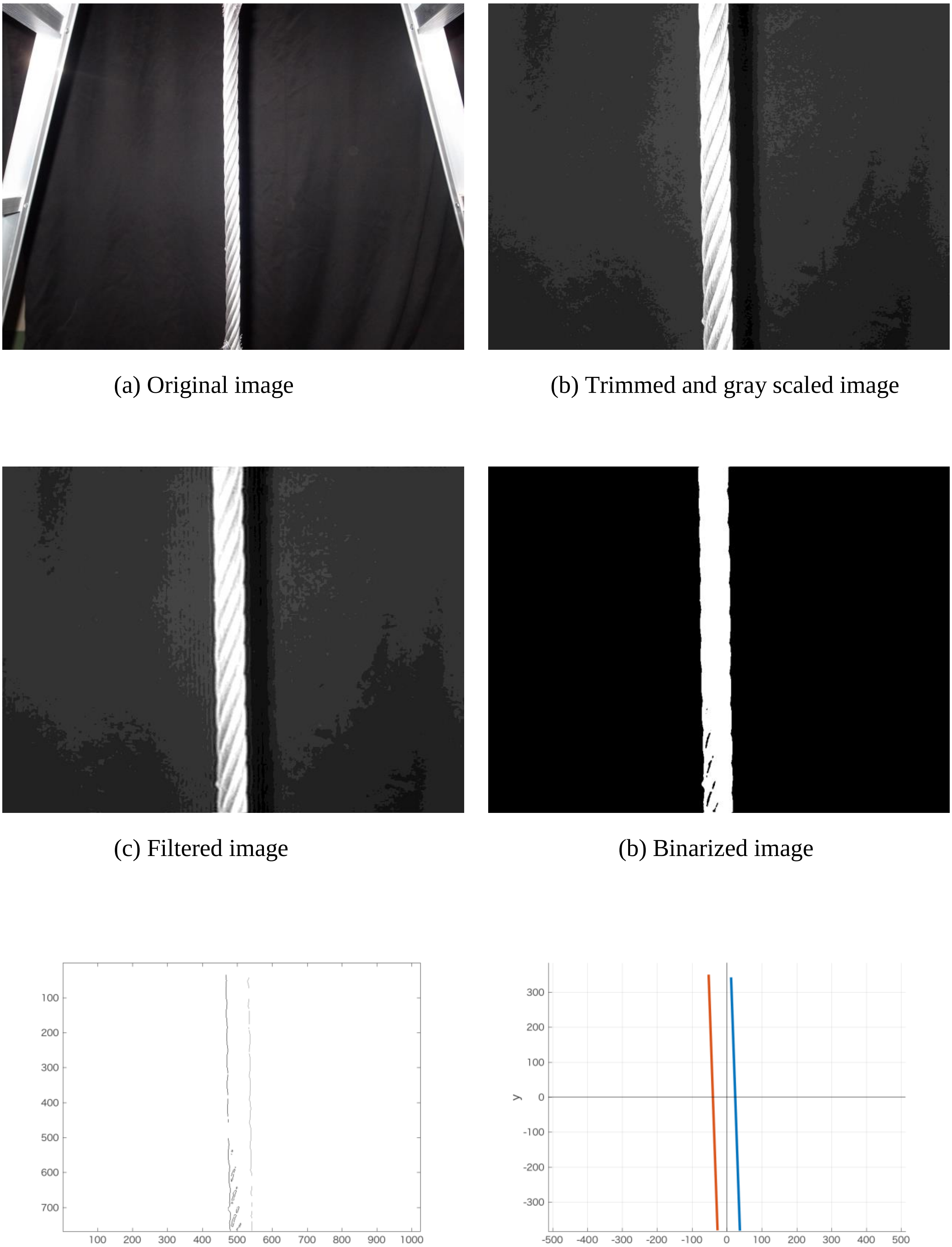


Figure 2 Flowchart of diameter measurement programme



(a) Original image

(b) Trimmed and gray scaled image

(c) Filtered image

(b) Binarized image

(e) Boundary line image

(f) Linearized image

Figure 3 Example of process of image processing

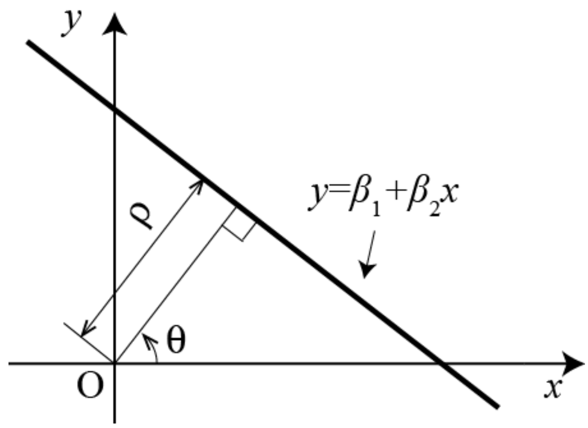


Figure 4 Linear function

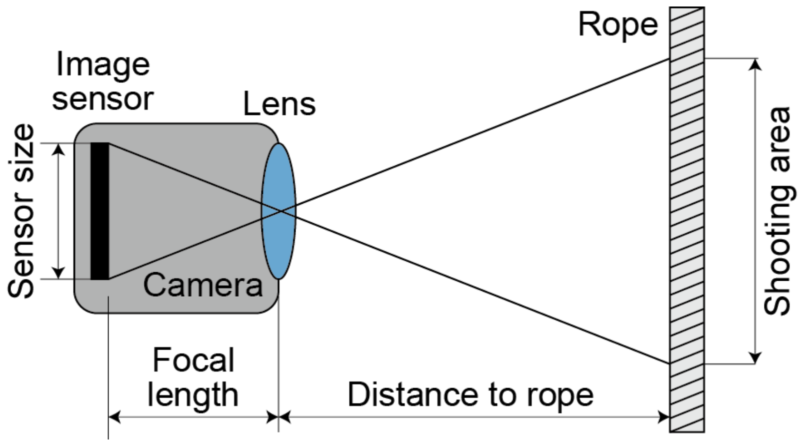


Figure 5 Calculation of actual size by specification of camera

3.2 Red rust detection by image processing

This section describes an algorithm of red rust detection of a rope by using image processing. Generally a colour image consists of three layered two-dimensional arrays as shown in Fig. 6. Each layer indicates the luminance of red, green and blue, and each luminance is expressed by 8bit (= 256) data. Therefore a colour is identified by combination of luminance of red, green and blue.

This system detects red rust by colour recognition. First, ranges of luminance that correspond with red rust is set, that is to say, the upper and lower limits of luminance of red, green and blue are set. Next, luminance of each pixel is inspected. Finally the pixel is marked if the luminance is in the range of red rust.

Figure 7 shows an example of red rust detection, and (a) shows original image, (b) shows red rust part. The object is a rust oilcan. The ranges of luminance of red rust were set as follows; red is 130 to 255, green and blue are 0 to 80. Although a background of the digital image had similar colour to red rust, red rust on the oilcan was detected well by suitable setting of the ranges of luminance.

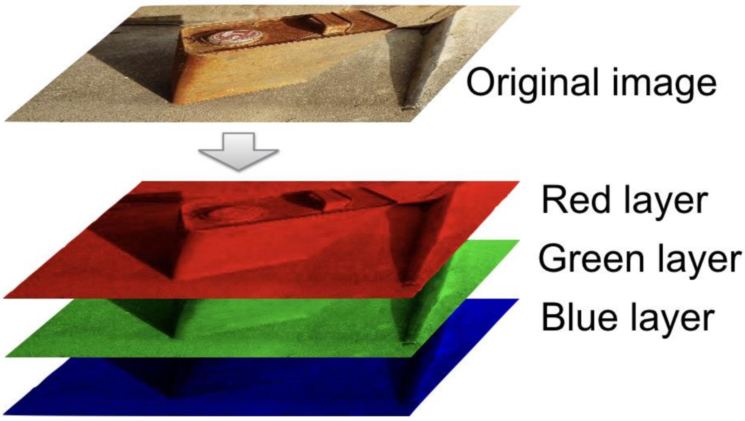
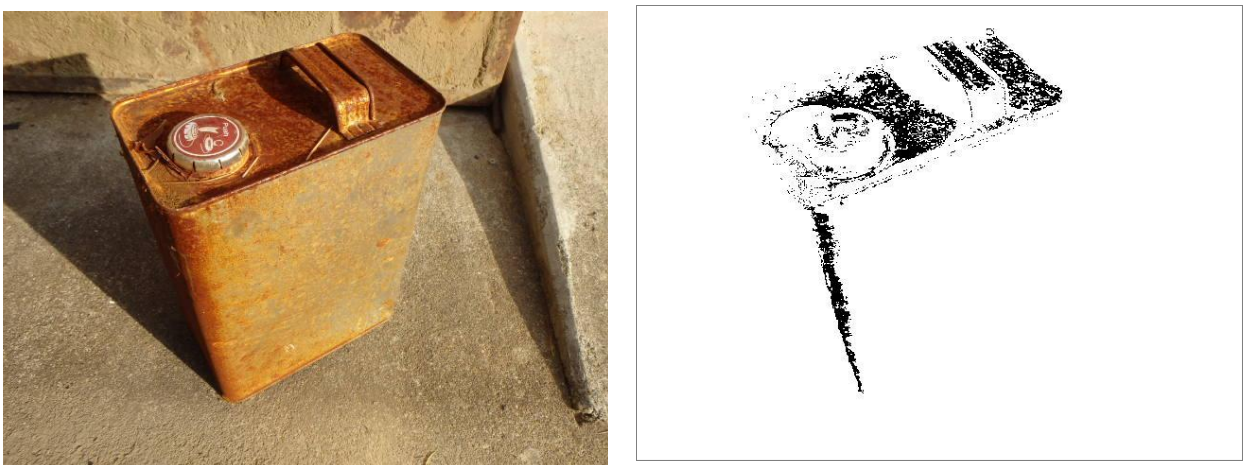


Figure 6 Resolution of digital image to RGB layer



(a) Original image (b) Red rust part

Figure 7 Example of red rust detection

4 VERIFICATION BY EXPERIMENTS

4.1 Diameter measurement

Experiments were carried out in order to verify accuracy of the proposed system and to clarify suitable condition of photography. Influence of diameter of ropes on measurement accuracy, influence of lighting conditions of photography on measurement accuracy and influence of resolution of digital images on measurement accuracy were investigated.

Figure 8 shows an experimental apparatus. The experimental apparatus consists of a wire rope, a weight to tighten the rope, a stepladder that the rope is suspended on and a digital camera. Three wire ropes made of carbon steel were used. Diameters measured by a vernier caliper were 6.00, 9.05 and 15.95mm, respectively. The digital camera had a focal length of 6mm and an 1/1.7-inch CCD image sensor. Distance between the rope and camera was 400mm.

First, influence of a diameter of a rope and lighting conditions of photography were investigated. Resolution of digital images was 1280 x 960pixel. In this condition, one pixel corresponded to about

0.4mm. Figure 9 shows comparison of measurement accuracy on diameters and the lighting condition. It is confirmed from Fig. 9 that the suitable lighting condition for photography is the condition without lighting and with the flash. In this condition, error ratio was less than 0.93% and there was no significant difference between diameters. Therefore proposed system has sufficient measurement accuracy.

Next, influence of resolution of a digital image was investigated. A 15.95-mm-diameter wire rope was used for the experiment. Lighting was turned off, and the flash was turned on. Figure 10 shows comparison of measurement accuracy and processing time on resolution of digital images. The error ratio decreased by increasing resolution, because the number of pixels per mm increased. On the other hand, the processing time increased by increasing resolution, because the number of calculations increased. In addition, error ratio of 1280 x 960pixel is larger than Fig. 9 though same image was used, because different parameters such as the low-pass filter and the threshold value for binarization were applied.

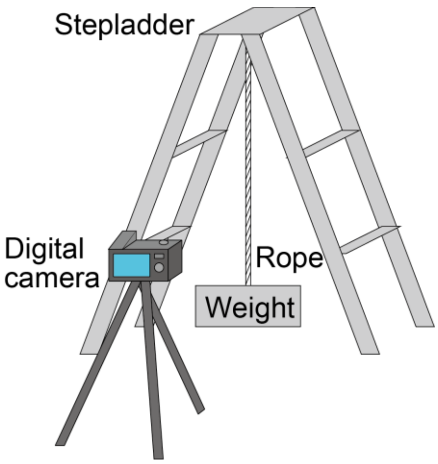


Figure 8 Experimental apparatus

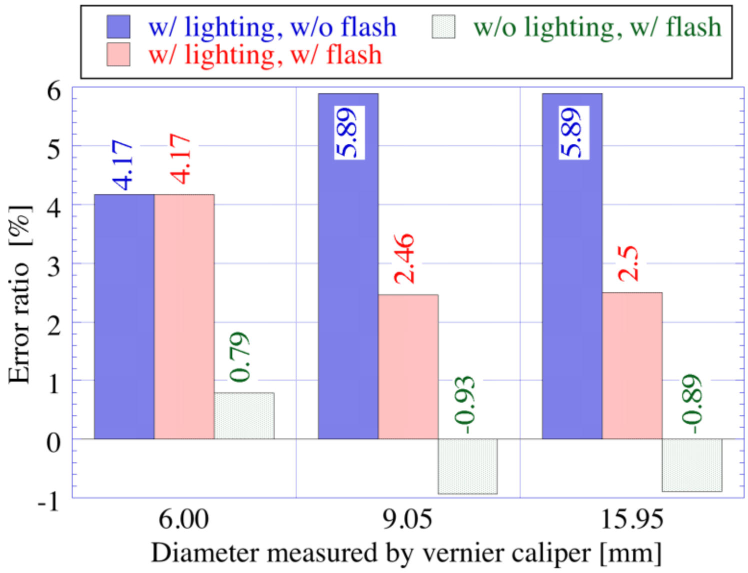


Figure 9 Influence of diameters and lighting condition

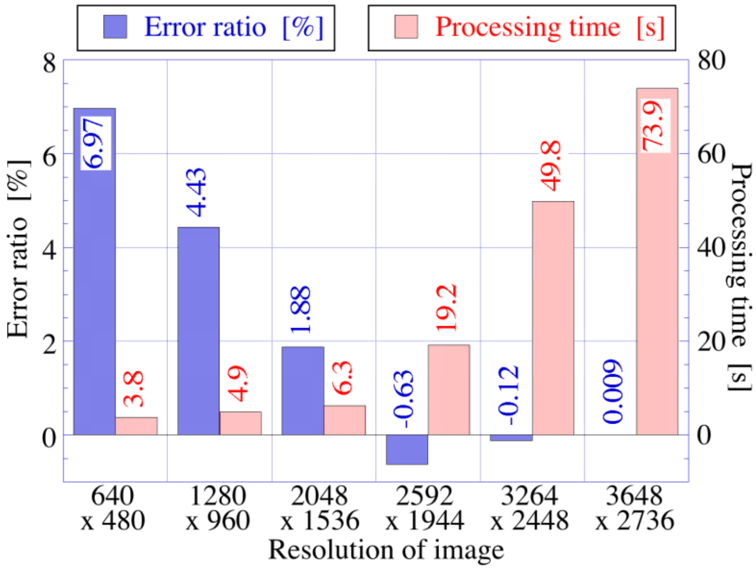


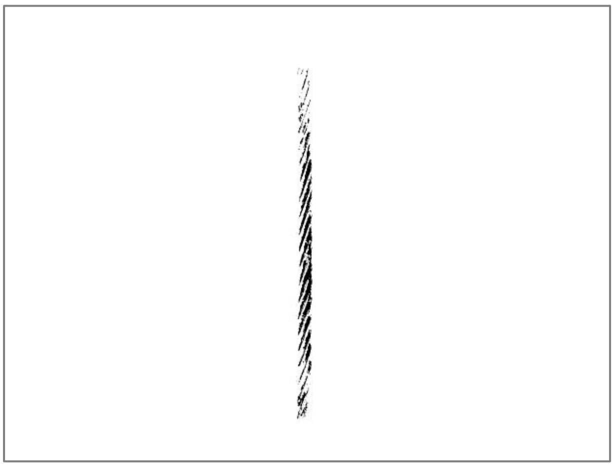
Figure 10 Influence of resolution of digital images

4.2 Red rust detection

Experiments using a rust wire rope were carried out in order to verify applicability of red rust detection of proposed system. Same experimental apparatus as section 4.1 was applied in the experiments. Distance between the rope and camera was 400mm. Resolution of digital images was 1280 x 960pixel. Lighting was turned off, and the flash was turned on.

Figure 11 shows a result of red rust detection, and (a) shows original image, (b) shows red rust part. The object is a rust rope made of carbon steel and having 12mm diameter. The ranges of luminance of red rust were same as section 3.2, i.e. red is 130 to 255, green and blue are 0 to 80. Red rust on the rope was detected well as shown in Fig. 11 (b). Although red rust was detected well by using parameters that is set in section 3.2, more accurate detection is possible by adjusting these parameters.

(a) Original image



(b) Red rust part

Figure 11 Red rust detection

5 CONCLUSION

This paper focused on decrease of diameter and occurrence of red rust of wire ropes that relate to rupture of wire ropes, and proposed the health monitoring system of wire rope using image processing. The system was built by using MATLAB and the accuracy was verified by experiments.

As a result, proposed system had sufficient accuracy of diameter measurement regardless of diameters, and the photography condition without lighting and with flash was suitable. In addition, proposed system was able to detect red rust on the wire ropes.

In order to improve accuracy and applicability of this system, adjustments of parameters of image processing, consideration for various situations such as a rope covered with grease and development of fast algorithms are required in the future. In addition, detection of wire breakage and counting the number of it by image processing will be also implemented. After this method using a still camera is constructed, a high-speed video camera will be used in order to measure diameter of a running rope.

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[3] N. Takai, *Getting Started With MATLAB Image Processing*. Kogakusha, Tokyo (2013). (in Japanese)

BIOGRAPHICAL DETAILS

Prof. Keisuke Minagawa is an associate professor of Saitama institute of technology and is a chair of the Technical Committee of Lifts, Escalators and Amusement Facilities held in JSME (Japan Society of Mechanical Engineers). He has been an evaluator of lift systems and mechanical car parking systems since 2015. He is also an expert of seismic isolation and vibration control.

Prof. Satoshi Fujita, a JSME (Japan Society of Mechanical Engineers) Fellow, has ten years of management experience as a director, a dean of school of engineering and currently a vice-president of Tokyo Denki University. He has been engaged in engineering research and development of seismic isolation systems and vibration control systems for buildings or key industrial facilities for over 35 years at both University of Tokyo and Tokyo Denki University. In recent ten years, he has been a committee member of the Panel on Infrastructure Development of Japanese ministry of land, infrastructure and transport (MILIT), and a chair of the Special Committee on Analysis and Evaluation of Lifts, Escalators and Amusement Facilities Accidents and Failures held in MILIT. In addition, he has been a chair of the ISO TC178 Japanese committee.

Control of Actuators for Cabin Vibration Damping of a Rope-Free Passenger Transportation System

Jonas Missler[1], Thomas Ehrl[2], Benedikt Meier[2], Stefan Kaczmarczyk[3] and Oliver Sawodny[1]

[1]Institute for System Dynamics (ISYS), University Stuttgart, Waldburgstr. 19, 70563 Stuttgart, Germany, Email: missler@isys.uni-stuttgart.de, sawodny@isys.uni-stuttgart.de
[2]thyssenkrupp Elevator Innovation GmbH, Berner Feld 60, 78628 Rottweil, Germany, Email: thomas.ehrl@thyssenkrupp.com, benedikt.meier@thyssenkrupp.com
[3]Faculty of Arts, Science and Technology, University of Northampton, St. George's Avenue, Northampton NN7 3NG, UK, Email: stefan.kaczmarczyk@northampton.ac.uk

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Abstract. The design of the novel rope-free passenger transportation system (PTS) differs from that of conventional traction lifts. The new propulsion, realized through a linear motor, requires lightweight constructions and thus shapes the design of the PTS. Additionally the possibility of horizontal travel has great influence on the difference between the design of conventional traction lifts and the PTS. Despite the different design, the aim for the rope-free PTS is to achieve at least the same ride quality as modern traction lifts. One important point in achieving the required ride quality is to reduce the vibrations felt by the passengers inside the cabin. In general, the damping concepts of conventional lifts cannot be readily applied to the new design of the PTS. Therefore, a damping concept for the rope-free PTS has to be developed. This paper will present the possibilities of active vibration damping for the PTS and a possible actuator position. The paper will focus on the modelling of the active damping components and the control of actuators deployed in the system. The performance of the damping actuators will be evaluated using a simulation with a Multi-Body System (MBS) of the PTS. The primary disturbance of the PTS for this paper will be the vibrations induced by the guidance.

1 INTRODUCTION

The rope-free PTS introduces a novel form of vertical transportation by eliminating the rope from the propulsion system. The propulsion of the PTS replaces the rope and the rotational motor by a linear motor, which directly provides the vertical driving force for the car of the PTS. The linear motor enables the simultaneous movement of multiple cars in a single shaft and makes horizontal travel possible. The new propulsion also demands a new lift design that differs from the design of conventional traction lifts. The car of the rope-free PTS consists of three main components: the sledge with the passive elements of the linear motor, the mounting frame for the cabin, and the actual cabin. The active components, thus the coil units, of the linear motor are placed in the shaft wall. The Fig. 1 shows a sketch of the rope-free PTS and its three main components. The design of the PTS omits the mounting frame around the cabin, which is used in standard lifts to decouple the motion of the cabin from the rest of the car and therefore provides good riding comfort. The omission of the frame around the cabin enables an easy realization of horizontal and vertical travel in a single system, but also reduces the ability to damp vibrations in the rope-free PTS. In order to achieve a similar riding comfort as in conventional lifts an active vibration damping is designed for the rope-free PTS. This paper will present a control scheme for active vibration damping of the rope-free PTS, which is based on the disturbance estimation and compensation. The compensation is based on the system inversion will be shown briefly.

In general, the active vibration damping task can be viewed as the rejection of undesired behaviour of the system. This undesired behaviour is in many cases caused by some external source such as deflections in the guidance system. This external source can be modelled as a disturbance input to the system. The problem with the disturbance, that shall be compensated, is that often the disturbance is not directly measureable at the real system. Therefore, the disturbance causing the vibrations has to be estimated, so it can be directly compensated. The estimation of disturbances is a common field in the control theory, and many different techniques exist to derive a disturbance estimator [1]. One technique for disturbance estimation augments is the model of the real system with a model of a disturbance generator [2]. In the simplest case, this model is chosen to be zero to estimate a constant disturbance. Finding the optimal observer under certain condition is often done by minimizing a quadratic objective related to the model of the plant for which it is design leading to a linear quadratic estimator, the well-known Kalman-Filter [3]. There also exist many different disturbance rejection controllers, which rely on much less knowledge of the system dynamics [4], the controllers can be implemented without deriving a model of the system. The disturbance rejection control was also already implemented on an under actuated MBS in [5], which describes systems with more degrees of freedom (DOF) than independent control inputs.

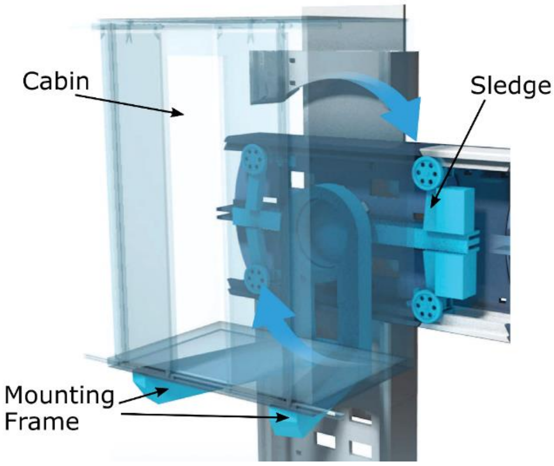


Figure 1 Rope-free passenger transportation system (PTS) in exchanger position.
Source: multi.thyssenkrupp-elevator.com

The modelling of the rope-free PTS was performed using the internationally standardized method of Multi-Body Systems (MBS). The method of MBS is especially useful in the context of rigid system undergoing large rotational and translational displacements. The MBS method is part of classical mechanical engineering [6]. The in this paper used model is a variant of the model presented earlier [7]. The disturbance estimation and compensation in this paper is based on the linearization of the MBS. The linearization of a system is a widely used technique for deriving a controller or observer for a nonlinear system [8], especially if the relevant motion of the system stays in a small range around the desired motion of the system.

The compensation mechanism will only be discussed briefly in this paper. The used compensation is based on the control of under actuated MBS. The technique for the control of under actuated MBS is described in [9], and is based on the well-known technique of input/output linearization for nonlinear systems [10, 11]. The advantage of the control of under actuated MBS is that it can be directly applied to the dynamic equations of MBS. As mentioned in [9] the main computational disadvantage of the control of under actuated MBS is that the non-actuated part of the MBS has to be simulated alongside the inversion of the system.

The fact that the disturbance will never be perfectly estimated also makes it necessary to implement a stabilizing feedback together with the disturbance compensation. The implementation of such a stabilizing controller will not be in the scope of this paper. The paper is structured in the following fashion. First, the nonlinear model used for the design of the estimator and disturbance compensation is described. The following chapter will display the design of the disturbance estimation and briefly sketch the design of the disturbance compensation. The fourth chapter will give a simulation example based on the model derived in the second chapter. The last chapter will conclude the paper and give an outlook on the possible extension of the disturbance compensation.

2 MODEL

The principle two-dimensional model used in this paper is the same as in [7]. The difference in the model is that the actuators underneath the cabin in the model were replaced by a single actuator, that can apply a force in the z-direction and a torque around the y-axes underneath the cabin. Therefore, the two forces F_{A1} and F_{A2} from the actuators are replaced by a single force F_C and a torque T_C underneath the cabin, see Fig. 2. The omission of the closed kinematic loop has the main advantage that the resulting model of the PTS is in tree structure, which is better suited for controller or observer design, due to the more simple structure. It is important to note that the new model only approximates the motion of the two parallel actuators, because the single actuator reduces the DOF of the model by one resulting in five degrees of freedom. The reduction in the DOF restricts the relative motions that run purely parallel to the x-axis of the cabin. This restriction in x-direction will not play a big role, because for the control design the relative motion in x-direction cannot be effectively damped by two parallel actuators underneath the cabin, which both face in z-direction. The reduction in generalised coordinates, by the reduction from two actuators underneath the cabin to a single one is also displayed in Fig. 2. The transformation between the new and old generalised coordinates can be approximated by

$$\begin{bmatrix} x_c \\ z_c \\ \beta_c \end{bmatrix} \approx \begin{bmatrix} \begin{bmatrix} x_b \\ z_b \end{bmatrix} + \begin{bmatrix} \sin(\beta_b + \varphi_c) \\ \cos(\beta_b + \varphi_c) \end{bmatrix} r_c + \begin{bmatrix} \cos(\beta_b) & \sin(\beta_b) \\ -\sin(\beta_b) & \cos(\beta_b) \end{bmatrix} \boldsymbol{r}_{B0}^{Cb} \\ \beta_b + \varphi_c \end{bmatrix}. \tag{1}$$

The transformation from the two actuators in parallel to the single actuator with force and torque can be performed using

$$F_C = [\cos(\beta_1)\ \cos(\beta_2)] \begin{bmatrix} F_{A1} \\ F_{A2} \end{bmatrix}, \qquad T_C = \sum_{i=1}^{2} [d_{z,i}\ \ -d_{x,i}] \begin{bmatrix} \sin(\beta_i) \\ \cos(\beta_i) \end{bmatrix} F_{A,i}, \tag{2}$$

where β_1 and β_2 are the respective angles of the actuators A_1 and A_2, they can be calculated from the closing condition of the original two-dimensional model. The distances $d_{z,i}, d_{x,i}$ are the distances from the contact P_i of the actuators to the point P_0, thus $\boldsymbol{r}_{Pi}^{P0} = \left[d_{x,i}\ \ d_{z,i}\right]^T$, $i = 1{,}2$.

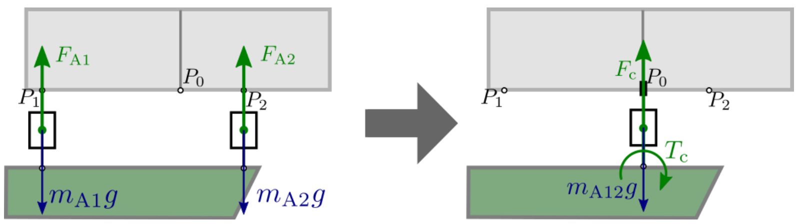
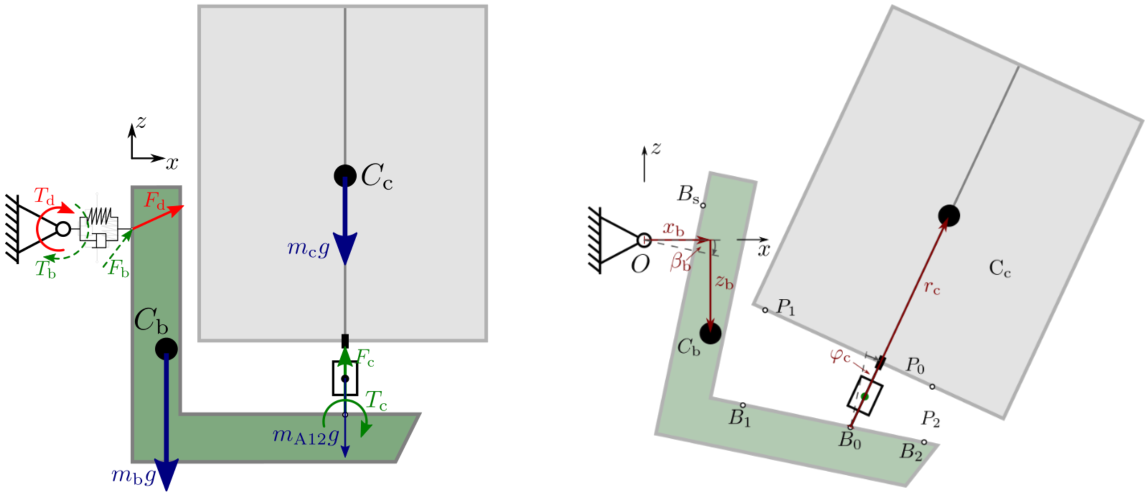


Figure 2 Reduction DOF by replacing the closed loop. The two parallel actuators in the model are replaced by a single actuator, which can apply the force F_C and the torque T_C.

The model can be rewritten with the new generalised coordinates $\boldsymbol{q} = [x_b, z_b, \beta_b, r_c, \varphi_c]^T \in \mathbb{R}^f$ with the DOF $f = 5$ in the standard form of MBS given by

$$\boldsymbol{M}(\boldsymbol{q}, t)\ddot{\boldsymbol{q}} + \boldsymbol{k}(\boldsymbol{q}, \dot{\boldsymbol{q}}, t) = \boldsymbol{g}(\boldsymbol{q}, \dot{\boldsymbol{q}}, t), \tag{3}$$

where the matrix $\boldsymbol{M} \in \mathbb{R}^{f\times f}$ is the symmetric mass matrix, $\boldsymbol{k} \in \mathbb{R}^f$ inherits the internal forces, such as spring and damping forces, and $\boldsymbol{g} \in \mathbb{R}^f$ contains the external forces, thus inputs and disturbances. Fig. 3(a) shows the two-dimensional model of the rope-free PTS including the disturbance force F_d and torque T_d, which convey the vibration from the guiding system through the point B_s to the mounting frame. Additionally, the generalised coordinates $\boldsymbol{q}$ of the system are also shown in the Fig. 3(b).



(a) Simplified two-dimensional MBS. **(b) Generalised coordinates.**

Figure 3 Simplified two-dimensional model consisting of mounting frame and cabin. In (a) are the disturbances from the guidance, force $\boldsymbol{F_d}$ and torque $\boldsymbol{T_d}$. The force $\boldsymbol{F_c}$ and torque $\boldsymbol{T_c}$ represent equivalence for the actuator forces and in blue are the gravitational forces. In (b) the generalised coordinates of the model are displayed, namely q $= [\boldsymbol{x_b}, \boldsymbol{z_b}, \boldsymbol{\beta_b}, \boldsymbol{r_c}, \boldsymbol{\varphi_c}]^{\boldsymbol{T}}$.

3 CONTROL CONCEPT

The overall control concept is based on two parts: The disturbance estimation and its compensation. The estimation is necessary because a measurement of the disturbance force F_d and torque T_d is not directly possible. The disturbance is estimated on base of the measurable output signals $\boldsymbol{y}$ and the control input $\boldsymbol{u}$ of the system. The Fig. 4 shows the principle structure of the control concept. The disturbance $\boldsymbol{d}$ of the system is assumed to be a force and torque acting as an additional input on the system, see also Fig. 3. The in Fig. 4 shown state feedback will not be part of this paper.

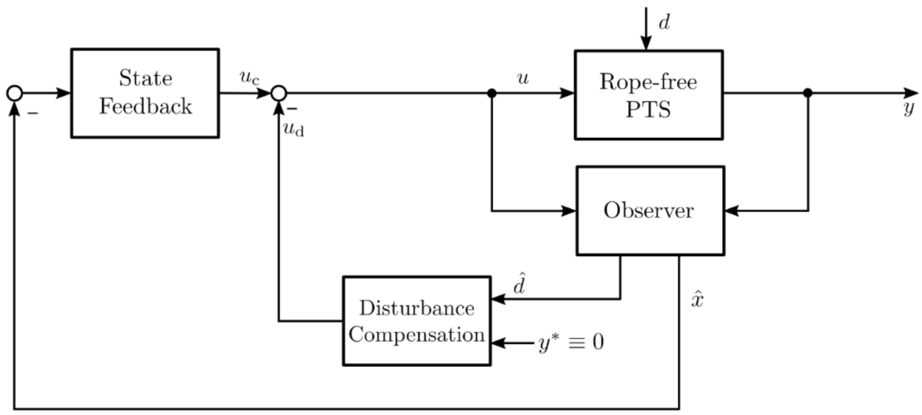


Figure 4 The disturbance compensation structure for the rope-free PTS. The disturbance $\boldsymbol{d} = [\boldsymbol{F_{dx}}, \boldsymbol{F_{dz}}, \boldsymbol{T_d}]^{\boldsymbol{T}}$ is estimated by $\widehat{\boldsymbol{d}}$ and compensated by the input $\boldsymbol{u_d}$.

The disturbance $\boldsymbol{d}$ is the torque and forces acting on the connection point between the bucket and the sledge B_s, thus $\boldsymbol{d} = [F_{dx}, F_{dz}, T_d]^T$. The measureable output is given by

$$\boldsymbol{y} = [x_c, z_c, \beta_c, r_c, \varphi_c]^T = \bar{C} \cdot \bar{\boldsymbol{q}}, \tag{4}$$

where $\bar{C}$ represents

$$\bar{C} = \begin{bmatrix} 1 & 0 & r_c^* - \boldsymbol{r}_{B0}^{Cb}(2) & 0 & r_c^* \\ 0 & 1 & -\boldsymbol{r}_{B0}^{Cb}(1) & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \tag{5}$$

the generalised coordinates of the linear system $\bar{\boldsymbol{q}}$ describe the small perturbation from the generalised coordinates $\boldsymbol{q}$, thus $\boldsymbol{q} = \boldsymbol{q}^* + \bar{\boldsymbol{q}}$ with the constant steady-state $\boldsymbol{q}^*$. The disturbance $\boldsymbol{d}$ is estimated by $\hat{\boldsymbol{d}}$ and the state $\boldsymbol{x}$ is estimated by $\hat{\boldsymbol{x}}$. The control input is the force and torque of the single actuator underneath the cabin $\boldsymbol{u} = [F_c, T_c]$.

In the following, the disturbance and state estimation will be shortly displayed and the rudimentary disturbance compensation used in this paper will be introduced.

3.1 Disturbance and state estimation

The estimation of disturbance $\boldsymbol{d}$ and especially the system state $\boldsymbol{x}$ is a wide field in the control theory and many different estimators exists. This paper will focus on observers that can estimate the state of a system alongside the disturbance, by augmenting, thus extending, the model with a model of the disturbance generator.

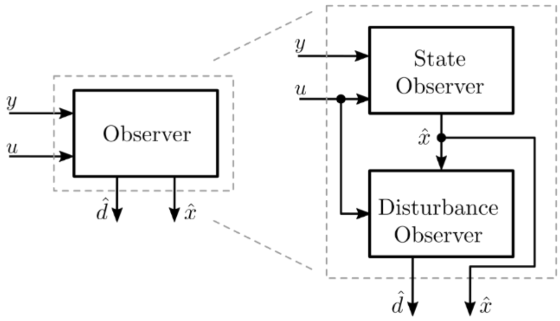


Figure 5 The observer can be split in a state observer, estimating the state $\hat{\boldsymbol{x}}$, and a disturbance observer, which estimates the disturbance $\hat{\boldsymbol{d}}$.

The estimator is based on the linearization of the nonlinear model in Chapter 2. The linearization of the MBS, [8, p.108], (3) shall be given by

$$\boldsymbol{M_{lin}}\,\ddot{\bar{\boldsymbol{q}}}(t) + \boldsymbol{P_{lin}}\dot{\bar{\boldsymbol{q}}}(t) + \boldsymbol{Q_{lin}}\bar{\boldsymbol{q}}(t) = \bar{\boldsymbol{B}}_{\boldsymbol{u}}\boldsymbol{u}(t) + \bar{\boldsymbol{B}}_{\boldsymbol{d}}\boldsymbol{d}(t), \tag{6}$$

where $\bar{\boldsymbol{q}}$ are the linearized generalised coordinates, $\boldsymbol{M_{lin}} \in \mathbb{R}^{f\times f}$, $\boldsymbol{P_{lin}} \in \mathbb{R}^{f\times f}$, $\boldsymbol{Q_{lin}} \in \mathbb{R}^{f\times f}$ represent the linearized dynamics of the MBS linearized around the steady-state $\boldsymbol{q}^s = \boldsymbol{q}(t_0)$ and f are the DOF. The matrices $\bar{\boldsymbol{B}}_{\boldsymbol{u}} \in \mathbb{R}^2$ and $\bar{\boldsymbol{B}}_{\boldsymbol{d}} \in \mathbb{R}^3$ are the input matrices for the input $\boldsymbol{u}$ and the disturbance $\boldsymbol{d}$. Using the linear matrices, (6), the system can be written in state-space representation with the state as $\boldsymbol{x} = [\bar{\boldsymbol{q}}, \dot{\bar{\boldsymbol{q}}}]^T$

$$\dot{\boldsymbol{x}} = A\boldsymbol{x} + B_u\boldsymbol{u} + B_d\boldsymbol{d}; \quad \boldsymbol{y} = C\boldsymbol{x}, \tag{7}$$

where

$$A = \begin{bmatrix} 0 & I \\ -\boldsymbol{M}_{\boldsymbol{lin}}^{-1}\cdot\boldsymbol{Q_{lin}} & -\boldsymbol{M}_{\boldsymbol{lin}}^{-1}\cdot\boldsymbol{P_{lin}} \end{bmatrix},\ B_u = \begin{bmatrix} 0 \\ \boldsymbol{M}_{\boldsymbol{lin}}^{-1}\cdot\bar{\boldsymbol{B}}_{\boldsymbol{u}} \end{bmatrix}, B_d = \begin{bmatrix} 0 \\ \boldsymbol{M}_{\boldsymbol{lin}}^{-1}\cdot\bar{\boldsymbol{B}}_{\boldsymbol{d}} \end{bmatrix},\ C = [\bar{C}\ \ 0]. \tag{8}$$

The measurable output $\boldsymbol{y}$ follows from the assumption, that the motion of the cabin (x_C, z_C, β_C) and additionally the motion of the actuator (r_C, β_C) can be measured. The state-space representation (8) has the advantage that many properties of the system can be checked easily. One property, which has to be checked before the design of an observer, is the observability of the system (7), thus if the state can be reconstructed from the output $\boldsymbol{y}$. For the linearized time invariant system (7) this can be checked by ensuring the rank of the observability matrix $O = [C^T, (C \cdot A)^T]^T$ of the system. The rank of the observability matrix is 10, which corresponds to the number of states of the linear system (7), and therefore the at least the linearized system is observable.

The state-space system (7) will be augmented with an assumed dynamics of the disturbance $\boldsymbol{d}$. Assume that the disturbance is generated by the system

$$\dot{\boldsymbol{x}}_{\boldsymbol{d}} = A_d \boldsymbol{x}_{\boldsymbol{d}} + G\boldsymbol{w}; \quad \boldsymbol{d} = C_d \boldsymbol{x}_{\boldsymbol{d}}, \tag{9}$$

where $\boldsymbol{x}_{\boldsymbol{d}} \in \mathbb{R}^{2 \cdot n_d}$ is the state of the disturbance generator and $\boldsymbol{w} \in \mathbb{R}^{n_d}$ is a white noise disturbance with its respective input matrix $G \in \mathbb{R}^{2 \cdot n_d \times n_d}$, here the number of disturbances $n_d = 3$. The augmented plant consisting of system (7) and (9) is then given by

$$\begin{bmatrix} \dot{\boldsymbol{x}} \\ \dot{\boldsymbol{x}}_{\boldsymbol{d}} \end{bmatrix} = \begin{bmatrix} A & B_d \cdot C_d \\ 0 & A_d \end{bmatrix} \begin{bmatrix} \boldsymbol{x} \\ \boldsymbol{x}_{\boldsymbol{d}} \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} \boldsymbol{u} + \begin{bmatrix} 0 \\ G \end{bmatrix} \boldsymbol{w}; \quad \boldsymbol{y} = \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} \boldsymbol{x} \\ \boldsymbol{x}_{\boldsymbol{d}} \end{bmatrix} + \boldsymbol{\nu}, \tag{10}$$

where $\boldsymbol{\nu} \in \mathbb{R}^5$ is an additional measurement noise. The overall state and disturbance observer, Fig. 5, for the augmented plant (10) is then implemented using

$$\begin{bmatrix} \dot{\hat{\boldsymbol{x}}} \\ \dot{\hat{\boldsymbol{x}}}_{\boldsymbol{d}} \end{bmatrix} = \begin{bmatrix} A - L_x C & B_d C_d \\ -L_d C & A_d \end{bmatrix} \begin{bmatrix} \hat{\boldsymbol{x}} \\ \hat{\boldsymbol{x}}_{\boldsymbol{d}} \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} \boldsymbol{u} + \begin{bmatrix} L_x \\ L_d \end{bmatrix} \boldsymbol{y}; \quad \hat{\boldsymbol{d}} = C_d \boldsymbol{x}_{\boldsymbol{d}}, \tag{11}$$

where the $\widehat{[\,]}$ states are the estimate of the respective state. The so far unknown observer gain $L = [L_x^T, L_d^T]^T \in \mathbb{R}^{(10+6)\times(10+6)}$ is found by solving a Ricatti equation using only the virtual noise $\boldsymbol{w}$ as input to the augmented system (10). The solution of the Ricatti equation will be an optimal linear quadratic estimator (LQE) with respect to the plant and the covariance matrices of the measurement noise V and the virtual disturbance noise W.

3.2 Disturbance compensation

The disturbance compensation will be performed using the estimation of the disturbance. The inverse system, thus the input/output linearization is used to estimate the input needed to compensate the disturbance. The disturbance compensation is based on the linearized MBS (6). The dilemma with the actuator is, that only two control goals are achievable, because the dimension of $\boldsymbol{u}$ is only two. Therefore, the goal of the disturbance is set to be $\boldsymbol{y}_{\boldsymbol{ctrl}} = [z_c, \beta_c]^T = \boldsymbol{h}(\overline{\boldsymbol{q}}_a, \overline{\boldsymbol{q}}_u)$, which shall be compensated with the two inputs $\boldsymbol{u} = [F_c, T_c]^T$. Only the basic idea of the inverse dynamics will be given here, due to the limitation in space, for details see [9]. The main idea for the control of under actuated MBS is the separation of the generalised coordinates $\overline{\boldsymbol{q}}$ in an actuated part $\overline{\boldsymbol{q}}_a = [r_c, \varphi_c]^T$ and and unactuated part $\overline{\boldsymbol{q}}_{\boldsymbol{u}} = [x_b, z_b, \beta_c]^T$. In the linear MBS represented by equation (6) the actuated coordinates $\overline{\boldsymbol{q}}_{\boldsymbol{a}}$ and their derivatives are replaced by the output $\boldsymbol{y}_{ctrl}$ using the inverse of the output function $\overline{\boldsymbol{q}}_{\boldsymbol{a}} = \boldsymbol{h}^{-1}(\boldsymbol{y}_{ctrl}, \boldsymbol{q}_{\boldsymbol{u}})$ and its derivatives, which is analytically possible for a linear system. The resulting representation of the MBS is than split in two parts:

$$\begin{aligned} \ddot{\boldsymbol{y}} &= \boldsymbol{f}_y(\boldsymbol{y}_{\boldsymbol{ctrl}}, \dot{\boldsymbol{y}}_{\boldsymbol{ctrl}}, \boldsymbol{q}_{\boldsymbol{u}}, \dot{\boldsymbol{q}}_{\boldsymbol{u}}) + \boldsymbol{g}_{\boldsymbol{yu}} \cdot \boldsymbol{u} + \boldsymbol{g}_{\boldsymbol{yd}} \cdot \boldsymbol{d} \\ \ddot{\boldsymbol{q}}_u &= \boldsymbol{f}_u(\boldsymbol{y}_{\boldsymbol{ctrl}}, \dot{\boldsymbol{y}}_{\boldsymbol{ctrl}}, \ddot{\boldsymbol{y}}_{\boldsymbol{ctrl}}, \boldsymbol{q}_{\boldsymbol{u}}, \dot{\boldsymbol{q}}_{\boldsymbol{u}}, \boldsymbol{u}, \boldsymbol{d}). \end{aligned} \tag{12}$$

The first part of (12) describes the dynamics of the output $\boldsymbol{y}$ and the second part describes the dynamics of the unactuated coordinates $\boldsymbol{q_u}$. The first part of (12) has to be inversed in order to calculate the input $\boldsymbol{u}$ with the given desired output $\boldsymbol{y} \to \boldsymbol{y}^* \equiv 0$ and the estimate of the disturbance $\boldsymbol{d} \to \widehat{\boldsymbol{d}}$. Note that $\boldsymbol{g_{yu}}$ has to have full rank for the inversion to work. The dynamics of the unactuated coordinates $\boldsymbol{q_u}$ has to be simulated online to achieve a consistent control input $\boldsymbol{u}$.

4 SIMULATION

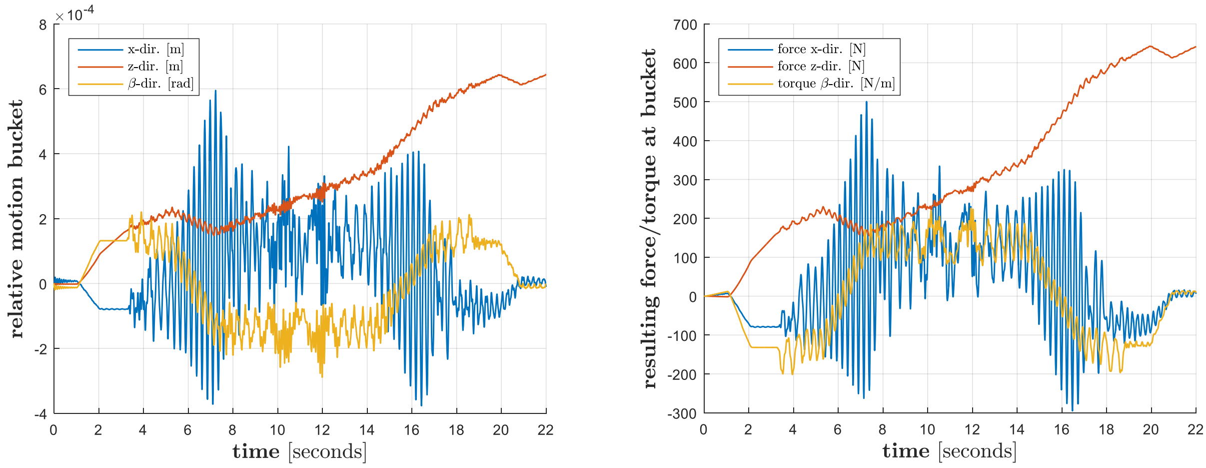
The simulation shown in this paper is a "worst-case" scenario simulation of a lift ride, where each guide rail of the rope-free PTS is perturbed. This perturbation of the rails results in the motion of the mounting point B_s of the bucket as shown in Fig. 6(a). The motion at the point B_s is transmitted through the springs and dampers and results in force and torque acting at point B_s as shown in Fig. 6(b), in order to be able to compare the disturbance $\boldsymbol{d}$ with its estimate $\widehat{\boldsymbol{d}}$. The linearized model (8) was achieved using the steady-sate $\boldsymbol{q}^s = \left[\boldsymbol{r_{Cb}^{O}}^T, 0{,}0.963{,}0\right]^T$ and its derivative $\dot{\boldsymbol{q}}^s = [0{,}0{,}0{,}0{,}0]^T$. The system matrices for each of the three disturbances are to be assumed the same and are given by

$$A_{d,i} = \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix} \; ; \; G_i = \begin{bmatrix} 0 \\ 1000 \end{bmatrix} ; C_{d,i} = [10^5 \quad 0], \text{ for } i = 1{,}2, \tag{13}$$

where ω is chosen to be 45, thus the disturbance generator displays a fast sinusoidal vibration. The large scaling factors in G_i and $C_{d,i}$ display the large force and torque, which are needed to move the cabin. The choice of the disturbance generator (13) is one of the design parameters of the disturbance estimation. Another design parameter are the covariance matrices of the measurement noise $\boldsymbol{v}$ and the disturbance noise $\boldsymbol{w}$ for the LQE design. The covariance matrices were here for simplicity and missing information of the measurement noise chosen to be identity matrices with respective sizes and a scaling factor

$$W = 10^6 \cdot I_3 \; ; \; V = 10^{-4} \cdot I_5. \tag{14}$$

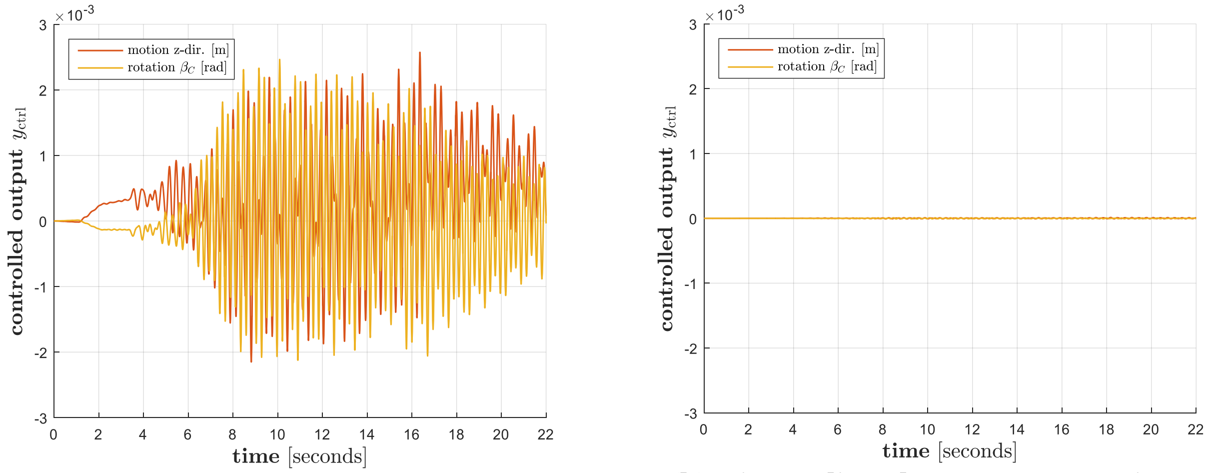
The choice of the covariance matrices (14) leads to a quit optimal estimation of the disturbance, due to the high trust in the output $\boldsymbol{y}$ determined by the small covariance V. The observer gain L of (11) is than found by solving the Ricatti equations in MATLAB by using the command `lqe`. The parameters have been chosen as shown in Table 1 and the damping parameters have been chosen to have the numeric value of the square route of its respective stiffness.



(a) Relative motion of bucket at B_s. **(b) Resulting force and torque at B_s.**

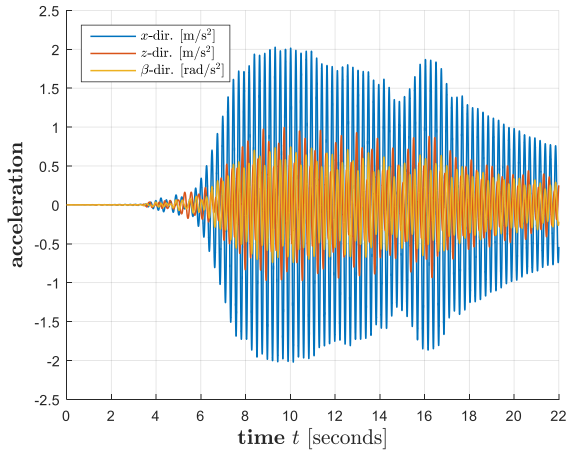
Figure 6 Pre-simulated motion of the bucket (a), using deviated rail profiles for each guidance rail. The resulting force and torque at B_s (b) conveyed through the spring damper system.

The result of the disturbance compensation is shown in the Fig. 7 by comparing the output $\boldsymbol{y}_{ctrl}$ without to the output with disturbance compensation. The improvement with the disturbance compensation is clearly visible in Fig 7. Fig. 8 shows the actually more interesting feature with respect to the vibration damping the actual acceleration inside the cabin filtered by the human sensitivity function from the ISO-Norm [12]. The improvement in the direction of the controlled output is again clearly visible in Fig. 8. Fig. 8 also displays the restriction of the chosen control output $\boldsymbol{y}_{ctrl}$ in combination with the two actuators, thus the input $\boldsymbol{u}$. The control scheme those not directly compensate any motion in the x-direction of the cabin, as visible in Fig. 8(b), because only two goals can be met with the given structure of the controller.

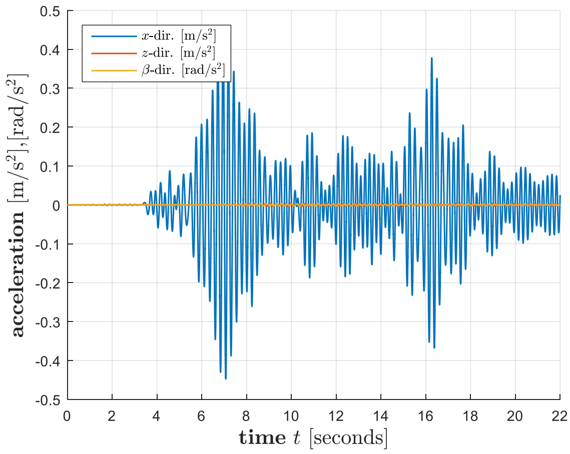


(a) Without disturbance compensation. **(b) Linear disturbance compensation.**

Figure 7 Controlled output $\boldsymbol{y}_{ctrl}$ without (a) and with linear disturbance compensation (b).



(a) Without disturbance compensation.



(b) Linear disturbance compensation.

Figure 8 Acceleration of controlled output and acceleration in x-direction of cabin filtered with the respective human sensitivity function [12].

5 CONCLUSION AND OUTLOOK

This paper presented a control strategy for the active cabin vibration damping of a rope-free PTS. The control strategy is based on the combination of disturbance compensation with estimation of the disturbance, which in general cannot be measured directly. The first simulation of the control strategy with a simplified two-dimensional model of the rope-free PTS shows promising results and suggests further investigation of the control technique. The many tuneable parameters, as the assumed disturbance generator model and the covariance matrices of the LQE design, includes room for the adjustment to the real world system.

The main limitation of the proposed control scheme is not the control strategy, but the actuator itself, which is not designed to damp vibrations in x-direction. In order to damp vibrations in the x-direction of the cabin an additional actuator input has to be designed. Another way to improve the control concept is to incorporate the real goal in the control output function $\boldsymbol{h}$, thus the damping of the acceleration inside the cabin. The used control output $\boldsymbol{y_{ctrl}}$ achieves this indirectly by damping all motions to zero, but a less restrictive damping rule might be better suited for the task. The model consisting only of mounting frame and bucket completely obviously omits the sledge and therefore neglects all feedback caused by the actuators to the sledge. In order to verify the model design further simulations including the sledge will be necessary.

Table 1 Parameter and initial distances for the simulation

Parameter	Value	Parameter	Value
Mass [kg]		**Inertia [kg m²]**	
Cabin	$\boldsymbol{m_c = 1000}$	Cabin	$\boldsymbol{I_c = 500}$
Mounting	$\boldsymbol{m_b = 200}$	Mounting	$\boldsymbol{I_b = 50}$
Actuator	$\boldsymbol{m_A = 2}$	Actuator	$\boldsymbol{I_A = 0.075}$
Initial distances [m]			
$\boldsymbol{B_s \rightarrow C_b}$	$\boldsymbol{r_{Cb}^{Bs}} = [\boldsymbol{0.165}, \boldsymbol{-0.6}]^{\boldsymbol{T}}$	$\boldsymbol{O \rightarrow B_s}$	$\boldsymbol{r_{Bs}^{O}} = [\boldsymbol{0}, \boldsymbol{0}]^{\boldsymbol{T}}$
$\boldsymbol{C_b \rightarrow B_0}$	$\boldsymbol{r_{B0}^{Cb}} = [\boldsymbol{0.75}, \boldsymbol{-0.3}]^{\boldsymbol{T}}$	$\boldsymbol{P_0 \rightarrow C_c}$	$\boldsymbol{r_{Cc}^{P0}} = [\boldsymbol{0}, \boldsymbol{0.9}]^{\boldsymbol{T}}$
$\boldsymbol{B_0 \rightarrow B_1}$	$\boldsymbol{r_{B1}^{Bs}} = [\boldsymbol{-0.5}, \boldsymbol{0}]^{\boldsymbol{T}}$	$\boldsymbol{P_0 \rightarrow P_1}$	$\boldsymbol{r_{P1}^{P0}} = [\boldsymbol{-0.5}, \boldsymbol{0}]^{\boldsymbol{T}}$
$\boldsymbol{B_0 \rightarrow B_2}$	$\boldsymbol{r_{B2}^{Bs}} = [\boldsymbol{0.5}, \boldsymbol{0}]^{\boldsymbol{T}}$	$\boldsymbol{P_0 \rightarrow P_2}$	$\boldsymbol{r_{P2}^{P0}} = [\boldsymbol{0.5}, \boldsymbol{0}]^{\boldsymbol{T}}$
Translational Stiffness [N/m]		**Rotational Stiffness [N/rad]**	
Point $\boldsymbol{B_s}$ $(\boldsymbol{x})$	$\boldsymbol{k_{xB} = 10^6}$	Point $\boldsymbol{B_s}$	$\boldsymbol{k_{\beta B} = 10^6}$
Point $\boldsymbol{B_s}$ $(\boldsymbol{z})$	$\boldsymbol{k_{zB} = 10^6}$		
Actuator	$\boldsymbol{k_{rc} = 2 \cdot 10^6}$	Actuator	$\boldsymbol{k_{\varphi c} = 2.2 \cdot 10^6}$

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BIOGRAPHICAL DETAILS

Jonas Missler received his bachelor’s degree in Engineering Cybernetics from the University of Stuttgart, Germany. He also obtained his master’s degree in Engineering Cybernetics from the University of Stuttgart. Since 2015, he is working towards his Ph.D. at the Institute for System Dynamics at the University of Stuttgart. His current research interests are the developing of an active damping concept and the respective control scheme for rope-free PTS.

Thomas Ehrl, Mechanical Design Engineer (degree in 1994), Part-time PhD student with the School of Science and Technology of The University of Northampton. Professional career started in 1994. Since 4/2008 with thyssenkrupp Elevator: Head of Research & Innovation Center of TKE Innovation GmbH, Pliezhausen; Engineering Training Manager at Corporate Level of TKE AG; Manager R&D Project Standards at Corporate Level of TKE AG. Interests: Travelling, sports, soccer, music, vintage English motor cycles, model building, photography.

Benedikt Meier received his Diploma in Mechanical Engineering from the University of Hannover, Germany. In 1992, he obtained his doctorate in Cold Testing of combustion engines. In thyssenkrupp Elevator AG, he is leading the Global Project Management Office (PMO). Since July 2015, he serves as Visiting Professor in the School of Science and Technology at the University of Northampton. His expertise is in the area of horizontal and vertical transportation and material handling systems. In addition, he is an internationally recognized expert in Project and Program Management. Professor Meier has published several journal and international conference papers in his area of expertise.

Stefan Kaczmarczyk has a master’s degree in Mechanical Engineering and he obtained his doctorate in Engineering Dynamics. He is Professor of Applied Mechanics and Postgraduate Programme Leader for Lift Engineering at the University of Northampton. His expertise is in the area of applied dynamics and vibration with particular applications to vertical transportation and material handling systems. He has been involved in collaborative research with a number of national and international partners and has an extensive track record in consulting and research in vertical transportation and lift engineering. Professor Kaczmarczyk has published over 90 journal and international conference papers in this field. He is a Chartered Engineer, being a Fellow of the Institution of Mechanical Engineers, and he has been serving on the Applied Mechanics Group Committee of the Institute of Physics.

Professor Oliver Sawodny received his Dipl.-Ing. degree in electrical engineering from the University of Karlsruhe, Karlsruhe, Germany, in1991 and his Ph.D. degree from the University of Ulm, Ulm, Germany, in 1996. In 2002, he became a Full Professor at the Technical University of Ilmenau, Ilmenau, Germany. Since 2005, he has been the Director of the Institute for System Dynamics, University of Stuttgart, Stuttgart, Germany. His current research interests include methods of differential geometry, trajectory generation, and applications to mechatronic systems. He received important paper awards in major control application journals such as Control Engineering Practice Paper Prize (IFAC, 2005) and IEEE Transaction on Control System Technology Outstanding Paper Award (2013).

Why PESSRAL is not PESS

Tijmen Molema

buikslotermeerplein 381, 1025XE, The Netherlands

Liftinstituut, tijmen.molema@liftinstituut.com

Keywords: PESSRAL, PESS, Safety

Abstract. The lift industry is quite old-fashioned in electric / electronic / programmable electronic (E/E/PE) safety: they used the electric safety chain for more than 30 years. However, since the EN 81-1/2 A1: 2005 amendment, the standard allows to use programmable electronics for safety systems (PESS). Also, the code committee decided to implement a subset of the leading norm (IEC 61508) into EN 81 in order to decrease the difficulty and increase the implementation speed: PESSRAL (Programmable Electronic System in Safety Related Applications for Lifts) was born. However, due to cherry picking and skipping the basics the old and even the newest code (EN-81-20/50) makes it possible to create unsafe systems. Where are the potential risks?

1 LEADING NORM

The IEC 61508 itself consists of 7 different pieces with a total of more than 500 pages. It describes the complete path to follow when creating an E/E/PE safety device. It contains calculations, assumptions, design strategies, risk analyses, and descriptions of quality systems. It results in a SIL (safety integrity level) which is a mathematical number expressing the safety of the system. All of this documentation is needed to end up in a safe system. In contrast: EN 81-20/50 uses 11 pages and claims to be a full package.

2 SYSTAMATIC CABABILITY

The entire process flow for making a PESS is described in a separate part of the standard, the 61508-1. By a clear way of working and project management we try to minimize systematic failures in a system. There are clear demands and this results in a SC (systematic capability) value. Techniques which can be used are e.g. project management, documentation, structured design and modularization as well as the SC, as these techniques are not demanded or described in EN 81-20. Projects without proper management can contain major mistakes, and these are hard to spot.

3 RISK ANALYSIS

For safety software, SIL (safety integrity level) is used to measure safety. It is a mathematical number expressing the safety of the system. For example: SIL 3 has an average chance of failure between 10^{-9} and 10^{-8} or 10^{-5} to 10^{-4} an hour depending on the demanded rate. Normally you have to perform a risk analyses in order to determine the needed SIL rate. The EN81-1/2+A3 and EN 81-20/50 have already performed this risk analyses in it and ask for SIL ratings. This way there is no need for a risk analyses anymore, which creates uniformity in the systems of competitors. However; a risk analyses gives insight in the project and influences the design. This is mandatory in IEC 61508 procedure, but not in EN 81-1/2 and EN 81-20.

4 DEMAND

So a SIL level is available, but it is not clear which SIL level we have to use exactly: the standard describes 2 types of SIL systems, high demand and low demand systems. Each of them have their own requirements. It is not clear by the EN81 if we are working in high or low demand. The difference in demand rate between these is mathematically a factor of 10.000 failures / hour. Low demand is explained in IEC 61508-4 as "where the safety function is only performed on demand, in order to transfer the EUC (Equipment under Control) into a specified safe state, and where the frequency of demands is no greater than one per year". For a lift, we do not use the over speed governor more than once a year, so is it than low demand? This is necessary to know because it gives a difference in the calculated safety by a factor of 10.000. It is not set clearly in the standard. However the IEC-62061 states that machines shall fulfill high demand. Most of the certifying organizations are following this guideline. Unfortunately it is not set plainly in the EN 81-20.

5 SAFE FAILURE FRACTION

When building a SIL 3 system, the relevant tables in EN 81-1/2+A3 and EN 81-50 require that a double channel system is mandatory. The main idea of this is 'when one channel fails, the other channel will put the system to a safe state'. IEC 61508 has the same principles, but there are some major discrepancies. IEC 61508 describes the model of SFF (Safe Failure Fraction): the fraction of failures which is safe and which is dangerous. For components where the failure mode cannot be predicted (like CPU's and other complex systems) the demands are set higher. Moreover, diagnostic software also increases the SFF. Due to the fact that EN81-20/50 demands a 2 channel system for SIL 3 it excludes the use of a totally fail-safe (SFF = 100%) 1 channel system and makes it possible to create a fail-unsafe (SFF << 90%) system. If every possible fault in a channel is directly dangerous (SFF = 0%), and if the fault remains undetected a second fault causes an unsafe system. This way, PESSRAL solutions can be less safe than the fault tree analyses present in the EN 81-20.

6 COMMON CAUSE

Due to not performing a risk analyses and the demand for 2 channels for SIL 3, a new difficulty occurs. By demanding 2 channels without any further specification it becomes possible to build 2 identical channels. These identical channels introduce the risk to fail at the same time due to the same error (common cause). Typical errors are a slightly to very low supply voltage, design faults inside a CPU, or temperature. When working with multiple channels, the common cause errors are the largest part of the total. I will demonstrate this with an example.

You can compare it with throwing a dice: by throwing a 1 you will lose: your chance of losing is exactly 1/6. To decrease this chance of losing you can add another dice, now you need two ones to lose the game. When calculating the chance of losing, we do 1/6 * 1/6 = 1/36. Now we introduce a common cause fault in this "system": a single fault which influences both channels (the dices). Due to the fact that on the other side of the dice the number "6" is represented, and for painting 6 dots we need slightly more paint. More paint means also more weight, and two opposite sides on a dice always give a total of 7. Due to this faulty design the chance of throwing a 1 is bigger than the other numbers. The chance of a double one is also bigger than the chance of another double combination. We assume that the change of throwing a 1 is 5% bigger; this value is token from the IEC-61508. The change of throwing one 1 is 1/6, a 5% higher change for one 1 is 1/6 + 1/6 * 1/20 comes to 7/40. The total change of throwing 2 times a 1 is now 7/40 * 7/40 = 49/1600, or +- 3%. As comparison, 1/36 is 2,8%.

The standard doesn't care which faults can be a common cause: all faults has to be taken into consideration as a possible common cause. Due to this, I can simplify the calculation: Take the dangerous fault and multiply it with the common cause factor. For the dices this will mean that we have the 1/6 (fault change of 1 channel) multiplied by 1/20: a factor of 1/120 is added as common cause, or 0,8%. We end up with a fault change of 2,8 + 0,8 = 3,6%. It is bigger than the full calculation, but it is on the safe side and we considered all possible common causes.

For this system the impact is still relatively small. However the fault chance of a PESS channel is a lot smaller: for example 10^{-9} Doing the same calculations, the two channel system has a chance of failing of 10^{-9}* $10{\wedge}^{-9}$ = $10{\wedge}^{-18}$. Now we calculate the common cause part: $5*10^{-2}$ * 10^{-9} .= $5*10^{-11}$ We can see clearly that the common cause part is way bigger than the single channel faults. If we have smaller failing chances in channels, than the common cause will become more important and be the dominant part of the safety calculations, as well as they are in real safety. EN 81 does not tackle this problem: the common cause risk is not described, there are no techniques for common cause avoidance described, and nothing is calculated.

7 DIAGNOSTIC TECHNIQUES

EN 81-20 cherry picks a number of techniques and states them as mandatory. There is no calculation needed anymore (EN 81-50 states that IEC 61508-6, which explains the calculations, is not needed for understanding). IEC 61508 gives a large number of options; the most suitable technique can be chosen for the system. It can happen that completely non-relevant techniques are demanded, where other techniques are quite more useful. For example; there are no demands for sensors in the lift standard, but when we use a CLPD (complex logic programmable device) there are still demands for RAM checks and watchdogs; this is not right according IEC 61508. Also, we cannot check if our diagnostics are good enough. Normally DC (diagnostic coverage) has a direct influence on the SFF (safe failure fraction), and so on the entire safety calculation of the system.

8 CALCULATIONS

The backbone of IEC 61508 are the underlying calculations. By looking at all components FIT (failure in time) rates and design, a calculation of the chance of failure can be made. The calculated numbers should be in line with the SIL rate. FMEA (Failure Mode Effect Analyses) on components and DC in order to improve the SFF ends up in a safer system. IEC 61508 has demands on the SFF which needs to be met. The calculation is the theoretical basis, it gives insight in the weakest points of the system and proves that the system is safe enough. This calculation is not needed for EN 81, by fulfilling all demands you are done. These demands describe techniques only, but does not give any numbers. There is no check if the system is “safe enough”. It is possible to end up with a mathematical unsafe system.

For example: I can use two really bad relays parallel. When they fail once in every 10 times, they will both fail at the same time every 100 times (excluding common cause!). It still fulfills EN81-20 (double channel with diagnostics): I can detect that both relays are failing. However: I cannot act on it anymore. When we calculate the failure rates for the system with IEC 61508, we will directly find out that the relays are not good enough for this system: the FIT (failure in time) values will be devastating for the PFH (Product Failure / Hour). Due to the calculation, bad components are filtered out.

9 TESTING

Every system needs testing after development: there are always unforeseen problems which are filtered out during the test phase. Of course a PESSRAL system will be tested, but what test strategy is the proper one? Known that most of the industry has no practical experience with safety software and there are no test strategies mandatory or even mentioned in the standard. Most commonly known test method is black- / white box testing: it is a basic way of screening a system. It is usable for electric- and mechanical systems. When creating PESS, the system is a full black box: However, IEC 61508 can also ask for traceability of the requirements, full modeling, software simulation and performance testing. Also there is no test procedure or awareness for common cause faults in the lift norm.

10 PROOF TEST INTERVAL

The lifetime of a system is not considered. Due to the fact that periodical inspection on PESS systems is almost impossible, a lifetime must be specified. Diagnostics in the system also cannot detect every possible fault, the DC is always smaller than 100%. Normally PESS systems have a “proof test interval”. The meaning of this proof test is to detect the normally undetected errors. EN 81 does not require this. This allows a system to build up an endless amount of errors and gives the possibility to end up with a dangerous fault.

11 DISCUSSION

At this moment, only a small amount of lifts work with PESS. For the ones that work, there are no major failures yet. PESS is possible since the first amendment of EN 81-1/2 in 2005. We do not know how many installations are in the field today, so we cannot determine why there were no failures. There are some possible explanations that can explain the fact that we did not have any accidents:

1. When making something revolutionary, a company must be absolutely sure that it is safe: otherwise the product will not be accepted in the market by the costumer. For PESSRAL, most lift company’s want to be absolutely sure that after several years it still works: so endurance tests will probably be done. This is a powerful testing method.
2. There are not that much PESSRAL systems in the world: most lifts have a long lifetime and controls are not regularly changed. Also the development of PESSRAL has just started: there are not that much PESSRAL systems on the market. Most of them are still in development.
3. The major certification bodies also perform tests on PESS systems. They have their own demands for testing, or will ask for a calculation. Certification bodies also want safe systems, and most of them know how to perform the tests properly due to the experience with IEC 61508.
4. There is no guideline for reporting crashes, and we cannot be sure that we will hear about all crashes in the world including the cause.

The biggest problems of these possible explanations are the fact that they are not mandatory: there are no demands on test time, there is no requirement for experience in PESS for notified bodies. Also worldwide information about lift catastrophes does not exists related to this topic.

12 CONCLUSION

PESSRAL is not PESS: and this is not only due the absence of a lot of background information. The entire mathematical backbone is gone: we cannot calculate if the chance of failure of the system is right. This has a huge impact on the common cause faults. These are the most dangerous faults for a double channel system. Also the channels itself can be made out of unsafe components. The only way to check the system now is by testing, but testing strategies are not described. Until this moment of writing, there are no fatal accidents yet. However we cannot explain why they did not happen, or predict that they will not happen. In the end, it is possible to build unsafe systems with the rules of PESSRAL. For now we can only hope that lifts will stay safe, for the future we need EN 81-20 to change as quickly as possible.

BIOGRAPHICAL DETAILS

Tijmen Molema is a product specialist certification for Liftinstituut. His specialty is in software and electronics. He studied Electronic Engineering and Design at the Hogeschool Utrecht. He started in 2014 as a lift inspector, but quickly became a product specialist for all kind of electronic challenges.

His personal goal is to help the lift industry to leave the “old” relays systems, and lead it to a new and progressive market.

Liftinstituut is an independent Body which is specialized in product certification and surveys of hoisting equipment for goods and persons. Liftinstituut is therefore also notified by the Dutch authorities as Notified Body(0400) for the Lift directive (95/16/EC) and machine directive (2006/42/EC) for e.g. *lifting devices of persons or of persons and goods involving a hazard of falling from a vertical height of more than three meters hoisting and logic controllers.*

In the USA Liftinstituut is also registered as AECO for Lifts (0842).

Some Thoughts on Rope Life

Julia Munday

20 Berrydale, Northampton NN3 5EQ, United Kingdom
munday_45@hotmail.com

Keywords: steel wire ropes, rope life, fleet angle

Abstract. This document explores the issues that affect the working lifetime of the ropes used with electric traction lifts and considers how “best practice” has changed over the years by using the modernisation of a common type of lift as an example.

1 INTRODUCTION

In the 1970’s engineers were taught the rope life for an electric traction lift depended on traction, groove pressure and rope drag (i.e. fleet angle).

Although modern methods of traction assessment where both the static and dynamic forces are considered are an improvement over the old; groove pressure has fallen out of fashion having been superseded by the mandatory requirements for the minimum rope safety factor in EN81-1 [1] and EN81-20 [2] but the effect of rope drag or fleet angle is mostly overlooked today.

Why does this matter? The fleet angle can have a deleterious impact on rope life; the old engineers considered it to have a worse effect than excessive groove pressure. Experts on ropes acknowledge the part it plays by including a correction factor for fleet angle in rope life calculations; but although recommendations for maximum limits were included in BS5655-6:1990 [3], it is conspicuous by its absence in current standards.

Patrick Ryan’s paper, presented at the 2015 lift symposium in Northampton [4] indicated issues with modern machine room less (MRL) lifts having inadequate rope life, despite the fact the requirements of that complex equation in Annex N of EN 81-1having been met.

This paper explores how the requirements of British Standards have developed over the last 40 years and discusses whether looking backwards to past best practice may help resolve this.

2 ROPE SELECTION THROUGH THE AGES

2.1 General Observations

When choosing the correct rope for an application the following factors need to be considered by the designer:

- The number of pulleys in the system and the roping ratio
- The ratio between the rope diameter and sheave diameter
- The material of the sheave and its hardness
- The groove form of the driving sheave
- The construction of the rope
- The minimum safety factor permitted by code
- The usage, i.e. the likely number of trips in a day

All the above factors are considered when checking there will be sufficient traction without excessive groove pressure, but the fleet angle needs to be considered separately. It can be said therefore that rope selection will depend on satisfactory traction, groove pressure, and fleet angle.

2.2 In the 1970s

It must be remembered that at this time the lift industry in the UK was very different to how it is today. Lift manufacturers generally designed, made, installed and serviced their own equipment; the independent sector did not yet exist. It was normal for a building owner to enter into a 25-year comprehensive maintenance agreement with the manufacturer of their lifts, and it was in the interest of the lift manufacturer to ensure their components were designed to give a long life to maximise their long-term profits. If the traction and groove pressure, (which had been calculated in the same way for many years), was close to the limits dictated by experience, the cost of replacement sheaves and additional ropes were factored into the maintenance costs, and so there are no specific requirements in BS 2655 [5] or the code of practice CP 407 [6] regarding traction or groove pressure because it wasn't perceived to be an issue.

As BS 2655 and CP 407 may be unfamiliar to most people under the age of 60, their requirements regarding rope related matters are summarised in Table 1 below.

Table 1 Requirements for Ropes in the 1970s

Item	Description	Source	Remarks
Minimum rope safety factor	10:1 ≤ 2.0 [m/s] rated speed 11:1 ≤ 3.5 [m/s] rated speed 12:1 ≤ 7.0 [m/s] rated speed	BS 2655-1:1970 clause 2.14.2	Note this is speed dependant.
Permitted rope terminations	Spliced or gripped return loops with thimbles or metalled sockets.	BS 2655-1:1970 clause 2.14.2	
Minimum sheave and pulley diameter	d (44 + 3S) with a minimum of 47 for 6 × 19 (9/9/1) construction ropes <u>or</u> d (37 + 3S) with a minimum of 40 for 6 × 19 (12/6 + 6 F/1) or 8 × 19 (9/9/1) construction ropes Where: d = rope diameter S = rope speed = rated speed x roping ratio [m/s]	BS 2655-1:1970 clause 2.14.4.2	Note limited rope types and speed dependant.
Single wrap vs double wrap	A 2:1 roped double wrap system with the rope to sheave ratio increased to 10% above the minimum recommended by BS 2655 will give a similar rope life to a 1:1 single wrap system	CP 407:1972 Clause 2.6.2.4	
Reverse bends	Increase the minimum diameters of the slower speed pulleys by 10% in all cases where the rope speed over such pulleys is more than 0.5 [m/s]	CP 407:1972 Clause 2.6.2.5	
Multiplying pulleys	For 2:1 roped lifts with rated speeds above 1.0 [m/s] only one pulley should be on the car and one on the counterweight	CP 407:1972 Clause 2.6.2.6	
Rope drag	Where the distance between two pulleys or a pulley and a sheave is fixed, the minimum drag ratio should be 100:1. Where the drag is between two points so that the distance between the two points and therefore the drag ratio varies as the car travels then the minimum drag ratio should be 41:1 when the car or counterweight rests on a completely compressed buffer.	CP 407:1972 Clause 2.6.2.8	The rope drag ratios are equivalent to maximum fleet angles of 0.6° between fixed pulleys and 1.4° between a fixed point and a moving point.

Other points to note:

1. Sheaves were generally made from cast iron and had a Brinell hardness in the region of 200-250, i.e. grooves were not hardened.
2. Rope anchorage plates were designed to keep the distances between the anchorages to a minimum to increase the rope drag ratio (i.e. minimise the fleet angle). “Long and short” eyebolts especially with the 2:1 roping anchorages were common and allowed an even more compact arrangement.

2.3 In the 1980s and early 1990s

In 1979 EN 81-1 was published in the UK as BS 5655-1 and included several national variations. The standard went through several amendments in the early 1980s, the “definitive” version which will be considered by this paper was published in 1986 [7].

The old code of practice CP 407 was replaced by BS 5655-6:1985.

Following some controversial remarks about the state of modern architecture by the Prince of Wales, and the planning authorities tightening up on interruptions to the skyline, designers wanted to avoid placing lift machine rooms on the top of their buildings, leading to the rising popularity of underslung lifts with the machine room located in a basement if you were lucky or at the top floor at the rear or side of the lift well if you were unlucky. As result of the experience gained by the industry in the UK during the 1980s, BS 5655-6:1990 [3] included a clause intended to reduce the permitted fleet angle between fixed pulleys to 0.4° (equivalent to 143:1 rope drag). But, due to an unfortunate typographical error, a figure of 4° was stated in the standard which has been adopted into common lift culture despite the clause being omitted from later issues of the standards.

The requirements of these standards are summarised in Table 2 below.

Table 2 Requirements for Ropes in the 1980s and early 1990s

Item	Description	Source	Remarks
Rope Specification	8 mm minimum diameter, wires to have a minimum tensile strength, characteristics to be as specified in international standards.	BS 5655-1:1986 clause 9.1.2	New requirement
Minimum rope safety factor	12 for systems with 3 or more ropes, 16 for those with two ropes A very high factor is not recommended since insufficient loading on a rope may reduce rope life.	BS 5655-1:1986 clause 9.9.2 BS 5655-6:1990 clause 4.4.1.2	No longer speed dependent. Note the comment on high safety factors!
Permitted rope terminations	Must withstand at least 80% of the breaking load of the rope. Spliced return loops with thimbles, gripped return loops with thimbles and at least 3 grips, metalled or resin sockets, self-tightening wedge sockets, ferrules or any system with equivalent safety.	BS 5655-1:1986 clause 9.2.3 clause 9.2.3.1	New strength requirement, more types of terminations now permitted
Minimum sheave and pulley diameter	40 x the rope diameter In some cases, it may be advantageous to increase this ratio to extend rope life.	BS 5655-1:1986 clause 9.2.1 BS 5655-6:1990 clause 4.4.1.3	No longer dependant on the rope construction or speed
Traction and groove pressure	Formulae are given for traction, limits specified for groove pressure.	BS 5655-1:1986 clause 9.3	New requirement
Rope tensioning devices	Must be fitted at one end at least, if a spring it must be in compression, slack rope switches to be fitted on systems with only two ropes.	BS 5655-1:1986 clause 9.5	New requirement

<table>
<tr><th>Item</th><th>Description</th><th>Source</th><th>Remarks</th></tr>
<tr><td>Single wrap vs double wrap</td><td></td><td></td><td>Withdrawn</td></tr>
<tr><td>Reverse bends</td><td>The minimum diameter of the pulleys should be increased by at least 10 % when the rope speed is greater than 0.5 [m/s].</td><td>BS 5655-6:1990 clause 4.4.1.6</td><td>Like CP 407:1972 clause 2.6.2.5</td></tr>
<tr><td>Multiplying pulleys</td><td>The more pulleys introduced into a roping system, the greater will be the rope wear.</td><td>BS 5655-6:1990 clause 4.4.1.4</td><td>No longer limits on the numbers of pulleys</td></tr>
<tr><td>Rope drag</td><td>Where the distance between two pulleys/sheaves is fixed, the fleet angle of the ropes in relation to the grooves should not exceed 0.4° (4° sic) either side of the groove axis. Where the distance between the two points varies as the car travels, the fleet angle should not exceed 1.4° when the car or counterweight is on a compressed buffer.</td><td>BS 5655-6:1990 clause 4.4.1.7</td><td>Conversion table<table><tr><th>Fleet Angle</th><th>Rope Drag Ratio</th><th></th></tr><tr><td>0.6°</td><td>100:1</td><td>CP 407</td></tr><tr><td>4°</td><td>14:1</td><td>Typo!</td></tr><tr><td>0.4°</td><td>143:1</td><td>Correct</td></tr><tr><td>1.4°</td><td>41:1</td><td>Same</td></tr></table>Increasing the fleet angle from 0.6° to 4° makes no sense!</td></tr>
<tr><td>Machine layouts</td><td>Machine above arrangements preferred, others require more pulleys and lead to greater rope wear.</td><td>BS 5655-6:1990 clause 4.4.1.8</td><td></td></tr>
</table>

Other points to note:

1. The independent sector started to take off in the 1980s; the harmonisation of British Standards with European Standards allowed for the importation of components and package lifts from suppliers in other parts of Europe.
2. It was discovered through bitter experience that hardened grooves on sheaves may require a different rope construction to the "standard" 6 or 8 strand Seale (9/9/1).

2.4 Late 1990s to Present Day

EN 81-1 [1] underwent a major revision in the late 1990s and has recently been superseded by EN 81-20 [2] and EN 81-50 [8]. These standards will be familiar to most within the industry so this section will briefly summarise the major changes from BS5655-1:1986 (EN 81-1:1985) regarding ropes:

- End terminations: spliced return loops with thimbles, gripped return loops with thimbles and at least 3 grips, metalled or resin sockets are no longer permitted, only self-tightening wedge sockets, ferrules or swaged terminations may be used.
- The method of calculating traction has changed.
- Groove pressure is no longer considered, replaced by a very complicated mandatory equation that gives a minimum permissible rope safety factor (EN 81-1:1998, Annex N). Note if this safety factor is less than 12 (three or more ropes) or 16 (two ropes) the higher figure should be used.

BS 5655-6 [9] only recommends the following it does not impose any restrictions:

- Machines should be located above if possible.
- The number of pulleys used in the system and the number of reverse bends should be minimised.
- Careful consideration should be given to the effect of the number of pulleys, the number of reversed bends, and the fleet angles of the ropes on and off the sheave or pulley.

3 WHERE HAS IT ALL GONE WRONG?

3.1 Some Anecdotal Evidence

Many people in the industry considered dropping the requirements for groove pressure from the standards to be a step backwards. Some still take it into consideration, but many do not.

One heard whispers from the mid-2000s onwards that ropes were not lasting as long as they should do, with the rope and machine manufacturers getting the blame in many cases.

One company the author worked for believed the Annex N equation only allowed a minimum rope life of three years and the safety factor should be increased.

Some of the technical people at Brugg wrote an article in Elevator World to set the record straight about the quality of modern ropes [10] and concluded that poor rope life was due to a combination of the following factors:

- High usage
- Small ratios between the rope diameter and sheave diameter
- Uneven load distribution between the ropes
- High acceleration and deceleration rates
- Poor quality sheaves
- Poor installation
- Poor maintenance

All valid points, but note fleet angle does not make the list.

3.2 It All Goes Back to Feyrer

According to Feyrer [11], the equation used to calculate the number of bending cycles is based on the following assumptions:

- The rope is well lubricated
- There is no side deflection (i.e. fleet angle)
- The grooves are steel (i.e. not lined with plastic) and the radius = 0.53 x the rope diameter
- The ropes are not twisted

If the assumptions made above do not hold true the number of bending cycles calculated in equation 3.55, it is corrected by multiplying by four endurance factors f_{N1}, f_{N2}, f_{N3} and f_{N4} which are shown in Table 3.

Table 3 Endurance Factors (Feyrer)

<table>
<tr><th>Endurance Factor</th><th>Description</th><th>Value</th></tr>
<tr><td>f_{N1}</td><td>Lubrication – assume the rope is well lubricated</td><td>1.0</td></tr>
<tr><td>f_{N2}</td><td>Fleet angle ϑ [degrees]</td><td>$1 - \left(0.00863 + 0.00243\frac{D}{d}\right)\vartheta - 0.00103\vartheta^2$ (1)
Where D = sheave/pulley diameter, d = rope diameter</td></tr>
<tr><td>f_{N3}</td><td>Groove form</td><td>Assuming an undercut U or V groove form:
<table>
<tr><td>Undercut β</td><td>75°</td><td>80°</td><td>85°</td><td>90°</td><td>95°</td><td>100°</td><td>105°</td></tr>
<tr><td>f_{N3}</td><td>0.40</td><td>0.33</td><td>0.26</td><td>0.20</td><td>0.15</td><td>0.10</td><td>0.066</td></tr>
</table>
(refer to Feyrer for other groove forms)</td></tr>
<tr><td>f_{N4}</td><td>Twisted ropes - assume the rope twist is negligible</td><td>1.0</td></tr>
</table>

Where lifts are concerned, the only one of these factors that are generally considered is the one for the groove form. Indeed, the value of the equivalent number of traction sheaves ($N_{equiv(t)}$) in the evaluation of the minimum rope safety factor is groove form dependent. Despite the lessons of experience, it must be assumed the ropes will be properly lubricated, installed without twist and fitted with anti-twist lanyards (although this is by no means certain given the diminishing skills of site personnel), but what about the fleet angle?

3.3 What About the Fleet Angle?

Figure 1 shows the results of using eq. 1 to calculate the endurance factor for the fleet angle depending on the rope to sheave ratio. The maximum fleet angles recommended by CP 407 and BS 5655-6:1990 are indicated for easy reference. The chart only goes up to 4°, as this appears to be the general consensus for the maximum limit.

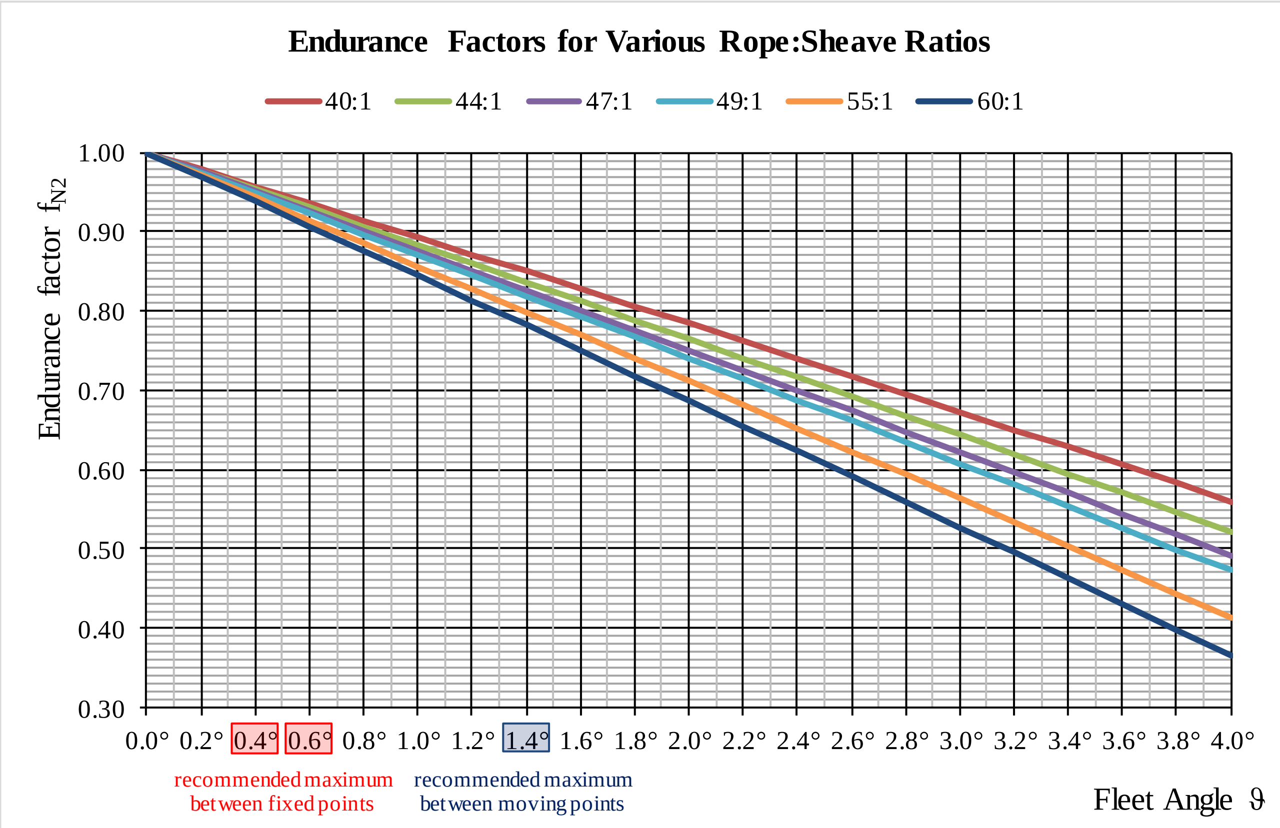


Figure 1

It is apparent that the endurance factor not only reduces as fleet angle increases but also as the rope to sheave ratios increase. To put this into context, assuming as a worst case a fleet angle of 4°, a 10mm diameter rope running over a 600mm diameter sheave would have an endurance factor approximately 35% smaller than the same rope running over a 400mm diameter sheave.

If the fleet angle is limited to the 1.4°, the CP 407 and BS 5655-6:1990 recommendation for the maximum between a fixed pulley and a moving pulley or anchorage, the endurance factor reduces by approximately 8%; and 2% if the fleet angle is reduced to the 0.4°, the figure BS 5655-6:1990 would have recommended between fixed pulleys if the typographical error hadn't occurred.

Although the fleet angle does not have as deleterious an effect on rope life as the groove form of the sheave, it will have some effect and this could be substantial depending on the circumstances.

3.4 But What Does It All Mean? – An Example

As all the standards and codes of practice recommend 1:1 roped gear above systems to maximise the rope life it has been decided to use the modernisation of a typical standard lift of this type installed in the early 1990s as an example that many people will be familiar with from their own experience. It is based on a standard "Omega" made by Express Lifts. The building is an office block, the details are summarised below:

Rated Load	:	630 kg
Rated Speed	:	1.6 m/s
Car weight	:	950 kg
Balance	:	50%
Travel	:	40 m
Number of floors served	:	12

The lift was fully compliant with the codes and standards of its day and has 6 x 11 mm diameter ropes of 8x19(9/9/1) Sz FC 1370/1770 N/mm^2; the sheave has 97° undercut "V" grooves; the ropes are terminated with sprung eyebolts with babbitted sockets at the counterweight end, and dead eyebolts with clipped returns at the car end; the other relevant details are shown in Figure 2.

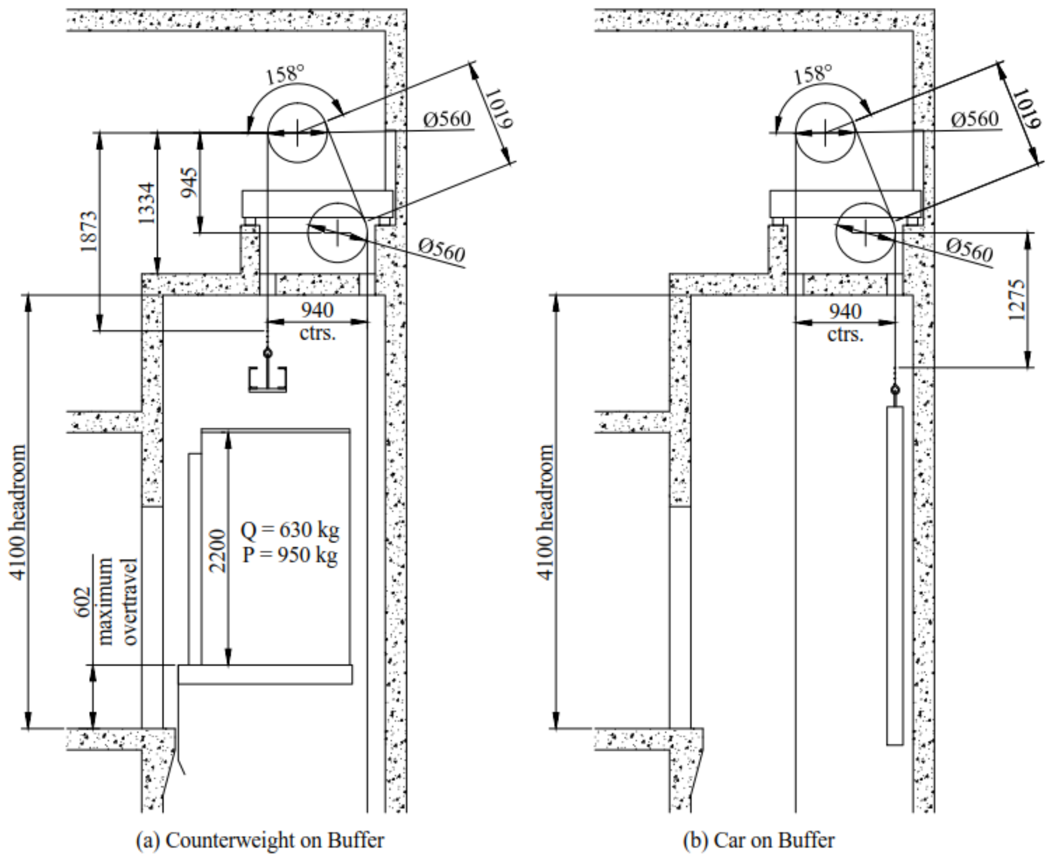
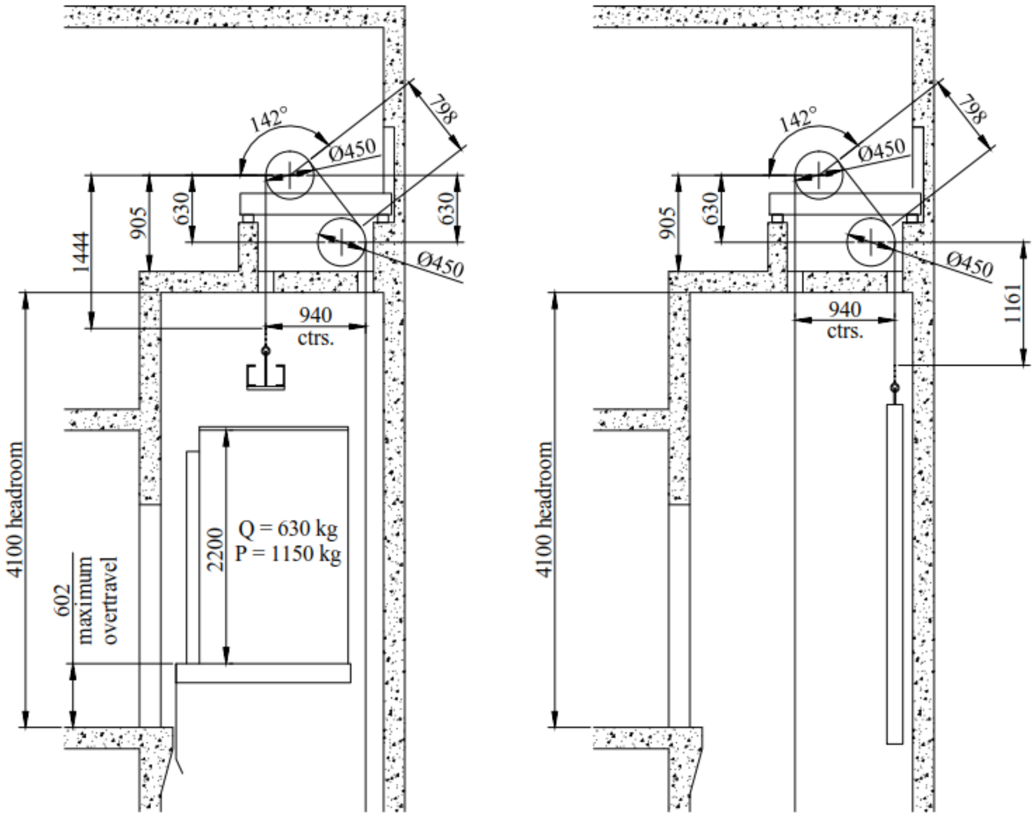


Figure 2 The Existing Arrangement

As the machine is approximately 25 years old, it has been decided to replace it, the diverter, supply a new raft re-using the existing concrete upstands, new ropes and anchorages, a new control panel and some cosmetic refurbishment to the car. The replacement of any other equipment and provision of devices to prevent the uncontrolled movement of the car have been disregarded as they will not have any bearing on the rope life.

A suitable new "Toro" machine has been determined using the software on Sassi's "Argaweb" website; using 97° undercut "U" grooves the same number, size and construction of ropes as the original will be required to meet EN81-20/50. It has been assumed the car weight will increase by 200 kg because of the refurbishment. The other relevant details are shown in



(a) Counterweight on Buffer (b) Car on Buffer

Figure 3 The Modernised Arrangement

The first problem arises trying to fit new anchorages with self-tightening wedge sockets on to the existing anchorage plates. They don't fit, so have to be replaced, with consequences for the fleet angles as shown in Figure 4 and Figure 5.

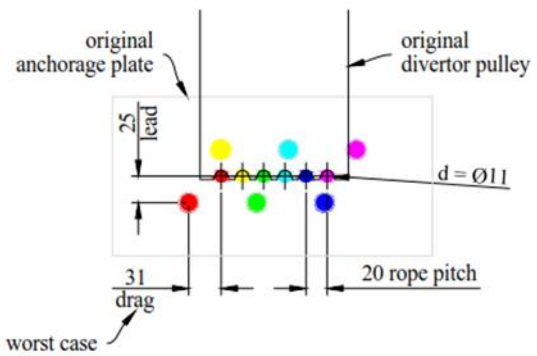


Figure 4 Original Arrangement

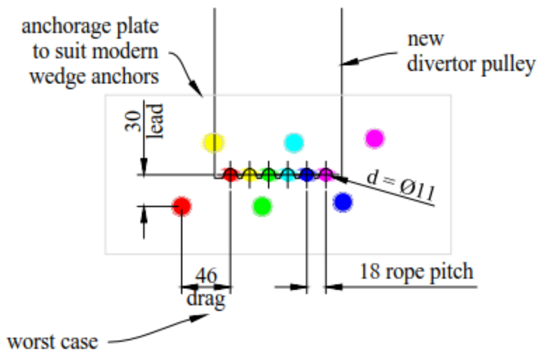


Figure 5 New Arrangement

The worst-case fleet angle was originally 1.4° (i.e. 41:1) but now has increased to 2.3° (approximately 25:1), but the rope to sheave ratio has decreased from 51 to 41 approximately. The only other parameter that will affect the rope lift calculation is the increase in the bending length.

Following the method used in Example 3.11 in Feyrer of a 1:1 roped lift (assuming the car is loaded with 50% of the rated load) for both the original lift and the modernised lift but also considering the effect of the fleet angle gives the results shown in Table 4. The total number of trips before discard ignoring the effect of the fleet angle has also been calculated for comparison.

Table 4 Calculation Results

		Original Lift		Modernised Lift	
		Sheave	Diverter	Sheave	Diverter
Rope Tensile Force	S [N]	3,347		3,831	
Endurance Factors	f_{N1}	1		1	
	f_{N2}	0.87	0.81	0.80	0.75
	f_{N3}	0.13	1	0.13	0
	f_{N4}	1		1	
Discard No Bending Cycles	N_{A10}	1,725,963	12,361,008	417,186	3,008,553
Number of trips to/from G	Z_{A10}	1,514,494		366,381	
Holeschak Ratio	f_{GF}	0.51		0.51	
Total trips before discard **with fleet angle considered**	$Z_{A10,tot}$	2,969,500		718,300	
Total trips before discard **With fleet angle disregarded**	$Z_{A10,tot}$	3,442,900		904,500	

4 CONCLUSIONS

Patrick Ryan states the modern requirements for the rope safety factor will ensure a rope life of 600,000 trips; the results above confirm this. Assuming the example lift will undertake 200,000 trips per annum the ropes on the original lift would have had a life of over 10 years (assuming proper maintenance), but the modernised lift would require the ropes to be replaced within 4 years.

As can be seen from the example in section 3.4 above using a larger rope to sheave ratio (on both the traction sheave and pulleys) has a massively beneficial effect on the rope life. The calculations indicate the ropes on the modernised lift will have an expected life of only 24% of that of the original lift with only a slight improvement if the effect of the fleet angle is ignored.

When the effect of the fleet angle is taken into consideration the anticipated life of the ropes will reduce by about 13% for the original lift, but about 20% for the modernised lift.

If the fleet angle can be shown to have this much of an effect on the rope life of a straightforward conventional 1:1 roped gear above lift, which all parties agree is the "best case scenario" for rope life, how much of an effect will it have on a modern MRL where fleet angles up to 4° are not uncommon and the number of pulleys and the roping arrangement are considerably more complex?

The rope safety factor equation in EN 81-50 is very complicated, its correct application is not explained in terms that are easily understandable and requires a level of mathematical ability many do not possess, thus making it difficult to check the calculations provided by machine manufacturers. The equation assumes the use fibre core ropes and disregards the effect of fleet angle and rope construction, perhaps it is time for it to be reviewed in the light of these concerns and consideration given to returning to a simpler system of placing limitations on fleet angles and increasing minimum rope to sheave ratios?

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BIOGRAPHICAL DETAILS

In 1979, Julia took a temporary job as a Trainee Draughtsman at the Express Lift Company in Northampton, becoming a Sales Engineer. During this time she worked on major projects in the UK and abroad (including Hong Kong, Singapore and Australia), before finally moving on to Modernisation. After the demise of Express Lifts, she worked as a Project Engineer for ThyssenKrupp, Elevator, and Kone before joining WSP as a consultant in 2013. Along the way she kept studying, eventually being awarded an MSc in Lift Engineering from the University of Northampton in 2010.

Creating Passengers in Batches for Simulation

Richard Peters, Sam Dean

Peters Research Ltd,
Bridge House, Station Approach, Great Missenden, Bucks, HP16 9AZ, UK
info@peters-research.com

Keywords: lift, elevator, simulation, passenger generation, batches, Poisson

Abstract. Lift passengers often travel together in groups rather than alone. In passenger generation for lift simulation these groups are referred to as batches, with the distribution of batch sizes sometimes presented in tabular form. This paper demonstrates how this distribution of batch sizes can be formulated. The advantage this has for users of simulation software is that the prospective grouping of passengers can be entered as a single number corresponding to the average batch size. The distribution of batch sizes generated using the new approach is compared with site survey data. Historically, most simulations have ignored grouping, effectively using a batch size of 1. The impact of using a batch sizes other than 1 for simulation results is discussed.

1 INTRODUCTION

In most elevator traffic simulations, passengers are assumed to arrive individually. If passengers arrive at the same time or are travelling to the same destination, this is only by chance.

It has been shown that passengers sometimes arrive in batches [1] [2] or bulks [3]. This influences lift operation and therefore quality of service. For example, if two people are travelling together, a batch of two, they are more likely to have the same destination. This equates to a lower probable number of stops.

This paper demonstrates how this distribution of batch sizes can be formulated. The advantage this has for users of simulation software is that the prospective grouping of passengers can be entered as a single number corresponding to the average batch size.

2 PREVIOUS WORK

In a traffic simulator one of the important software modules is passenger generation. Peters et al. [4] discuss a range of possible passenger arrival models including:

1. constant inter-arrival time
2. random inter-arrival time with uniform probability density function
3. random passenger arrivals applying Poisson probability density function
4. random inter-arrival time with exponential probability density function
5. random arrival time in a given time period

The authors propose a methodology for generating passengers that assumes:

1. a random inter-arrival time with exponential probability density function
2. the total number of passengers is consistent with the expected number of passengers
3. a batch size that may be building and time specific

The probability density function that is to be used for the generation of the batch sizes, based on reference [1], is given in Table 1.

Table 1 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 method allows for passengers to be generated, see Figure 1. The second plot (adjusted arrival time) ensures the numbers of passenger generated in the time period correspond to the arrival rate.

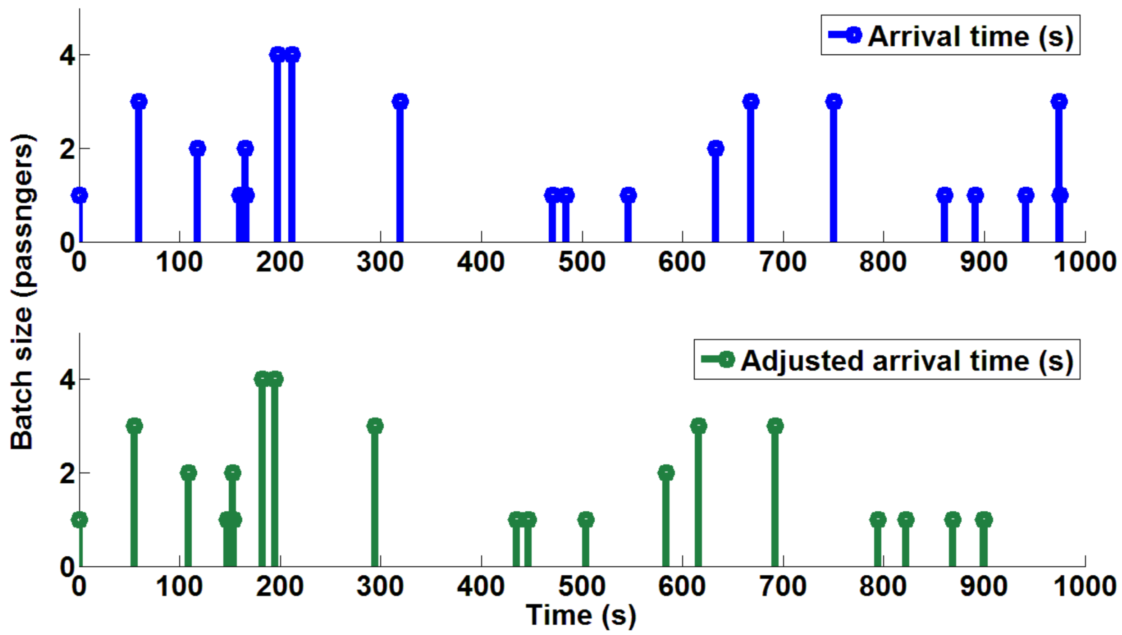

Figure 1 Initial and adjusted batch arrivals

3 TRAFFIC SURVEY DATA

A traffic study [5] was undertaken at a transport terminal to collect batch size data with a larger data set than in Table 1. Observers used their judgment to determine if people were travelling individually, or in groups. 1249 batches were observed, results are given in Table 2.

Table 2 Probability density function for the batch sizes

Batch size	1	2	3	4	5	6
Probability	811/1249	340/1249	71/1249	19/1249	6/1249	2/1249

The results in Table 2 yield an average batch size of 1.46.

The Poisson distribution may be used to model the batch size, see Equation 1.

$$p_b(n) = \frac{(b-1)^{n-1}}{(n-1)!} e^{-(b-1)} \qquad \text{for } n = 1, 2, 3\ldots \qquad (1)$$

Where $p_b(n)$ is the probability of a batch size of n and b is the average batch size. Note: it is not suggested that the underlying distribution is Poisson, but that the curve follows a similar pattern. The classical Poisson formula is offset by 1 as there cannot be a batch size of 0.

Figure 2 shows the probability of different batch size based on measurements and as calculated using Equation 1 with an average batch size or 1.46. The R-Squared value is 0.999 showing a good fit for the data. At high batch sizes, Equation 1 under predicts the probability, however these instances are rare.

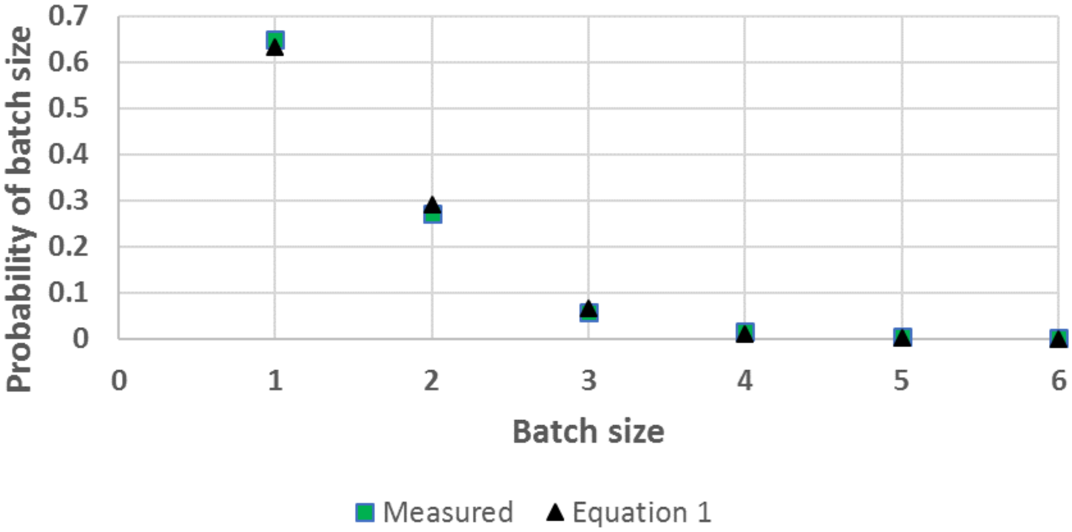

Figure 2 Comparison of batch size probability measured versus Equation 1

The data suggests it is reasonable for a passenger generator used by simulation software to accept input of an average batch size, then to create passenger batches assuming Equation 1.

4 METHODOLOGY FOR GENERATING PASSENGERS

4.1 Introduction to the methodology

This section provides a step by step methodology for generating passengers with random inter-arrival time with an exponential probability density function. Passenger batches are selected assuming Equation 1 given an average batch size.

For example, using terminology from CIBSE Guide D Section 4 [6], consider a passenger demand represented as having an arrival rate of 24.95 person per five minutes at the entrance floor for a time period of one hour (3600 s). There are 10 upper floors with equal population resulting in a destination probability of 10% to each floor. The average batch size, b = 1.2.

The software implementing the methodology should generate a list of passengers corresponding to the passenger demand. All random numbers generated should be uniformly distributed.

4.2 Determining how many people to generate

With an arrival rate of 24.95 persons per five minutes, the number of passengers in this period is 12 x 24.95 persons which is 299.4 persons.

With simulation, there cannot be part passengers. Use a random number to decide if to create 299 or 300 persons, i.e. does the person corresponding to the 0.4 turn up?

Generate a random number between 0 and 1. If the random number is ≤ 0.4, then use 300 people, otherwise use 299 people. Assuming the random number was 0.21, the number of persons generated, N_p = 300 persons. Continue by dividing these N_p people into batches.

4.3 Generation of batches

Calculate the probability of each batch size using Equation 1. Based on an average batch size of 1.2, results are given Table 3.

Table 3 Probability density function for the batch sizes of 1.2

Batch size	1	2	3	4	5	6
Probability	0.819	0.163	0.016	0.001	0.000	0.000

Proceed as follows:

i. Generate a uniformly distributed random number between 0 and 1.
ii. If the random number is ≤ 0.819, then the batch size is 1. Otherwise, if the random number is ≤ (0.819+0.163) then the batch size is 2. Otherwise, if the random number is ≤ (0.819+0.163+0.016) then the batch size is 3. And so on.
iii. For example, if the random number is 0.82 this will yield a batch size of 2. There are now 300-2 = 298 people left to assign to batches.

Repeat the procedure (i) to (iii) until all 300 passengers are part of a batch.

In the final repeat of the procedure, there may not be enough people left for the batch size selected by the random number. For example, if the random number generated calls for a batch size of 3, but already 298 people have been put in batches, then the final batch size is taken to be 2.

Call the number of batches generated N_b. Once the passenger batches have been generated, the arrival times of the batches can be determined.

4.4 Generation of arrival times

A procedure to generate batch arrivals and random inter-arrival time with exponential probability density function as described by Peters et al [4] is summarized in Section 2.

The average batch size is 1.2 persons, and there are 300 persons. On average, there are 300 persons/ 1.2 persons per batch = 250 batches. In this example, the software generated 252 batches. These arrive in one hour (3600 seconds). So, the batch arrival rate λ_b is

$$\lambda_b = \frac{252}{3600} = 0.07\ batches/second \tag{2}$$

Δt_i is the inter-arrival time between batch *i* and batch *i+1* [4]

$$\Delta t_i = \frac{-\ln(1 - Rand)}{\lambda_b} \tag{3}$$

for $i = 0\ to\ N_b + 1$. *Rand* is a function that generates a random number between 0 and 1.

In Section 2, Figure 1 the first passenger arriving at time = 0 s. In the context of simulation software which may have many consecutive periods, it is preferable not to have a passenger arriving at the instant each period begins. To address this, add half a randomly generated inter-arrival time after the period start time. This allows multiple periods to follow each other without a person marking the start of each period, see Δt_0 in Figure 3.

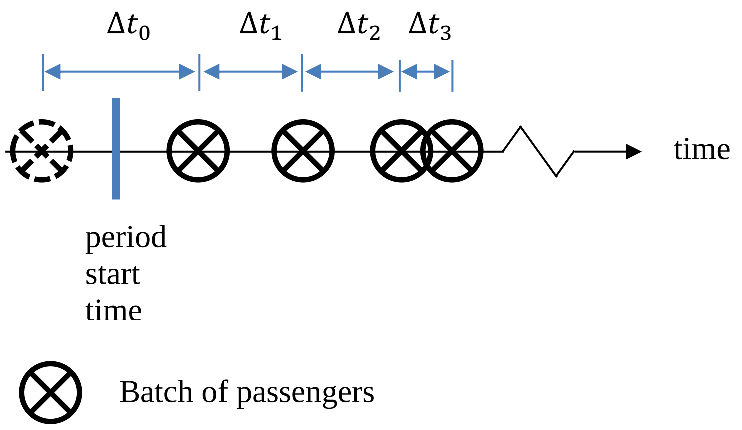

Figure 3 Placing the first batch on the time line

Continuing placing all the batches on a time line using Equation 3, see Figure 4. The period end time is only approximate as the calculation of inter-arrival times includes a random element.

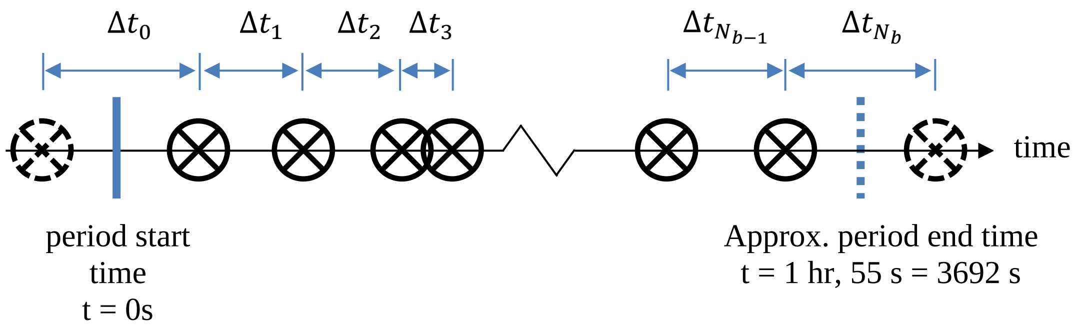

Figure 4 Passenger batches on time line

Shrink or stretch the inter-arrival times so that the batches arrive within the period. A scaling factor, *SF*, can be determined by establishing the ratio between the sum of the generated inter-arrival times and equivalent time taken with passengers arriving at the batch arrival rate, λ_b, see Equation 4.

$$SF = \frac{time\ period}{\frac{\Delta t_0}{2} + \left(\sum_{i=1}^{i=N_{b-1}} \Delta t_i\right) + \frac{\Delta t_{N_b}}{2}} = \frac{3600}{\frac{2.296}{2} + 3682.272 + \frac{19.010}{2}} = 0.975 \tag{4}$$

The adjusted inter-arrival times, Δts_i can then be determined, see Equation 5.

$$\Delta ts_i = \Delta t_i \cdot SF \tag{5}$$

Apply the SF so that the batch of passengers aligns with the actual period end time, see Figure 5.

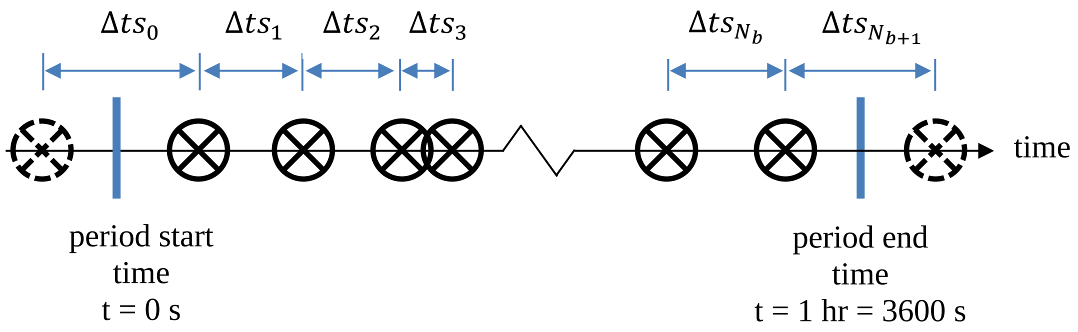

Figure 5 Passenger batches with inter-arrival time adjusted to align in actual period end time

4.5 Passenger destinations

It is assumed that each passenger batch has the same destination. The destination probability to each floor above the entrance floor was 10% (=0.1), see Table 4.

Table 4 Batch destination probabilities

Floor	1	2	3	4	5	6	7	8	9	10	11
Destination probability	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

For each batch, generate a random number between 0 and 1. If the random number is ≤ 0.1, the destination is floor 2. Otherwise, if the random number is ≤ (0.1 + 0.1), the destination floor is floor 3. Otherwise, if the random number is ≤ (0.1 + 0.1 + 0.1), then destination floor is 4. And so on.

5 EXAMPLE RESULTS

5.1 Passenger generation

Example results for the above example with a batch size of 1.0 and 1.2 are given in Table 5.

Table 5 Example passenger generation results

Average batch size of 1				Average batch size of 1.2			
Seconds	Arrival Floor	Destination Floor	Batch Size	Seconds	Arrival Floor	Destination Floor	Batch Size
2.1	1	4	1	1.1	1	2	1
6.2	1	9	1	13.1	1	3	1
9.3	1	11	1	39.0	1	8	1
25.5	1	10	1	51.3	1	6	1
35.3	1	10	1	64.9	1	7	1
51.4	1	6	1	76.5	1	7	1
73.9	1	4	1	88.3	1	10	2
79.8	1	9	1	101.4	1	5	1
82.1	1	5	1	102.9	1	6	1
107.2	1	11	1	171.2	1	5	2
108.0	1	8	1	175.6	1	11	1
117.5	1	11	1	203.5	1	7	1
131.1	1	5	1	209.4	1	4	1
132.1	1	10	1	249.9	1	9	1
148.6	1	9	1	250.4	1	10	1
157.1	1	11	1	261.9	1	5	1
161.0	1	5	1	284.5	1	4	1
172.6	1	6	1	293.8	1	5	1
187.3	1	9	1	294.8	1	3	1
193.6	1	8	1	300.7	1	7	1
194.1	1	9	1	303.8	1	8	1
201.3	1	6	1	331.7	1	4	1
230.6	1	11	1	350.9	1	4	2
231.2	1	5	1	355.3	1	2	1
253.9	1	10	1	360.6	1	3	2
264.8	1	11	1	369.3	1	9	1
267.9	1	11	1	374.8	1	10	1
292.1	1	3	1	399.1	1	7	2
297.5	1	8	1	408.7	1	3	1
336.4	1	6	1	412.7	1	2	2
341.0	1	11	1	417.7	1	6	1
373.3	1	5	1	449.1	1	9	2
375.2	1	3	1	456.7	1	10	1
384.7	1	7	1	475.7	1	7	1
415.2	1	6	1	476.0	1	11	2
428.1	1	9	1	477.6	1	7	1
448.5	1	10	1	493.0	1	3	1
472.8	1	9	1	498.3	1	2	2
495.0	1	2	1	509.0	1	2	2
513.1	1	4	1	516.6	1	2	1
515.1	1	7	1	528.3	1	3	1
529.8	1	8	1	552.5	1	4	1
544.6	1	2	1	555.5	1	8	1
547.0	1	10	1	563.0	1	11	1
560.0	1	10	1	619.9	1	7	1
580.9	1	5	1	626.7	1	7	1
582.6	1	11	1	627.9	1	10	1
593.8	1	2	1	630.0	1	8	1
620.1	1	6	1	636.5	1	4	2
637.0	1	8	1	641.3	1	11	1
640.5	1	4	1	661.9	1	3	1
642.9	1	4	1	709.6	1	11	1
648.3	1	8	1	739.7	1	9	1
656.3	1	8	1	768.1	1	8	1
656.9	1	3	1	776.6	1	4	1
664.6	1	3	1	781.5	1	4	1
670.6	1	5	1	803.2	1	7	1
699.3	1	2	1	808.8	1	4	2
718.4	1	3	1	870.8	1	4	1
725.2	1	2	1	884.6	1	11	1
731.5	1	7	1	940.3	1	7	1
732.8	1	8	1	946.0	1	2	1
748.3	1	4	1	970.6	1	11	1
751.8	1	9	1	991.3	1	3	1
757.2	1	11	1	1024.6	1	9	1
758.8	1	3	1	1031.2	1	4	1
765.7	1	8	1	1040.3	1	9	1
776.2	1	7	1	1058.1	1	8	1
789.6	1	10	1	1072.0	1	6	1
795.6	1	9	1	1089.2	1	11	1
797.9	1	9	1	1096.3	1	9	1
809.4	1	7	1	1173.7	1	5	1
814.0	1	10	1	1179.8	1	9	1
821.2	1	8	1	1208.9	1	2	1
824.1	1	4	1	1253.2	1	2	1
826.6	1	8	1	1296.4	1	6	1

Average batch size of 1				Average batch size of 1.2			
Seconds	Arrival Floor	Destination Floor	Batch Size	Seconds	Arrival Floor	Destination Floor	Batch Size
834.6	1	5	1	1299.0	1	10	1
837.9	1	6	1	1312.2	1	7	1
857.1	1	7	1	1319.7	1	6	1
899.1	1	8	1	1352.8	1	10	2
907.5	1	7	1	1358.2	1	11	1
913.8	1	9	1	1360.9	1	4	1
929.2	1	7	1	1371.6	1	4	1
951.6	1	4	1	1380.5	1	5	2
955.8	1	6	1	1400.0	1	4	1
986.3	1	10	1	1424.6	1	11	2
987.5	1	6	1	1445.5	1	9	1
1006.6	1	11	1	1446.6	1	11	1
1011.1	1	6	1	1450.4	1	4	1
1025.0	1	8	1	1462.2	1	3	1
1029.1	1	10	1	1477.3	1	3	1
1034.2	1	8	1	1477.6	1	9	1
1066.4	1	4	1	1503.1	1	4	2
1068.1	1	7	1	1531.2	1	4	1
1075.4	1	11	1	1536.3	1	9	1
1093.5	1	5	1	1578.1	1	11	1
1100.3	1	4	1	1578.8	1	11	1
1117.0	1	3	1	1586.2	1	10	1
1160.5	1	7	1	1602.4	1	9	2
1161.9	1	10	1	1606.6	1	9	1
1171.1	1	3	1	1611.2	1	9	1
1175.2	1	7	1	1627.2	1	2	1
1176.9	1	11	1	1640.9	1	3	1
1182.1	1	11	1	1644.0	1	2	1
1191.0	1	6	1	1645.8	1	7	1
1207.5	1	2	1	1652.9	1	8	1
1264.8	1	6	1	1653.8	1	11	3
1278.5	1	11	1	1656.8	1	10	1
1279.0	1	8	1	1657.3	1	8	1
1307.7	1	2	1	1667.2	1	9	2
1311.3	1	4	1	1682.1	1	6	1
1314.3	1	2	1	1685.6	1	5	1
1324.9	1	4	1	1707.8	1	6	1
1331.2	1	7	1	1755.7	1	3	1
1356.3	1	7	1	1758.2	1	2	2
1359.6	1	4	1	1774.8	1	11	1
1367.7	1	6	1	1785.5	1	6	1
1369.7	1	9	1	1808.6	1	2	1
1371.4	1	7	1	1827.9	1	9	1
1453.0	1	5	1	1846.6	1	11	3
1485.2	1	9	1	1857.1	1	8	2
1487.2	1	8	1	1880.9	1	7	1
1489.5	1	9	1	1897.0	1	3	1
1497.8	1	10	1	1900.6	1	10	1
1507.8	1	4	1	1915.3	1	4	1
1515.8	1	3	1	1921.4	1	3	1
1521.8	1	8	1	1929.6	1	4	1
1522.9	1	11	1	1941.0	1	11	1
1542.8	1	6	1	1957.1	1	5	1
1547.8	1	6	1	1968.1	1	5	1
1579.0	1	10	1	1989.3	1	6	2
1585.5	1	4	1	2001.4	1	8	1
1588.7	1	7	1	2006.1	1	10	1
1593.7	1	7	1	2014.4	1	8	1
1605.8	1	10	1	2039.4	1	5	1
1614.1	1	3	1	2047.0	1	4	1
1623.9	1	9	1	2087.7	1	11	1
1632.1	1	6	1	2095.1	1	9	1
1642.8	1	3	1	2111.7	1	3	1
1646.8	1	11	1	2139.5	1	8	1
1660.5	1	8	1	2152.5	1	5	1
1662.8	1	4	1	2156.1	1	6	1
1679.8	1	4	1	2168.5	1	2	1
1716.6	1	10	1	2223.1	1	7	2
1725.6	1	10	1	2229.1	1	2	1
1748.0	1	6	1	2233.2	1	7	2
1761.9	1	3	1	2234.8	1	7	1
1781.2	1	8	1	2244.9	1	9	1
1815.4	1	7	1	2272.5	1	11	2
1820.8	1	6	1	2275.0	1	10	1
1850.2	1	3	1	2286.9	1	6	2
1851.8	1	2	1	2325.6	1	3	1

Average batch size of 1				Average batch size of 1.2			
Seconds	Arrival Floor	Destination Floor	Batch Size	Seconds	Arrival Floor	Destination Floor	Batch Size
1860.1	1	11	1	2365.8	1	5	1
1888.4	1	6	1	2375.2	1	2	2
1889.1	1	8	1	2376.1	1	3	1
1893.3	1	7	1	2385.6	1	2	1
1897.3	1	3	1	2418.5	1	2	1
1903.2	1	6	1	2431.3	1	2	1
1904.2	1	3	1	2432.7	1	2	1
1926.9	1	11	1	2437.0	1	11	2
1947.7	1	8	1	2438.2	1	2	1
1949.6	1	2	1	2442.5	1	10	1
1969.4	1	7	1	2453.5	1	8	1
1971.1	1	4	1	2465.1	1	11	1
2027.3	1	10	1	2469.2	1	7	3
2028.6	1	5	1	2478.5	1	10	1
2031.7	1	4	1	2500.9	1	5	1
2041.3	1	4	1	2513.0	1	8	1
2042.6	1	8	1	2518.2	1	8	1
2067.6	1	3	1	2536.4	1	6	2
2080.7	1	6	1	2551.8	1	10	1
2083.3	1	3	1	2570.8	1	5	1
2083.7	1	11	1	2594.9	1	10	1
2085.8	1	3	1	2598.1	1	8	1
2087.3	1	4	1	2600.4	1	2	1
2109.6	1	3	1	2614.0	1	6	2
2120.9	1	5	1	2652.3	1	7	1
2122.1	1	7	1	2659.8	1	9	1
2125.3	1	4	1	2669.2	1	6	1
2132.3	1	11	1	2694.5	1	9	1
2133.7	1	9	1	2698.9	1	6	1
2141.6	1	10	1	2709.3	1	8	1
2163.3	1	2	1	2722.1	1	2	2
2165.8	1	8	1	2749.9	1	5	1
2167.4	1	6	1	2752.4	1	4	1
2183.9	1	4	1	2773.9	1	3	1
2199.4	1	5	1	2782.1	1	6	1
2213.9	1	6	1	2783.9	1	2	1
2222.7	1	2	1	2845.0	1	4	1
2248.1	1	9	1	2860.8	1	9	2
2263.5	1	11	1	2865.4	1	7	1
2278.7	1	2	1	2869.8	1	6	1
2293.9	1	9	1	2900.2	1	5	1
2309.4	1	5	1	2926.4	1	9	1
2313.4	1	9	1	2934.1	1	9	1
2322.1	1	2	1	2936.2	1	8	1
2330.0	1	3	1	2951.3	1	6	1
2362.5	1	6	1	2963.4	1	5	2
2364.6	1	5	1	2971.8	1	6	1
2365.3	1	9	1	2973.9	1	2	1
2383.7	1	11	1	2975.3	1	9	1
2389.2	1	3	1	3013.8	1	10	1
2389.9	1	9	1	3022.8	1	8	1
2391.6	1	9	1	3036.7	1	3	1
2395.4	1	2	1	3047.2	1	3	1
2414.8	1	3	1	3049.7	1	3	1
2444.0	1	8	1	3058.0	1	8	2
2453.8	1	6	1	3059.5	1	3	1
2454.0	1	7	1	3094.8	1	11	1
2477.5	1	7	1	3108.1	1	2	2
2496.6	1	10	1	3109.3	1	2	1
2509.4	1	5	1	3121.7	1	9	1
2531.7	1	6	1	3125.1	1	6	2
2534.7	1	5	1	3147.8	1	6	1
2570.9	1	11	1	3153.5	1	8	2
2574.5	1	7	1	3157.3	1	5	1
2601.4	1	4	1	3161.9	1	7	2
2619.3	1	9	1	3178.1	1	9	1
2620.0	1	10	1	3180.2	1	2	1
2622.1	1	5	1	3187.7	1	5	1
2622.8	1	4	1	3190.8	1	2	1
2639.9	1	5	1	3231.7	1	11	1
2641.5	1	3	1	3234.5	1	6	1
2647.5	1	7	1	3239.3	1	3	1
2659.7	1	8	1	3242.1	1	10	1
2681.3	1	4	1	3247.8	1	5	1
2684.1	1	4	1	3258.0	1	11	1
2687.5	1	2	1	3262.0	1	11	1
2702.0	1	3	1	3295.9	1	9	1

Average batch size of 1				Average batch size of 1.2			
Seconds	Arrival Floor	Destination Floor	Batch Size	Seconds	Arrival Floor	Destination Floor	Batch Size
2734.1	1	9	1	3317.2	1	7	2
2739.1	1	10	1	3347.1	1	10	1
2751.6	1	7	1	3348.2	1	3	1
2752.2	1	3	1	3361.1	1	6	1
2767.8	1	2	1	3368.4	1	6	1
2787.8	1	6	1	3372.2	1	10	1
2792.8	1	9	1	3378.6	1	9	1
2819.3	1	10	1	3387.6	1	10	2
2836.3	1	7	1	3389.0	1	6	1
2840.3	1	11	1	3406.7	1	10	1
2860.5	1	7	1	3442.4	1	10	1
2887.7	1	3	1	3443.4	1	5	2
2888.0	1	2	1	3465.3	1	2	1
2906.4	1	2	1	3470.3	1	2	1
2913.0	1	2	1	3489.2	1	9	1
2918.4	1	3	1	3489.7	1	2	1
2920.0	1	4	1	3492.8	1	11	1
2974.4	1	8	1	3501.4	1	7	3
2981.3	1	11	1	3506.5	1	8	1
2997.4	1	7	1	3528.1	1	7	1
3003.4	1	7	1	3570.4	1	8	1
3005.8	1	10	1	3572.1	1	6	1
3021.6	1	8	1	3590.7	1	7	1
3023.7	1	4	1				
3034.6	1	11	1				
3058.2	1	3	1				
3069.4	1	11	1				
3081.8	1	9	1				
3092.3	1	8	1				
3103.2	1	4	1				
3115.1	1	4	1				
3116.4	1	7	1				
3178.7	1	4	1				
3182.7	1	4	1				
3208.2	1	11	1				
3213.6	1	7	1				
3250.5	1	2	1				
3250.9	1	11	1				
3261.4	1	3	1				
3282.0	1	9	1				
3290.5	1	4	1				
3291.4	1	9	1				
3296.8	1	8	1				
3299.6	1	6	1				
3325.1	1	11	1				
3342.6	1	9	1				
3346.6	1	5	1				
3351.4	1	9	1				
3359.3	1	2	1				
3364.3	1	2	1				
3386.5	1	6	1				
3395.3	1	10	1				
3398.9	1	7	1				
3403.4	1	6	1				
3432.1	1	10	1				
3439.1	1	11	1				
3456.3	1	4	1				
3456.6	1	4	1				
3458.0	1	5	1				
3472.2	1	4	1				
3476.9	1	11	1				
3486.7	1	9	1				
3493.6	1	11	1				
3504.3	1	4	1				
3526.3	1	3	1				
3529.1	1	3	1				
3536.0	1	9	1				
3587.8	1	4	1				
3594.0	1	4	1				
3595.1	1	9	1				
3597.1	1	11	1				

5.2 Discussion of results

24.95 persons per five minutes yields 299.4 person in one hour. In this example, a single run, 300 people have been generated. With multiple runs, sometimes 299 people will be generated. As the number of runs increases, the average will tend to 299.4.

Likewise, the distribution of destinations will tend to 10% (0.1) for each floor as the number of runs increases. Table 6 shows the distribution of destinations generated for the run with batch size 1.

Table 6 Example input and actual destination probabilities

Floor	1	2	3	4	5	6	7	8	9	10	11
Input destination probability	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Generated destination probability	0	0.08	0.10	0.13	0.07	0.10	0.11	0.10	0.11	0.09	0.12

Table 7 shows the input and output probability density function of batch size for the run with average batch size 1.2. As the individual batch size probabilities get smaller, the occurrences get rarer. The input probability of a batch size of 4 is one in a thousand. So, with 300 passengers generated, it is not surprising that no batches of 4 were generated.

Table 7 Example input and output probability density functions with average batch sizes 1.2

Batch size	1	2	3	4	5	6
Input probability	0.819	0.163	0.016	0.001	0.000	0.000
Output probability	0.825	0.159	0.016	0.000	0.000	0.000

5.3 Effect of batching on simulation results

In a test simulation with this sample data, the average time to destination of passengers was reduced by approximately 5 seconds with batching. No generalizations can be made from this single run, but it does demonstrate that batching has an impact on simulation results.

In most cases batching is likely to improve waiting time in simulation, as in the real world. This is because the stops arising from the calls are coincident; overall the number of lift stops is less.

There may be some other unexpected consequences of batching. For example, a simulation program may, by default, assume that batched passengers insist on travelling together. So, if the lift had space for one person and the batch was two people, they will wait for the next lift.

6 CONCLUSIONS AND FURTHER WORK

Lift passengers often travel together in groups rather than alone. For this to be reflected in lift simulation software, batches must be considered. Batches influence simulation results as passengers travelling in groups generate less calls.

This paper provides a procedure for generating passengers including batches. Passengers are generated assuming a random inter-arrival time with an exponential probability density function. Passenger batches are selected using Equation 1, given an average batch size. Traffic survey data has been collected and shows a good fit to the proposed passenger generation process. Further site data will be collected in different building types, and other batch size probability distributions may be considered. The objective is for users to describe batching with a single number for each application.

The discussion also provides an insight into the numerous decisions a simulation software designer needs to make. Many of these decisions are not normally considered as inputs, yet they influence simulation results.

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BIOGRAPHICAL DETAILS

Richard Peters has a degree in Electrical Engineering and a Doctorate for research in Vertical Transportation. He is a director of Peters Research Ltd and a Visiting Professor at the University of Northampton. He has been awarded Fellowship of the Institution of Engineering and Technology, and of the Chartered Institution of Building Services Engineers. Dr Peters is the author of Elevate, elevator traffic analysis and simulation software.

Sam Dean is a Software Engineer with Peters Research Ltd. He is part of the team working on enhancements to Elevate and related software projects. He is the lead developer behind the databases and servers managed by Peters Research.

Energy Saving through the Application of Variable Speed Technology

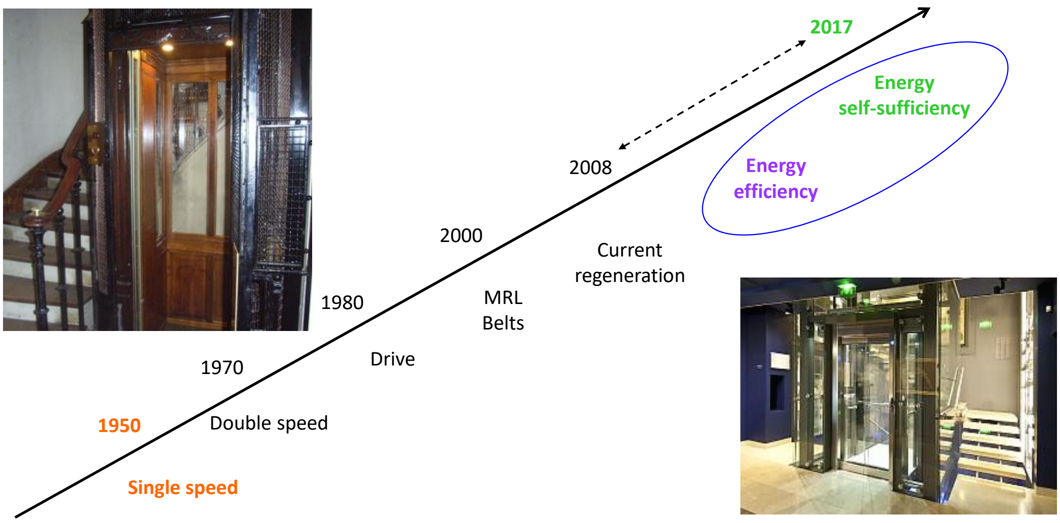
Stephane REAU, 11 rue Ampère 26 600 Pont de l'Isère - France, Stephane.REAU@Sodimas.net
Darren VANDERMEULEN, 11 rue Ampère 26 600 Pont de l'Isère France, Darren.VANDERMEULEN@Sodimas.net
Jeremy LANDRAUD, 11 rue Ampère 26 600 Pont de l'Isère France, Jeremy.Landraud@sodimas.net
Martine DUCHAMPT, 11 rue Ampère 26 600 Pont de l'Isère France, Martine.DUCHAMPT@sodimas.net

Keywords: Velocity – Variable speed – Reduced Balancing – Energy saving – Energy consumption

Abstract. Saving energy is a worldwide challenge for everybody, in particular, the lift profession. Different technologies exist on the market and are used to reduce the lift energy consumption. For example, we can note different algorithms as group control systems, regenerative device to batteries or power network, standby power cutting when the lift is not working, etc. After reading the VDI 4707, we have understood in 90% of use, the carload was under or equal to 50% of the rated load, meaning a lot of energy was lost to move only the counterweight. To try and find a solution to solve this problem, we decided to work on a new kinematic lift device to reduce the balancing of the counterweight. In parallel, we designed a special motor with a range of velocity adapted to the torque. For every trip, the motor torque is monitored by the drive to calculate the real load in the car and in function of the direction (up or down), the velocity is calculated in relation with the maximum power machine. To optimize the energy consumption through a reduced counterweight, the kinematic is based on a traction-closed loop. For example, the reducing of the lift balancing up to 32% can save energy consumption of up to 30%. This technology is applied to gearless synchronous motor. Different motors exist to allow the connection from the three phases 400V or single-phase 220V power supply network. Due to the small energy consumption, "*the speed technology"* lift is compatible with all other renewable energy power supplies. Solutions incorporating photovoltaic solar energy are currently being investigated.

1 Lift Technological Developments History

Since 1950, the lift technology has continued to move and to stick to the evolution of society:



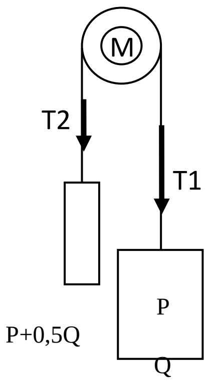
At the moment, all tasks are focused on the energy consumption and the autonomy for lift.

The Concept of "*The Speed Technology*"

Load in % of nominal load	Trip ratio in %
0	50
25	30
50	10
75	10
100	0

Figure 1 – Lift Using in Residential Buildings

<table>
<tr><th colspan="2">Traction drive calculation</th></tr>
<tr><th>Traditional concept
Open loop</th><th>Proposed concept
Closed loop</th></tr>
<tr><td>

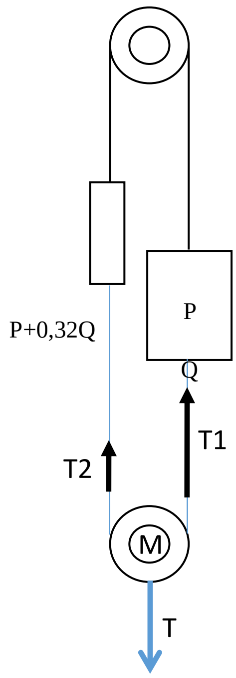


Empty car : $\frac{T2}{T1} = \frac{P+xQ}{P}$

Full car : $\frac{T1}{T2} = \frac{P+Q}{P+xQ}$

P = Weight of the car (N)
Q = Rated Load (N)
X = Balancing (%)

</td><td>



Empty car: $\frac{T1}{T2} = \frac{T+gxQ}{T-gxQ}$

Full car : $\frac{T2}{T1} = \frac{T+g(1-x)Q}{T-g(1-x)Q}$

Q = Rated Load (N)
X = Balancing (%)
T = Tensioner (N)
g = Gravity of acceleration (m/s²)

</td></tr>
</table>

Figure 2 – Traction drive calculation

We had this idea while reading the VDI 4707 [1] which showed that in residential buildings, the lift moves in 90% of using with a carload under or equal to 50% of the rated load (see figure 1). In this case, we understood that the energetic balance was not optimized and that 50% of trip used power energy to move just the counterweight. Therefore, we decided to optimize the energy consumption by reducing the weight of the counterweight.

Unlike a traditional lift where the traction drive depends on the car weight and the balancing (often 50%), the proposed concept is based on a closed loop of the traction device. In this case, the car weight is out of the traction drive calculation. Only the tensioner of the belt, the rated load and the balancing are taken into account in the traction drive calculation (see figure 2).

With this approach, if in 90% of cases, the car moves with a carload under or equal 50% to the rated load, then there are 10% of cases with a carload above 50%. With a balancing of 32% in the counterweight, the full car is equivalent to 68% of the rated load for the torque of the motor (see figure 3). In these conditions and in up direction, the power of the machine and the current increase by 36% compared to a lift with 50% of balancing ($\frac{68-50}{50}$).
Actually, with a balancing of 32%, the torque for a car loading is not the same in up and down direction.

	Empty car	Full car
Up Direction	Resistant torque for 32% of rated load	Motor torque for 68% of rated load
Down Direction	Motor torque for 32% of rated load	Resistant torque for 68% of rated load

Figure 3 – Difference of Motor Torque

	In 90% of cases Load ≤ 50%	In 10% of cases Load > 50%
Up Direction	Ω = 1,6 m/s 32% rated load ≤ C ≤ 18% rated load C*Ω ≤ Rated power Motor operation (load > 32% rated load) Generator operation (load < 32% rated load)	1,6 m/s < Ω ≤ 0,7 m/s 18% rated load < C ≤ 68% rated load C*Ω ≤ Rated power Motor operation
Down Direction	Ω = 1,3 m/s 32% rated load ≤ C ≤ 18% rated load C*Ω ≤ Rated power Motor operation (load > 32% rated load) Generator operation (load < 32% rated load)	Ω = 1,6 m/s 18% rated load < C ≤ 68% rated load Generator operation

Figure 4 – Speed and torque control

In order to not oversize the power of the machine to cover the 10% of use with carload above 50%, we decrease the speed to reach the maximum power of the motor. Therefore, the concept of the "*speed technology"* is based on a specific motor design capable of producing for the maximum power (see figure 04 and 5):
=> A maximum torque with a minimum
speed,
=> A minimum torque with a maximum speed

$P = C_{maxi} \times \Omega_{mini} = C_{mini} \times \Omega_{maxi}$
P = Rated power (W), Ω = Motor speed technology (m/s), C = Motor torque (Nm)

	630Kg - 1.6m/s	
Speed / Vitesse	0.7	1.6
DATA LIFT / DONNEES ASCENSEUR	Rated load : **630Kg** Rated speed : **1.6 m/s** Main Shaft load : **2500Kg**	
SUSPENSION	Susp : **1/1**	
MACHINE GEARLESS MACHINE DATA / DONNEES MACHINE	**Voltage : 220V 50Hz** Motor frecency : **23.5Hz** Poles number : **20p** Rpm : **141 tr/mn** Rated power : **4Kw** Rated current : **32.8A** Rated torque : **270Nm** Machine weight : **173Kg**	**Voltage : 220V 50Hz** Motor frecency : **53.5Hz** Poles number : **20p** Rpm : **321 tr/mn** Rated power : **4.4Kw** Rated current : **16.5A** Rated torque : **130Nm** Machine weight : **173Kg**

Figure 5 – motor data sheet

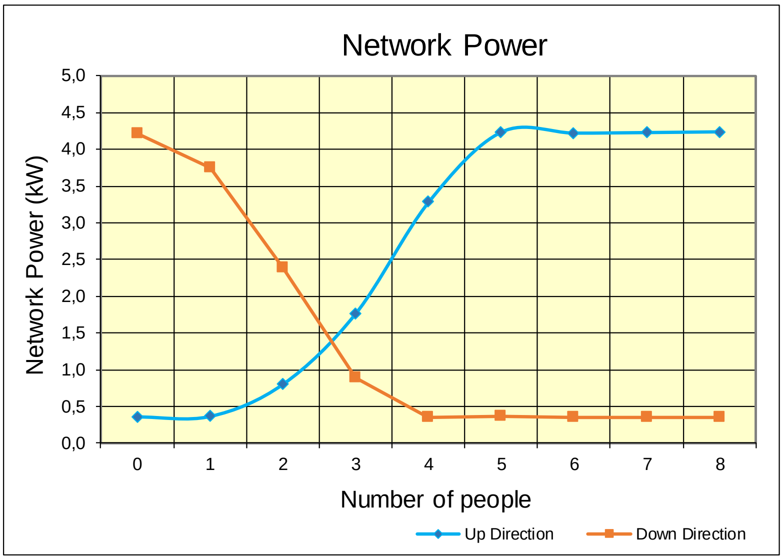


Figure 6 – Network power according to the carload

Before each start, the controller measures the load inside the car and calculates the maximum speed of the motor in accordance to the rated power without ever exceeding it (see figures 6 & 7).

Many measurements have been done on our test tower in Valence to compare the performance between lifts at 1 m/s, at 1,6 m/s and a lift with "*the speed technology"*.

Details of the lifts and the test tower :

Lifts : 3 lifts with the same kinematic and with a traction drive in closed loop [2],
Rated Load : 630 Kg, Car Weight : 731 Kg, Balancing: 50% for rated speed 1 m/s and for 1,6 m/s, Balancing : 32% for the lift with the "*speed technology"*.
Shaft : Rise : 24 m, Number of level: 8.

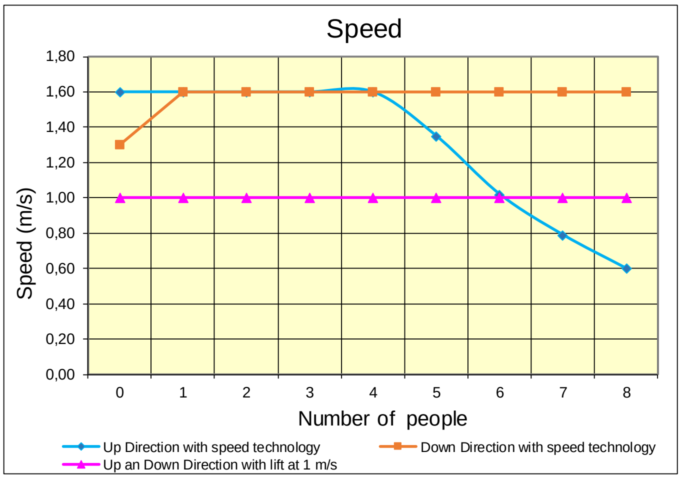


Figure 7 – Speed according to the carload

The Energy consumption was mesured in compliance with EN ISO 25745-1 [3] and EN ISO 25745-1 [4] for the following trip cycle:

1) Begin of reference trip with open lift door
2) Closing lift door
3) Trip up or down using the full lifting height
4) Opening and immediate closing of the lift door
5) Trip up or down using the full lifting height
6) Opening lift door

To attest the results, tests and measures were done and provided by an independent third party [4].

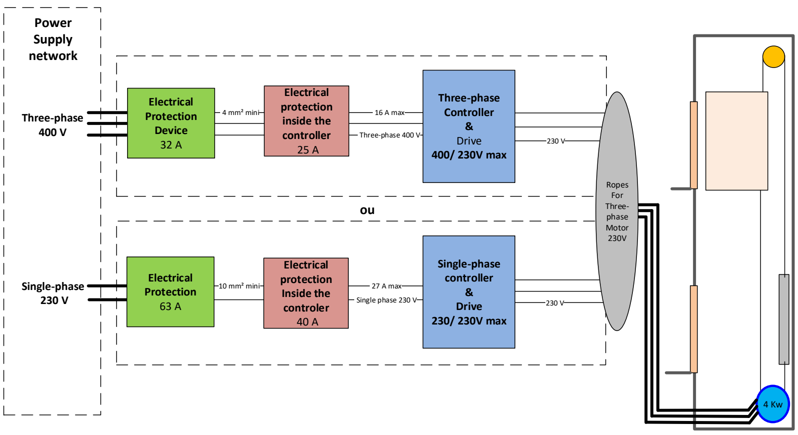


Figure 8 – Power supply network for 630 Kg lift

We apply this technology on a gearless synchronous three-phase 220V motor. Therefore, it is easy to connect the installation to a three phases 400V or single-phase 220V power supply network (see figure 8). As a result, it can be connected to renewable energy power supplies. Solutions incorporating photovoltaic solar energy are currently being investigated.

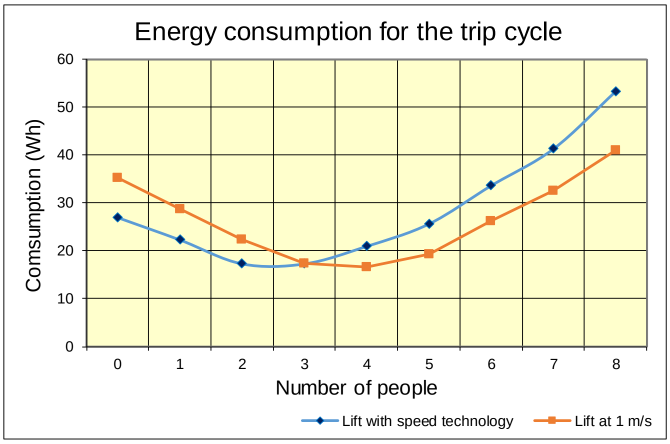


Figure 9 – Energy consumption for the Trip Cycle

When the car is empty, the figure 9 shows that the difference of energy consumption for the trip cycle is close to 30% between a lift at 1 m/s and a lift with the "*speed technology*":

Lift at 1 m/s with 50% balancing = 36 Wh
Lift with "*speed technology*", 32% balancing = 26 Wh

The difference is equal to 27.8 %

When the car loading reaches 32%, the trend is reversed. Then the lift at 1 m/s consumes the least per trip cycle.

Even if the result above is interesting for a trip cycle, it is important to compare simulation in terms of energy consumption and in terms of traffic on a day. To do it, we used a popular simulation tool [6], and compared different templates for the same previous lifts (lifts at 1 m/s, 1,6 m/s and lift with "*speed technology*"). For simulations, we fixed the speed at 1,6 m/s for the lift with "*speed technology*" because even if the car is full at a moment, at the next floors for stopping, some passengers will go out and the speed will quickly increase to 1,6 m/s [see figure 7].

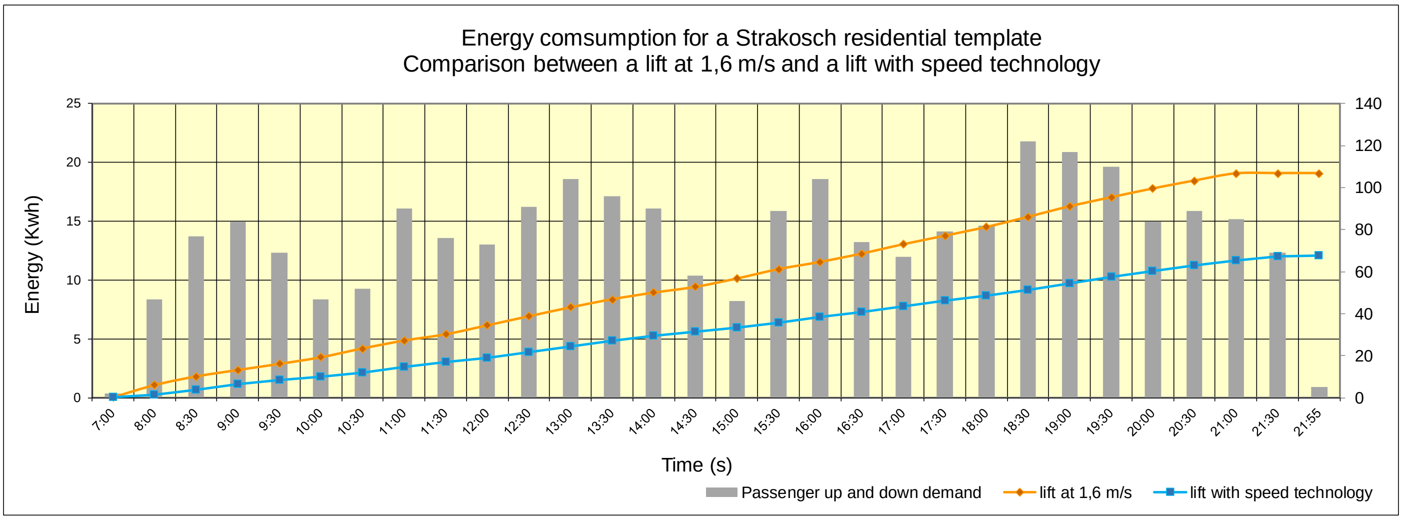


Figure 10 – Energy Consumption for a Strakosch Residential Template [6]

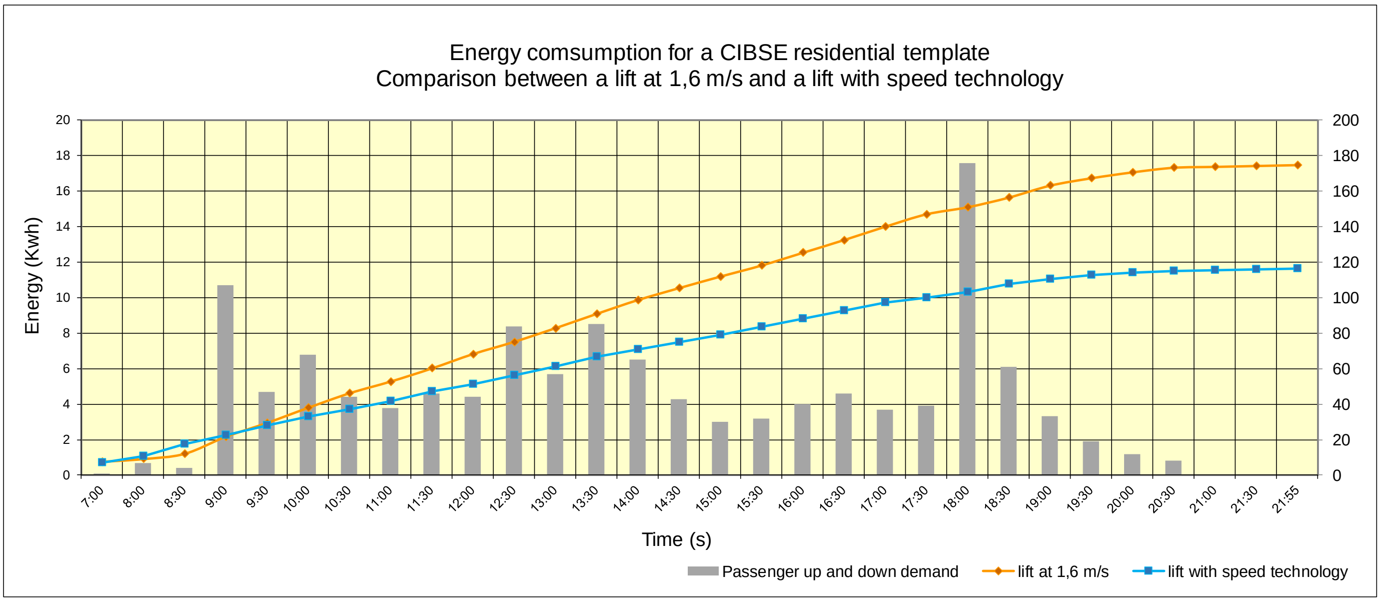


Figure 11 – Energy Consumption for CIBSE Residential Office Template [6]

For Straksoch residential template (see figure 10) and for CIBSE residential template (see figure 11), the energy consumption (cumulated) is more important for the lift at 1,6 m/s than for the lift with "*speed technology*".

	Energy consumption(KWh)		
	Lift at 1,6 m/s	Lift with speed technology	Saving
Strakosch Residentiel	19,1	12,1	37%
CIBSE Residential	17,5	11,6	33%

Figure 12 – Energy consumption comparison

At the end of the day, we note results of energy consumption on the figure 12.
Even if we did some assumptions like the speed used in the simulation tool, the results are very promising for the two types of template.

The average of saving for the lift with "*the speed technology"* is close to 35% a day.

On below, two simulations to compare traffic of a lift at 1 m/s and a lift with "*the speed technology"* for office building.

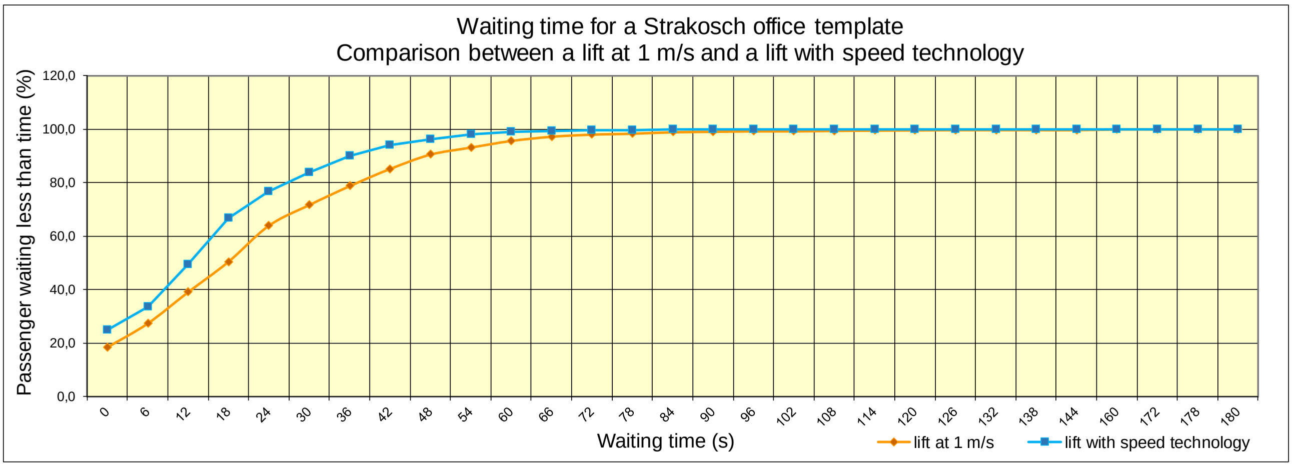


Figure 13 – Waiting Time for a Strakosch Office Template [6]

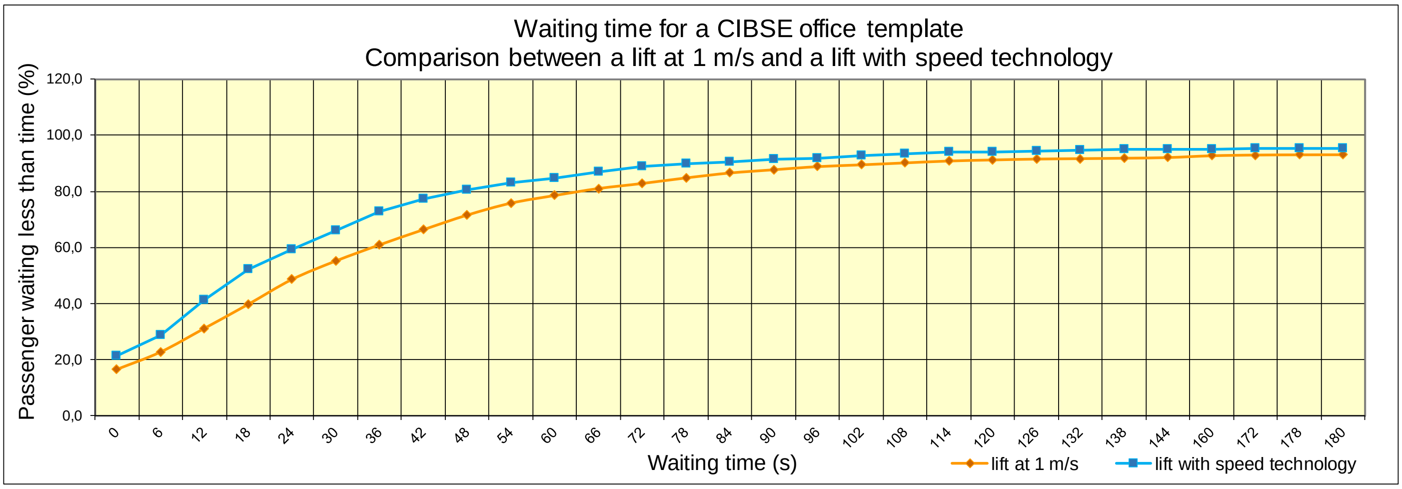


Figure 14 – Waiting Time for a CISBE Office Template [6]

For Straksoch office template (see figure 13) and for CIBSE office template (see figure 14), the waiting time is always more important for the lift at 1 m/s than the lift with "*the speed technology"*.

	Average Waiting Time (s)			Energy Consumption (KWh)		
	Lift at 1 m/s	Lift with speed technology	Saving	Lift at 1 m/s	Lift with speed technology	Saving
Strakosch Office	99,7	57,4	42%	11,17	10,72	4%
CIBSE Office	104,7	64,4	38%	13,2	11,6	12%

Figure 15 – Energy Consumption Comparison

We note the results of the average waiting time (ATW) on the figure 15.

Even if we did some assumptions like the speed used in the simulation tool, the results are very promising for the two types of template.

The average waiting time for the lift with "*speed technology"* is close to 40% less than the lift a 1 m/s.

For this important gain of traffic, we can note that the energy consumption at the end of the day is very similar (the differences are only 4% and 12% in favour of "*the speed technology"*).

2 CONCLUSION

In conclusion, the results of "*the speed technology*" is very promising. Indeed, in these simulations we can note that for different examples of using (Strakosch and CIBSE templates for residential and office building):

1 For a same traffic, "*the speed technology"* consumes an average of 35% less than the lift at 1,6 m/s,
2 For a same energy consumption, "*the speed technology"* has a traffic 40% more important than the lift at 1m/s.

In addition, in reference to the ISO 25745, with the "*speed technology"*, the energy consumption for the trip cycle when the car is empty, is 27.8 % less than a lift at 1 m/s.

Still under development, "*the speed technology"* is very promising and we will continue to investigate on this way.

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[5] ENERTECH Laboratory, Ingénieurs conseils - 26 160 Félines sur Rimandoule – France,

[6] ELEVATE™, Elevator traffic analysis & simulation software – Peters Research Ltd

BIOGRAPHICAL DETAILS

Stephane REAU, Technical Director in SODIMAS, in charge of innovation and research and development department.
Engineer from the ENSEM School in France (Electricity and Mechanic degree) and graduated from the University of Nancy in the field of Electricity.
More than 20 years' experience in the lift profession through a career in an American corporation. Member of the French Lift Association as an expert of the Fire Safety and former expert of the ISO TC178 WG6.

Darren VANDERMEULEN, Export Sales Director in SODIMAS

Jeremy LANDRAUD, Export Sales Engineer in SODIMAS

Martine DUCHAMPT, Export Sales Assistant in SODIMAS

In-Car Noise Computation for a High-Rise Lift

Gabriela Roivainen[1], Jaakko Kalliomaki[2], Antti Lehtinen[3] and Jukka Tanttari[4]

[1]KONE Corporation, Finland, gabriela.roivainen@kone.com
[2]KONE Corporation, Finland, jaakko.kalliomaki@kone.com
[3]FS Dynamics, Finland, antti.lehtinen@fsdynamics.fi
[4] VTT Technical Research Centre of Finland Ltd, Finland, jukka.tanttari@vtt.fi

Keywords: aero-vibro-acoustics, lifts, high speed, high rise, FEM, BEM, CFD, SEA.

Abstract. The authors have developed an acoustic model of a lift, using a multi-disciplinary approach. The model enables a full understanding of how the lift design is affected by noise requirements inside the car, and in buildings that are still in planning or construction phase. The approach is based on a hybrid model combining structural finite element (FEM); computational fluid dynamics (CFD); boundary element method (BEM) and statistical energy analysis (SEA); to cover both low and relatively high frequency acoustical domains in a sufficiently detailed model with a reasonable computational time. Special attention has been paid to modelling of the noise sources. Structure-borne sources (point forces) due to roller guide shoes and ropes were applied on the system. Forces were determined on grounds of FEM-computed point mobilities and measured vibration velocity responses at the same excitation points. Airborne sources due to flow-induced noise were computed using an incompressible transient CFD analysis. The resulting time variable air surface pressure was then applied on the car walls. The surface pressure spectra were used both directly (the convective source) and as a source for the acoustic propagation (giving the acoustic source). The reverberant sound field in the hoistway, generated by the flow sources, is a significant contributor. This part was modelled using BEM. The time variable pressure field on the car surface was used as a source distribution for BEM. The end result of the computation was applied as a diffuse acoustic field on the car surfaces. All the sources: structure-borne and airborne, were applied as forces and pressures. They were internally converted to power inputs for solving the SEA model. All transfer paths in the sling, car, doors, fairings and hoistway, including relevant leaks were simulated. After validation, the hybrid model now allows the users to quantify and rank noise contribution of each source and make predictions based on changes in the lift structure, hoistway design and car running parameters.

1 INTRODUCTION

In the recent past, lift ride comfort (noise, vibration, car dynamics, etc.) has been receiving increasing attention by lift users, developers, building owners and leading lift manufacturers. The megatrend of urbanization and the need of building taller buildings, combined with a higher demand for comfort has forced the lift manufacturer to find computational solutions for predicting the dynamic behaviour of the car, in order to ensure that all the ride comfort requirements are fulfilled. Passenger ride comfort covers a broad area of objective (measurable) and subjective properties, representing one of the main aspects of the brand image for lift manufacturers. In this paper, the focus lies on the acoustic performance of high-rise lifts.

The challenge was to create a model for predicting interior sound pressure level in the car for a specific lift architecture, ride parameter and component selection. Then the model had to be validated on a site and ultimately used to rank the noise sources and offer engineering solutions for decreasing them.

2 CHALLENGES AND SELECTION OF THE COMPUTATIONAL STRATEGY

Acoustic models have been developed for many years for automotive and train industries. The challenge to adapt them to lift industry comes from the uniqueness of every lift installation, low speed and tight clearance between lift and hoistway walls.

Although the basic components are similar, the combination of parameters like the height of the building, the dimensions and the cross section of hoistway, the numbers of car sharing the same hoistway, the number and distribution of landing doors and the location of counterweight make each lift different to the next.

Validating cars and trains in wind tunnels are a common practice for understanding the limitations of the CFD results. However, since the lifts are designed to be suspended and move in vertical direction, the validation in a wind tunnel is very challenging. In addition, if the clearance between the road vehicles or trains and the tunnel wall can be one or two meters, in lift industry, the clearances can vary from few centimetres to the landing doors up to half a meter or more for the rest of hoistway. The small clearances combined with low speed result in a lower Mach number, which makes the computation and the testing very challenging.

Regardless these differences, the same methods used for computing and validating the acoustic models can be applied for the lift industry. The basic type of simulation chosen for covering low, middle and relatively high frequencies was Statistical Energy Analysis (SEA). The method was developed within the US Space Program in the early 1960's [1]. Application of SEA in automotive industry was published first time in 1980's [2] and on a lift in 1990's [3].

The basis of SEA is the principle of conservation of energy from which a set of power balance equations can be derived for a given frequency band and subsystem. For every subsystem *i* there is a steady-state power balance; the power injected (P_{in}) equals to the power consumed (P_{out})

$$P_{in,i} = P_{out,i} \tag{1}$$

The power injected and consumed is either dissipated in the subsystem (P_{diss}) or transmitted (P_{trans}) out from the subsystem:

$$P_{out,i} = P_{trans,i} + P_{diss,i} \tag{2}$$

The set of SEA equations for the total system composed of a number of subsystems is

$$\{P_{in}\} = [L]\{E\} \tag{3}$$

Where $\{P_{in}\}$ is the input power vector, $[L]$ is the loss matrix governing the power dissipation and transmission between the subsystems and $\{E\}$ is the subsystem energy vector. Once power inputs for all subsystems and the loss factor matrix are formed, the system of equations is solved for the subsystem energies. The subsystem energies are then converted into engineering units of interest, i.e., sound pressure (acoustic subsystems like ducts and cavities) or vibration velocity (structural subsystems like beams and plates).

SEA works best in case of broadband random excitations and reverberant (lightly damped subsystems with as many resonant modes as possible [4, 5]. The advantages of SEA are very short solve times and that fewer details are needed to calculate reasonable results. The main disadvantages are the limited accuracy at low frequencies, the average character of results, and that parts with complex shapes may be difficult to model with standard SEA subsystems.

For the low frequencies, as well as for stiff subsystems, where the number of modes is low, FEM can be used. Theory of combining FEM and SEA into a coupled hybrid model is available in [6, 7, 8]. This is the method also used in this paper.

3 IDENTIFYING THE SOURCES OF NOISE

The noise sources inside a lift car can be divided based on their excitation and travelling path into structure-borne and airborne sources.

3.1 Structure-borne source

Structure-borne sources are induced by vibrations of lift components that are located close or in contact with the car: roller's guides, ropes, safety gears, car walls, fans, air condition devices, door operator, sling-car interface, etc. The energy of these vibrations is transmitted to the walls of the car, creating pressure fluctuation of the air inside the car that is perceived as noise.

The excitation forces were determined from FEM-computed point mobilities and measured vibration velocity responses at the same excitation points (Fig. 1).

The structure of the sling and the platforms for the cars were modelled using FEM, due to their stiffer structure.

3.2 Airborne sources

The airflow around the car creates two types of pressure fluctuation [9]; turbulent fluctuation due to sudden change in cross section of the hoistway and acoustic fluctuation, due to interaction of eddies travelling within the flow and rigid surfaces. Acoustic waves are also reflected from the hoistway walls. The two types of fluctuation have to be modelled differently because they are coupling in a different way with the car walls and they transmit different types of sound energy that will be radiated inside the car. (Fig. 1).

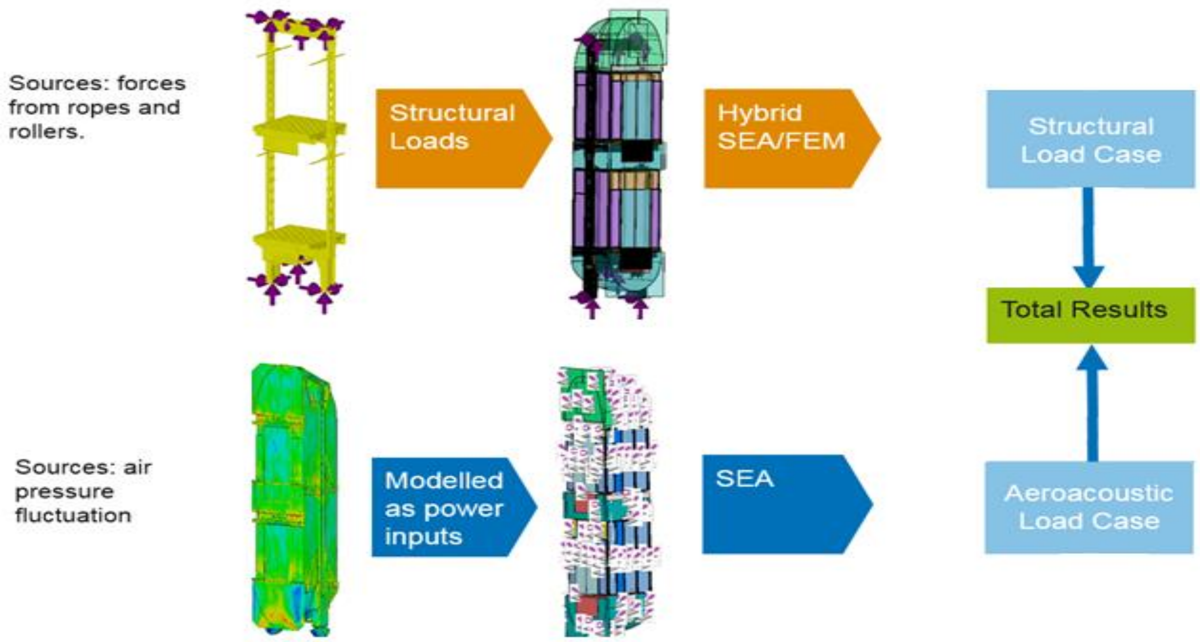

Figure 1 Noise sources in the lift car

The turbulent air sources were computed using a transient CFD with incompressible air, for a section of hoistway that did not include landing doors or the counterweight. The direction of the lift movement was downwards at the speed of 10 m/s (Fig. 2)

The equations solved are the transient, incompressible, filtered Navier-Stokes equations [10]:

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (4)$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = \frac{\partial}{\partial x_j}\sigma_{ij} - \frac{\partial p}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_i} \qquad (5)$$

In Equations (4) – (5) u = velocity vector, x = spatial coordinate, t = time, ρ = density, σ = stress tensor due to molecular viscosity and p = pressure. From the acoustic point of view, the main outcome of the simulation is the fluctuating surface pressure $p(x,t)$, which is further transformed into the frequency domain.

The simulations were scale-resolving, meaning that the large and medium size turbulent vortices were solved explicitly instead of Reynolds averaging. The subgrid-scale stress tensor τ in Equation (5) is modelled with the Detached Eddy Simulation (DES) method [11]. The transient, scale-resolving simulations are significantly more time consuming than steady state simulations, but necessary in order to obtain the turbulent acoustic source terms.

This convective pressure flow source was modelled as a Turbulent Boundary Layer (TBL) type load. The TBL load is defined by a pressure spectrum and a wavenumber (i.e., wavelength) spectrum. This data was computed from the CFD-results at all the main surfaces of the lift and the wind deflectors.

The acoustic component or air source was computed using BEM, (Fig. 3). The fluctuating pressure (FSP) result from CFD at the surface of the car was used to excite the air around the car. The reflective walls of hoistway were modelled by adding absorption properties on the wall and considering the hoistway having anechoic ends.

Several assumptions have been done to compute the acoustic component: in BEM, only the surface pressure terms of Curle analogy were considered; the analysis is time -invariant stationary, which means that the computation is performed for each frequency separately and that additional contribution of standing waves could influence the results. In addition, it is assumed that the flow field and the acoustic field do not influence each other.

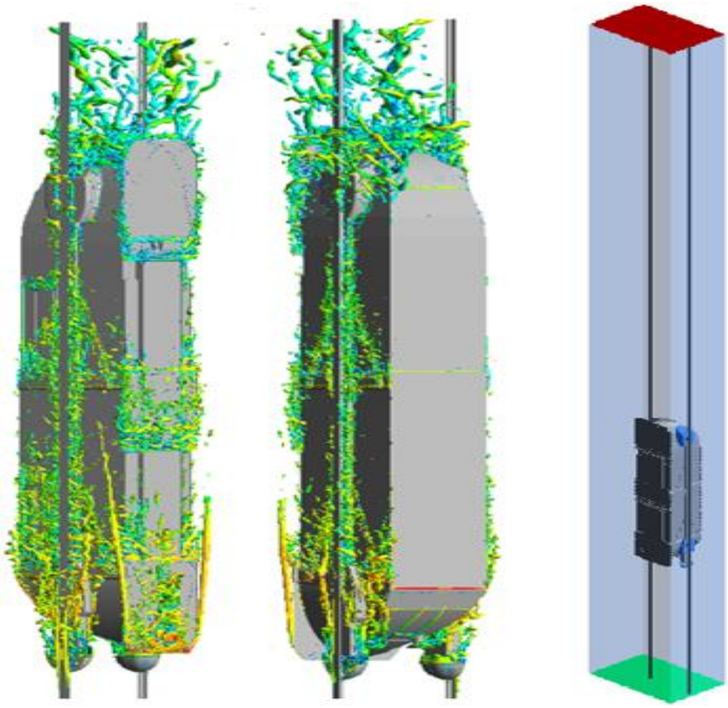

Figure 2 Turbulent air sources and the CFD simulation domain

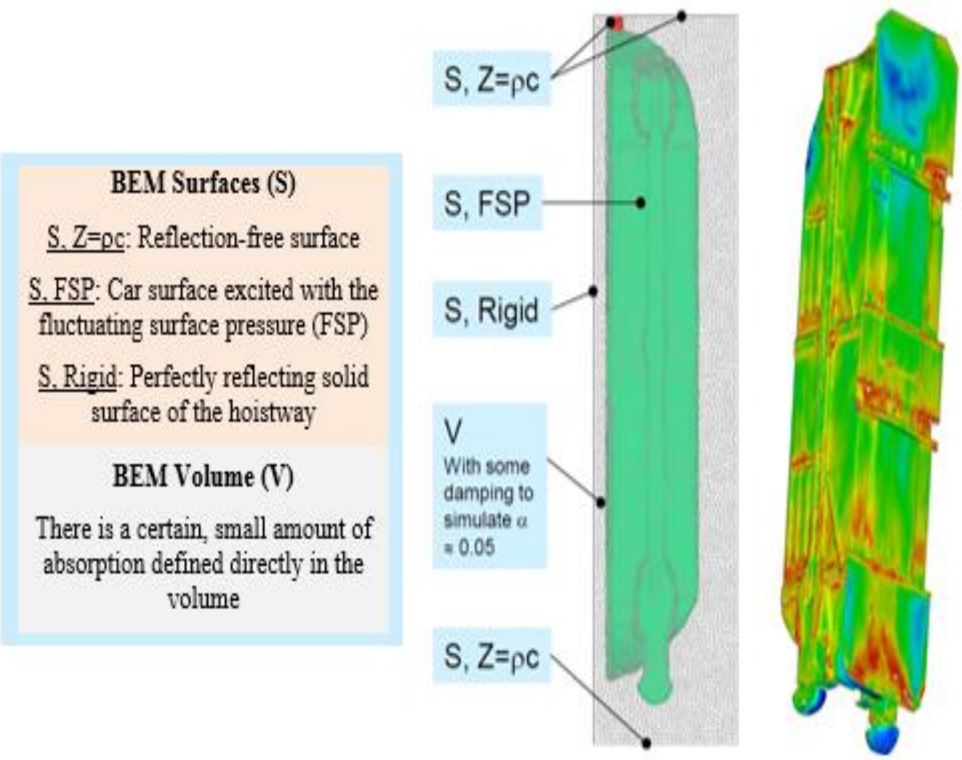

Figure 3 Composition of a BEM-model. FSP distribution shown on the right.

These procedures are described in more detail by Blanchet et al in [12].

4 APPLYING THE SOURCES OF NOISE IN SEA MODEL OF THE CAR

A special attention has been paid in modelling the structure of the car with SEA. The sandwich structure of car panels, the ventilation holes, the roof structure, the fan labyrinth, the air gaps around the panels and doors were included (Fig. 4). The connection between SEA structure and FEM structure has been modelled using hybrid junctions.

The frequency of interest for in car noise was 20 – 500 Hz. The noise was computed for the entire air cavity inside the car with 1/3 octave frequency resolution.

Due to the hybrid junctions, the structure-borne computation for the frequency range of interest was straightforward. The structural loads were applied as forces at relevant points in the sling.

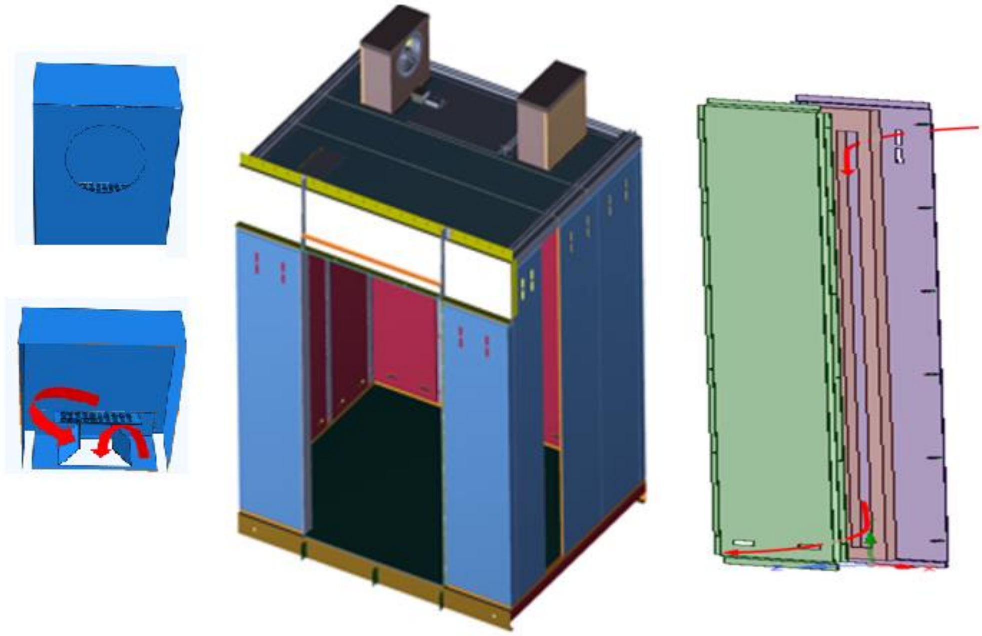

Figure 4 Car structure and details: fans, car, panel structure

The airborne loads were applied as a sum of two different contributions. The Turbulent Boundary Layer (TBL) loads and the Diffuse Acoustic Field (DAF) loads were applied on all lift and wind deflector surfaces as relevant pressures-wavenumber combinations (Fig. 5).

To solve the SEA set of equations, pressures and forces are first converted into power inputs. The equations are then solved for the subsystem energies. Finally, the subsystem energies are converted into engineering units (sound pressures and vibration velocities).

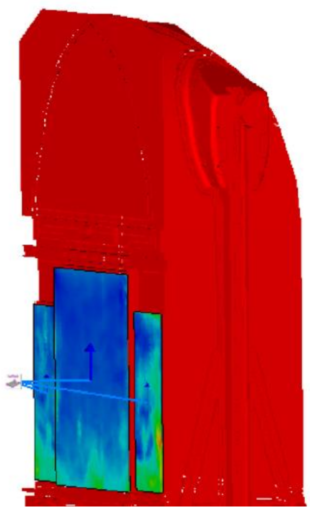

Figure 5 Example of surface pressure fluctuation at lift surface in the frequency domain

5 RESULTS AND DISCUSSIONS

Four different computational methods (Fig. 6) were used to analyse and rank the noise sources inside a lift car for a specific frequency range.

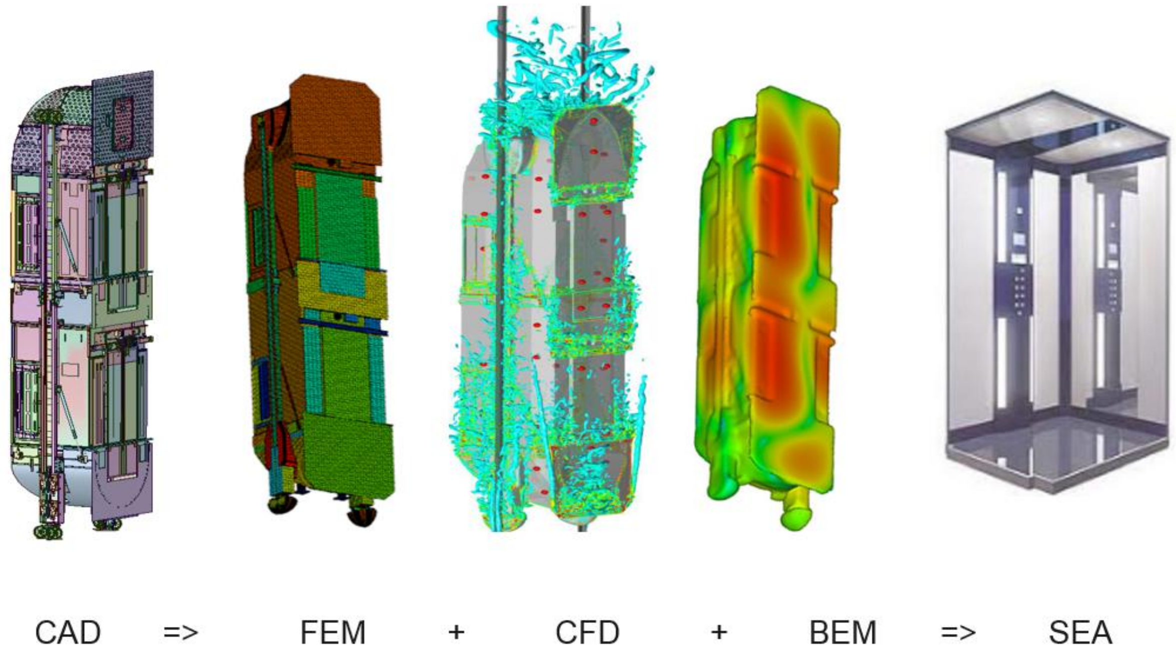

Figure 6 Simulation workflow

The computed result of in-car sound pressure level spectrum is shown in Figure 7. On top of the total sound pressure level, the contributions from the three different kind of sources are shown.

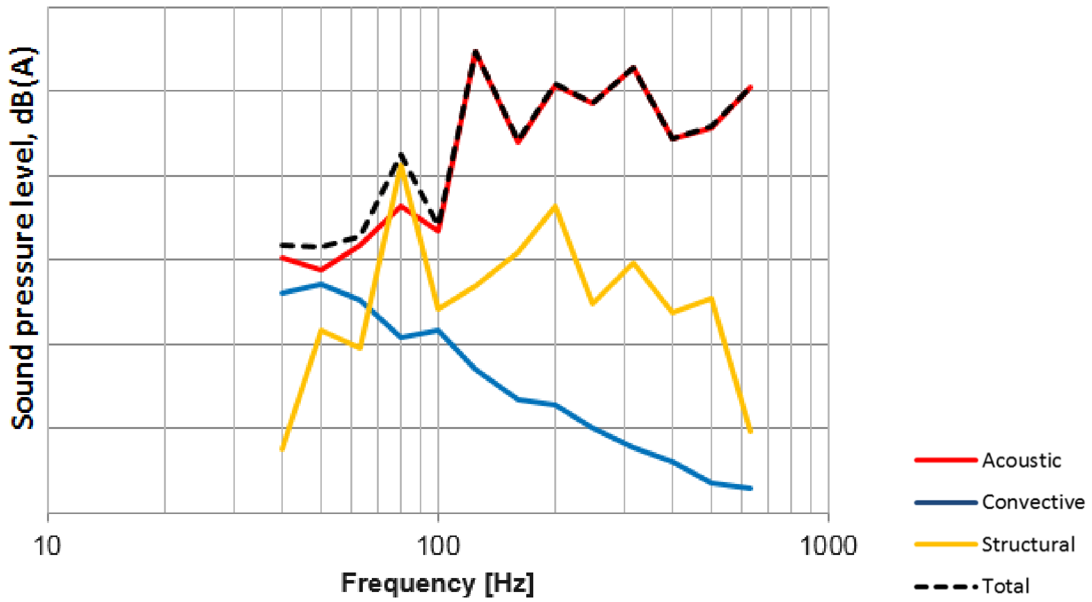

Figure 7 Influence of different sources on in-car noise

The results are providing valuable information regarding each source contribution: for high speed, the acoustic contribution is dominant, excepting the lowest frequency below 100 Hz; which means that any noise reduction should be done starting with reducing the acoustic component: streaming the shape of car, minimizing the changes in the hoistway section, adding absorption structure to the hoistway surfaces. The convective component (TBL) has relevant contribution only at the lowest frequencies. The structural component shows a distinctive peak at 80 Hz but is otherwise non-significant.

There is good agreement between computed and measured data (Fig. 8), with one exception.

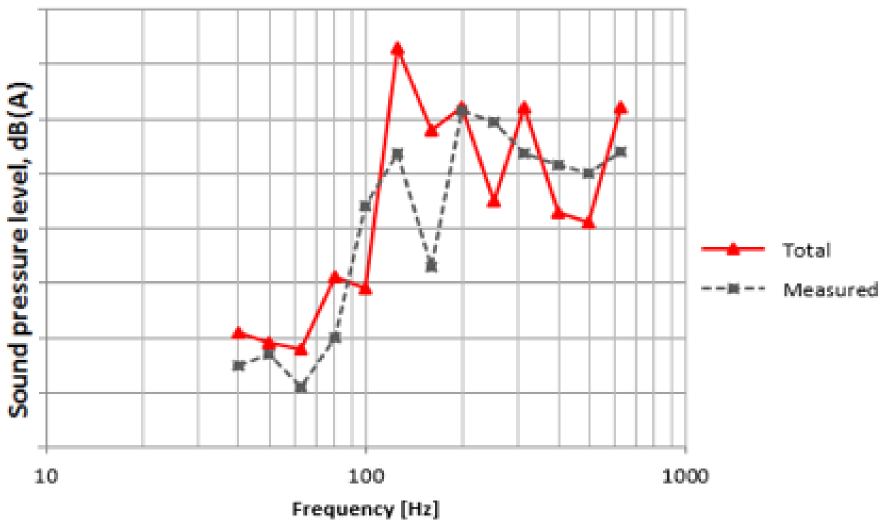

Figure 8 Comparison between simulation and measurements

At frequencies above 100 Hz the predicted spectrum is peakier than the measured spectrum; this difference can be explained because the BEM-based procedure does not take the lift movement into account. Formation of high-pressure standing waves in the hoistway is predicted in the stationary situation. In reality, the relative movement of the lift hoistway does not support formation of strong standing waves. This smooths out the spectrum.

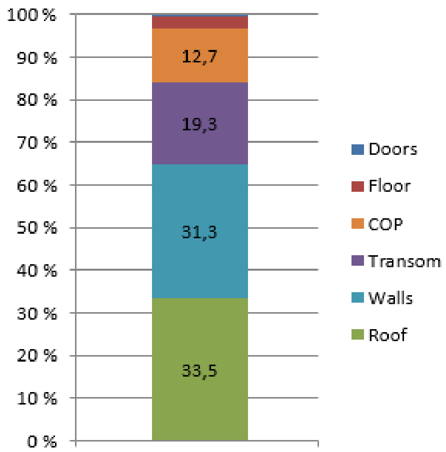

Figure 9 Ranking the noise sources based on components

The method can be used to rank the noise contribution of each component of the car (Fig. 9) and therefore to start optimising the car structure based on the noisiest source.

Apart from imminent technical results and information thereof, development of simulation competence has many short and long term benefits.

Interpretation of measurement results becomes easier. With a good model one is able to study effects of system parameters and gain a deeper understanding on various observations. Models can also be used to conduct virtual measurements and, in that way, they can be extremely useful in planning of real measurements.

Measurements in situ have a limited repeatability and reproducibility. This means that it is challenging to experimentally ascertain noise level changes in order of ± 1 dB, because the level may change more in repeated measurements for unknown and uncontrollable reasons. Simulations do not suffer from that kind of weakness.

The method developed in this paper is a powerful tool in predicting in-car noise for lifts that have not been built and it opens the world of “what if” providing the designers a tool to take controlled risks and the managers a tool to understand the capabilities of their products.

The long term aim and megatrend is frontloading [13]. This concept means the driver of simulation competence development may reach the situation where more simulation effort is directed to the very early design phases. More and more design challenges, difficult and expensive to deal with afterwards, are solved cost-effectively before any physical prototype is built.

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BIOGRAPHICAL DETAILS

Gabriela Roivainen

Education

2000 Doctor of Science in Electric and Mechanic Engineering, Petroleum-Gas University, Romania

2014 Licentiate of Science in Acoustic Engineering, Aalto University, Finland

Work Experience

2003 – 2008 Research Engineer, Metso Paper, Finland – paper machineries

2008 onwards Senior Expert, KONE Corporation, leading Multiphysics simulation projects.

Jaakko Kalliomaki

Education

2003 MSc in Mechanical Engineering, Helsinki University of Technology, Finland

Work Experience

2003 – 2005 Mechanical Designer, ABB Oy (Drives and Power Electronics), Finland

2005 – 2007 Designer, Delta Energy System (Finland) Oy

2007 – 2014 (Senior) Chief Design Engineer, KONE Corporation, Finland

2014 onward Global Platform Manager (High Rise Platforms), KONE Corporation, Finland

Antti Lehtinen

Education

2005 Doctor of Science in Fluid dynamics & heat transfer, Tampere University of Technology, Finland

Work Experience

2012 onwards Principal Engineer (Fluid dynamics and acoustics), FS Dynamics Finland

Jukka Tanttari

Education

1985 MSc in Mechanical Engineering, Tampere University of Technology, Finland

Work Experience

1985 – 1987 Research Worker, Tampere University of Technology, Finland

1987 onwards Research Scientist, Senior Research Scientist, Principal Scientist (Noise Control Engineering and Vibro-Acoustics), VTT Technical Research Centre of Finland Ltd.

Lift Planning and Selection Graphs

Mirko Ruokokoski and Marja-Liisa Siikonen

KONE Corporation, P.O. Box 7, FI-02151 Espoo, Finland
mirko.ruokokoski@kone.com
marja-liisa.siikonen@kone.com

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Abstract. In the lift planning phase of a building, the number of lifts, their sizes and rated speeds are selected. Traditional performance criteria for the lift selection are the nominal travel time, handling capacity and interval. In this paper a pure up-peak traffic condition is considered since it is the most demanding traffic situation from the viewpoint of handling capacity. If lifts can handle the up-peak situation, they have enough handling capacity for other traffic situations too. In addition, the values of the up-peak handling capacity as well as interval can be quite accurately calculated by using a theoretical up-peak round-trip time formula. Handling capacity and interval calculations for other traffic conditions require approximations or simulations. For common buildings, suitable lift installations can be pre-calculated and the results combined in a graph. The most appropriate lift configuration can be read from a selection graph for the given number of served floors and the given population in upper floors. This paper describes in detail the creation of the selection graphs and discusses when the graph can be created by utilizing rather simple mathematical formulas and when more sophisticated analysis methods such as simulations are needed.

1 INTRODUCTION

Lift selection in buildings is historically based on a pure up-peak traffic. During the pure up-peak traffic all people arrive at the entrance floor and are destined to populated floors of the building. Up-peak condition typically designates the morning traffic in commercial office buildings. It is the worst traffic situation from the viewpoint of lift group handling capacity. If lifts can handle the up-peak situation, they have enough handling capacity for other traffic situations. The number of people using the lifts in the building can be higher at other times of day, e.g., during lunch time. In mixed lunch-time traffic people arrive from many floors, and the lifts are not filled to the same extent as in up-peak since people can exit the lift before new people enter the car. Waiting times can become longer in mixed traffic situations with the same passenger arrival rate as in up-peak. Although residential buildings and hotels do not have similar morning up-peaks, the up-peak round trip time formula is the only generally accepted equation for lift traffic analysis, and it can be also applied to define a lift selection for these building types as well. Nowadays, mixed traffic profile is more and more used, so up-peak traffic calculation in such a case provides some initial guidance only for the lift selection.

The values of the up-peak handling capacity and interval can be calculated by using a theoretical round-trip time formula. Conventionally, the up-peak round-trip time equation is based on the probable number of stops and the highest reversal floor of the lift. The equation for the probable number of stops was first published by Jones in 1923 [1], and the equation for the average highest reversal floor by Schröder in 1955 [2]. Tables for probable number of stops and highest reversal floors in up-peak have been published, e.g., in IAEE [3]. There are many other up-peak formulas in the industry which are slightly different [4-13]. The equations produce, however, about the same answers for similar sets of inputs, and the differences are not too significant when considering lift selection. The round-trip time formula used in this paper is adopted from [8] which takes into account the exact flight times for different running distances in the up-peak situation.

Traditionally in lift selection, the nominal travel time, the up-peak handling capacity and interval criteria are used to define the number of lifts, their sizes and kinematic parameters such as rated speed. Different criteria may be used by different planning specialists. The mentioned selection criteria, however, have become more or less stable for certain types of buildings. Although lift planning professionals know how to utilize the up-peak equations, also, nomograms for lift selection have been published [13]. Lift companies have published selection graphs for architect use, see e.g. [14]. ISO 4190-6 [15] gives selection graphs for lift selection in residential buildings. This paper describes in detail the creation of general selection graphs, discusses when selection graphs are valid, and when more sophisticated methods such as simulations are needed. Values of the selection criteria may vary from a building type to another.

This paper is organized as follows. Section 2 presents the general round trip formula as well as the formulae for handling capacity, interval and nominal travel time. The round-trip time formula for unequal floor heights is presented in Section 3 together with the equations for the expected number of different running distances and their probabilities. Sections 4 and 5 describe the selection graph creation process, and a full selection graph is presented in Section 6. Section 7 discusses when the selection graphs are valid and conclusion follows in Section 8.

2 GENERAL ROUND TRIP TIME CALCULATION

Round trip time (RTT) is the time for a single lift to complete a cyclic path around a building, starting from the entrance level from the time the lift's doors start to open until the doors start to reopen after making a full trip up and down. It is assumed that calls are served in sequential order as in the conventional collective control system.

Traditionally RTT calculations for up-peak traffic are based on the average number of stops and average highest floor reached. The RTT can be calculated using the following expression:

$$RTT = 2 * H * \frac{d}{v} + (S+1) * \left(t_o + t_c + t_{st} + t_{ph} + t_f(1) - t_{ado} - \frac{d}{v}\right) + 2 * P * t_p \tag{1}$$

where:

H	is the average highest reversal floor;
d	is the floor height [m];
v	is the rated speed [m/s];
S	is the expected number of stops;
t_o	is the door opening time [s];
t_c	is the door closing time [s];
t_{st}	is the start delay [s];
t_{ph}	is the photocell delay before doors start to close after last passenger transfer [s];
$t_f(1)$	is the single floor flight time [s];
t_{ado}	is the advance door opening time [s];
P	is the average number of passengers carried;
t_p	is the average one way passenger transfer time [s].

The average highest reversal floor can be calculated using Eq. 2, [2]:

$$H = N - \sum_{i=1}^{N-1} \left[\frac{i}{N}\right]^P . \tag{2}$$

The average number of stops (S) for N floors can be calculated using Eq. 3, [1]:

$$S = N\left[1 - \left[\frac{N-1}{N}\right]^{P}\right]. \tag{3}$$

The up-peak handling capacity ($HC5$) of a lift group is the number of passengers it can transport from the entrance level to upper floors in a period of 5 minutes during the up-peak traffic condition with a specific average car loading P. Let L denote the number of lifts in a group. A value of $HC5$ can be calculated by using the following equation

$$HC5 = \frac{300}{RTT} * P * L. \tag{4}$$

The $HC5$ is usually expressed as the ratio of the $HC5$ and the building population U and is given as a percentage, that is

$$\%HC5 = \frac{HC5}{U} * 100\ \%. \tag{5}$$

If we are given a requirement for the minimum $\%HC5$, the maximum number of persons the building can accommodate satisfying the requirement is

$$U = \frac{HC5}{\%HC5} * 100\ \%. \tag{6}$$

With a single lift, interval (INT) is the same as RTT. If a lift system includes L identical lifts, INT becomes:

$$INT = \frac{RTT}{L}. \tag{7}$$

Nominal travel time (NTT) is the time to travel at rated speed v from the lowest to the highest served floor of the lift group. Often NTT recommendations do not take into account the acceleration, deceleration or levelling and can be calculated as:

$$NTT = \frac{d * N}{v}. \tag{8}$$

3 ROUND TRIP EQUATUION CONSIDERING UNEQUAL FLOOR HEIGTHS

RTT Eq. 1 assumes the equal floor heights as well as the nominal speed of a lift is reached during a single floor flight. This leads to some approximations for high-speed lifts as it may take a flight of several floors to reach the nominal speed.

Roschier and Kaakinen [8] presented a round-trip time formula which takes into account the exact running times of each flight during the round trip. This section reviews the probabilities of lift runs, expressed in floor heights, and the expected number of them. The population can vary floor by floor. Round trip time formula used in this paper can be written in the following form:

$$RTT = \sum_{r=1}^{N}\left[\sum_{i=0}^{N-r}\left(q_{i,i+r} * t_f(i,i+r)\right) + q_{r,0} * t_f(r,0) + (W_r + D_r) * \left(t_o - t_{ado} + t_c + t_{ph} + t_{st}\right)\right] + 2 * P * t_p \tag{9}$$

where:

$t_f(i,j)$	is the exact flight time from level i to j;
q_{ij}	is the probability of a lift travel from level i to j;
W_r	is the expected number of r-floor runs upwards;
D_r	is the expected number of r-floor runs downwards.

Consider a general building. Suppose that the ground level, indexed as 0, is the entrance level, and the upper floors are indexed as $1, \ldots, N$. Let u_k denote the population on floor k, $1 \leq k \leq N$. The total population U is then:

$$U = \sum_{k=1}^{N} u_k. \tag{10}$$

The population fraction on level k is defined as:

$$p_k = \frac{u_k}{U}. \tag{11}$$

The following inequalities give the probabilities for all run combinations [8]:

$$q_{0r} = \left(1 - \sum_{k=1}^{r-1} p_k\right)^P - \left(1 - \sum_{k=1}^{r} p_k\right)^P, \qquad 1 \leq r \leq N; \tag{12}$$

$$q_{i,(i+r)} = \left(1 - \sum_{k=i+1}^{i+(r-1)} p_k\right)^P - \left(1 - \sum_{k=i}^{i+(r-1)} p_k\right)^P - \left(1 - \sum_{k=i+1}^{i+r} p_k\right)^P + \left(1 - \sum_{k=i}^{i+r} p_k\right)^P, \qquad 1 \leq r \leq N-1, 1 \leq i \leq N-r; \tag{13}$$

$$q_{r0} = \left(\sum_{k=1}^{r} p_k\right)^P - \left(\sum_{k=1}^{r-1} p_k\right)^P. \tag{14}$$

The expected number of r-floor runs in the up-direction, W_r, and in the down-direction, D_r, can be derived from Eq. 12-14:

$$W_r = \sum_{i=0}^{N-r} q_{i,i+r}, \qquad 1 \leq r \leq N, \tag{15}$$

$$D_r = q_{r0}, \qquad 1 \le r \le N. \tag{16}$$

4 ASSUMPTIONS FOR BUILDING, LIFT AND SELECTION CRITERIA

This section lists all assumptions used in the graphs shown in this paper. The considered building type is assumed to have only one entrance floor at ground level and no express zone. The floor height and the population are expected to be the same on every floor. In addition, the following values are considered:

a. floor height 3.0 m;
b. maximum number of cars in group 3;
c. range of speed 1- 2 m/s;
d. acceleration 0.8 m/s^2;
e. jerk 1.2 m/s^3;
f. rated car capacity 8-13 persons;
g. initial value for the average car loading is taken P as 80% of rated car capacity;
h. advanced door opening 0 s;
i. start delay 0.7 s;
j. door widths and their operating times are given in Table 1. All doors are here assumed to be centre opening.

Table 1 Door widths and their operating times for considered lift capacities

Capacity [persons]	Door width [mm]	t_o [s]	t_c [s]	t_{ph} [s]	t_p [s]
8	800	1.7	2.5	0.9	1.15
10	900	1.4	2.7	0.9	1.1
13	1100	1.4	3.1	0.9	1.0

The selection criteria used in this paper are the nominal travel time, interval and handling capacity. Example values used in this paper are shown in Table 2. These values do not represent requirements for any specific building type.

Table 2 Example selection criteria

%HC5 [%/5 min]	INT [s]	NTT [s]
12	30	32

5 CREATION A SELECTION GRAPH

This section illustrates how to create a selection graph for a general building by a simple example.

Firstly, consider a group of 3 identical 13-person lifts with nominal speed of 1.6 m/s. The region in which this group satisfies the $\%HC5$ requirement of 12% is illustrated in Fig. 1. The borderline of the region is obtained by calculating the total population above the entrance floor using Eq. 6 as a function of the number of upper floors.

Secondly, for a given nominal speed and NTT requirement, the maximum number of upper floors can be solved from Eq. 8, which gives the value of 17 floors for the selected speed of 1.6 m/s. Fig. 2 illustrates the feasible region after the NTT requirement is also taken into account.

Thirdly, the interval of the group, calculated as a function of the number of upper floors is depicted in Fig. 3. From this figure one sees that some part of the region is infeasible with respect to the INT requirement of 30 seconds which can be taken into account as follows. First calculate the RTT, and then INT according to Eq. 9 and 7, respectively. If INT is greater than the requirement, reduce the average car loading P by a certain amount, then recalculate RTT and INT. Repeat this until the INT requirement is fulfilled. Fig. 4 shows the interval after the requirement is taken into account. The region meeting the interval requirement is illustrated in Fig. 5.

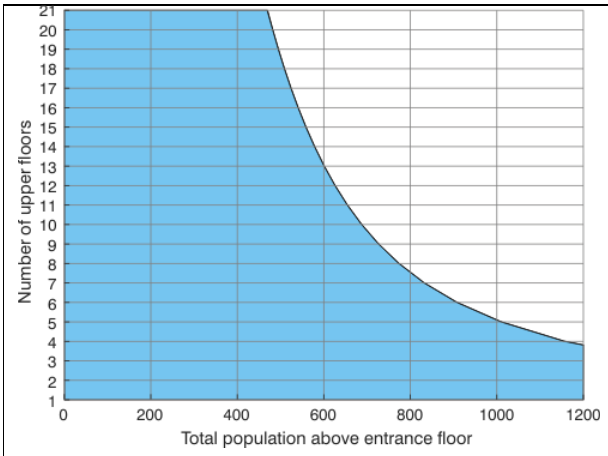

Figure 1 Feasible region of a group of three 13-person lifts with nominal speed of 1.6 m/s taking into account $\%HC5$ requirement

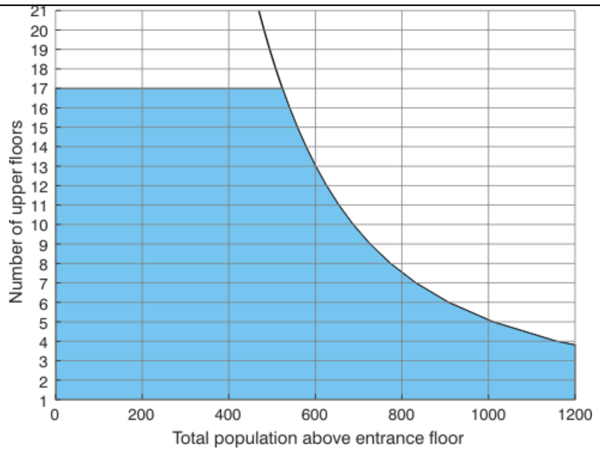

Figure 2 Feasible region of a group of three 13-person lifts with nominal speed of 1.6 m/s taking into account $\%HC5$ and NTT requirements

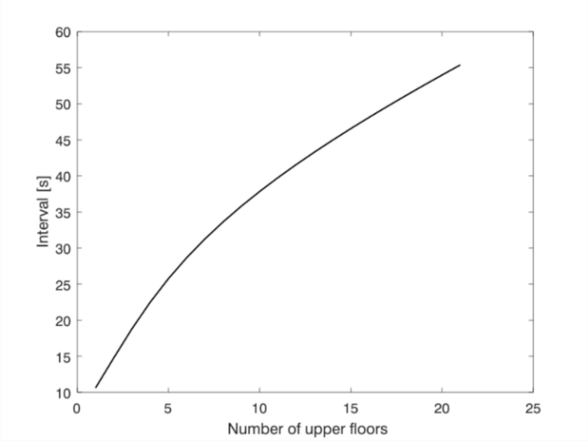

Figure 3 INT of a group of three 13-person lifts with nominal speed of 1.6 m/s

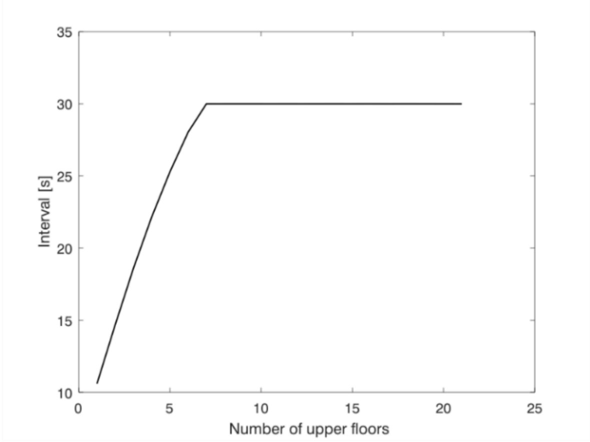

Figure 4 Interval of a group of three 13-person lifts with nominal speed of 1.6 m/s where the INT requirement is applied

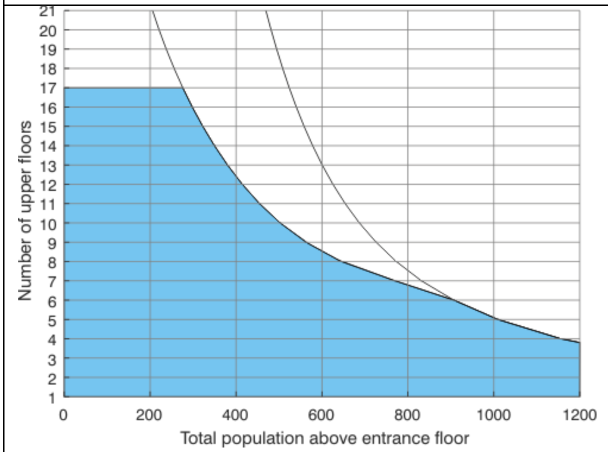

Figure 5 Feasible region of a group of three 13-person lifts with nominal speed of 1.6 m/s taking into account $\%HC5$, NTT and INT requirements

6 RESULTS

The selection graph is created by first calculating the feasible region for a lift group, as described in the previous section. A feasible area can be calculated for as many lift combinations as desired. Then the regions are combined into a single graph. With overlapping regions, the area with minimum arrangement, i.e., number of lifts, speed or passenger capacity, is selected. A graph with 11 feasible areas is shown in Fig. 6. The symbols used in the figure are given in Table 3.

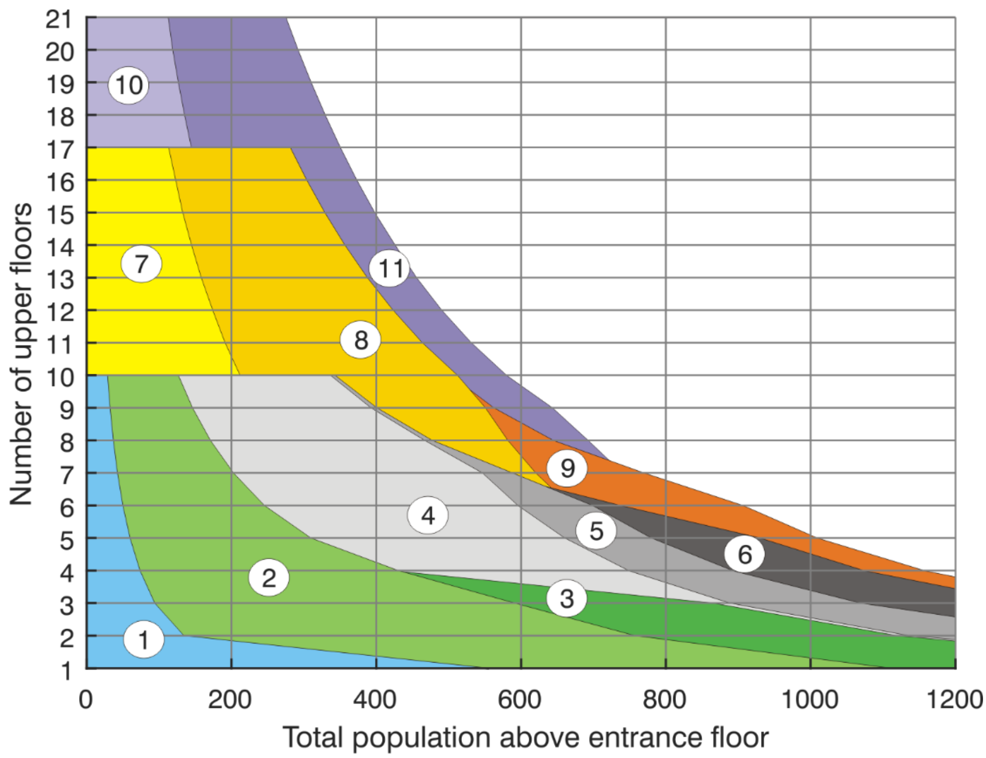

Figure 6 Lift selection graph

Table 3 Explanation of the symbols in lift selection graph

Id	Number of lifts	Capacity [kg]	Speed [m/s]
1	1	630	1.0
2	2	630	1.0
3	2	1000	1.0
4	3	630	1.0
5	3	800	1.0
6	3	1000	1.0
7	2	630	1.6
8	3	630	1.6
9	3	1000	1.6
10	2	630	2.0
11	3	800	2.0

7 DISCUSSION

Round-trip time formula presented in this paper implicitly makes some assumptions. This section goes through them one by one in detail, and discusses how they can be relaxed.

Number of entrance floors. The RTT formula assumes that there is only one entrance floor located at the lowest floor. The case of multiple entrances is considered in [17].

Passenger arrival process. Passenger arrivals at the entrance level are assumed to follow a uniform distribution. According to work of Alexandris [6], passenger arrivals follow a Poisson distribution. Poisson distributed loads can be taken into account by using travel probabilities presented in [18].

Control system. Conventional control with up and down call giving devices are assumed. In destination control with destination keypads, the lift control system has more information in call allocation. That is, it knows the exact number of passengers waiting at elevator lobbies and their destination floors (assuming that each passenger gives a destination call at an elevator lobby). The destination control system can utilize this information to gather passengers with the same destination floors in the same lift. This yields to shorter round trips, and therefore the round trip time formulae presented in this paper are not valid for destination controls. The first equations for estimating the up-peak round trip time for destination control were given in [19]. The equations were later improved in [20].

Express floors. No express floor was assumed. Express floors can be addressed by setting for each express floor f the population of it to zero, i.e., $u_f = 0$.

Heterogeneous lifts. Interval Eq. 7 assumes that all elevator are identical. Suppose for now that all lifts are unique. Let RTT_i be the RTT of lift $i = 1, \ldots, L$, calculated using Eq. 9 and denote by P_i the number of passengers in the car i when it leaves from the entrance level. Handling capacity of the group is now

$$HC5 = \sum_{i=1}^{L} \frac{300}{RTT_i} * P_i, \tag{17}$$

and the interval becomes

$$INT = \left(\sum_{i=1}^{L} \frac{1}{RTT_i} \right)^{-1}. \tag{18}$$

Traffic type. In the round trip calculation, pure up-peak traffic condition is considered since it is the most demanding traffic situation considering the handling capacity. If lifts can handle the up-peak situation, they have enough handling capacity for other traffic situations. There are several works that extend the RTT formulae for other traffics such as down-peak and mixed traffic [9, 11]. All of these assumes that lifts follow the collective control principle. The collective control may not however lead to optimal control policy, except pure up-peak condition in a building with single entrance at the lowest floor, see [21]. This means that the lift group selected based on, for example, mixed traffic round trip time could be too large. Therefore if a traffic condition other than up-peak needs to be taken into account, we strongly recommend to use simulation techniques to calculate the border curves. Simulations though, may take some time.

Number of decks. All lifts are assumed to have single deck. Double-deck case is studied in [22]

Selection criteria. The selection criteria used in this paper are the nominal travel time, interval and handling capacity. Nowadays many set requirements for other criteria. Waiting time, ride time and journey time requirements can be taken into account by first deriving their distributions in an up-peak situation and then calculating the value of the requirements from them. Distributions of these requirements can also be used as a selection criteria [23].

As a summary, up-peak round trip time formula can be extended to cover a number of different cases. Extensions to traffic conditions other than up-peak, such as down-peak and mixed traffic, leads to some approximations since they do not take into account the impact of elevator controller. Therefore in such a case, simulation methods are recommended in selection graphs drawing. For complicated and unique buildings there is no sense to make selection graphs.

8 CONCLUSION

In this paper, a method for drawing lift selection graphs using up-peak equations is described. The up-peak round-trip time equation presented in [8] was chosen as a basis in this paper since it takes into account the exact flight times for different running distances in the up-peak situation. Other up-peak round-trip time equations can be used as well. In the selection graph, population and number of upper floors are defined as an input. From the graph, the number of lifts, their passenger capacities and speeds can be deduced. This paper also discussed the cases where the round trip time formula has been extended.

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BIOGRAPHICAL DETAILS

Mirko Ruokokoski graduated from the Department of Engineering Physics and Mathematics, Helsinki University of Technology in 2008. Currently, he is finalizing his doctoral thesis at Systems Analysis Laboratory in the Aalto University, School of Science and Technology. He joined KONE in 2012 and has been working for R&D.

Marja-Liisa Siikonen received her MSc in Technical Physics, and later licentiate and doctoral degrees in Applied Mathematics from Helsinki University of Technology in 1997. She has worked in the Technical Research Center of Finland, Nokia, and since 1984 in KONE. Currently she is the Director of People Flow Planning in KONE Corporation.

Our Accessible World & The New Part 70

Adam J Scott

Sweco UK Limited, 1 Bath Road, Maidenhead, Berkshire, SL6 4AQ, UK
adam.scott@sweco.co.uk

Keywords: Accessibility, disability, Part 70, EN81-70, BS EN81-70, contrast

Abstract. Advances in education, diet and medicine have brought wonderful benefits to us all over recent decades, not least of which is the potential to live longer. Average age is on an upward trend creating a growing need for us to influence our built environment in such a way as to maintain and improve accessibility for all.

Since its first publication in 2003, EN 81-70 [1] has provided us with the framework for the design of safe, accessible passenger lifts for all. As a harmonized standard it is a key document referenced in both The Building Regulations Approved Document M and British Standard 8300, and has established itself as the *de facto* standard on the subject throughout Europe and beyond. Recent developments suggest the standard may indeed have the potential to become an ISO with global reach.

This year should see the publication of the first revision to EN81-70 [2] since its original publication nearly fifteen years ago. It is the result of three years of work and much heated debate, consultation and comment. The presenter represented the British Standards Institution (BSi) on the CEN TC10/WG7 European drafting committee and therefore has insight into the new standard.

This paper will present the key changes we will see in the new document, and the thinking behind them.

1 BACKGROUND

It is a statistical fact that humans are living longer. Advances in education, medicine and diet are the primary enablers for this trend at a global scale, and for most of us it is likely to be a welcome feature of a developing society. But such evolution presents society with challenges as well as opportunities, and to benefit from extended lives we need to maintain our health, both physical and mental.

The news and political agenda here in the UK regularly highlights the extent to which poor mental health, in the form of dementia and other associated debilitating conditions, appears to be afflicting a greater and greater number of people. Also, for many, our physical health is also under pressure from the new world of instant convenience within which we now reside. As Dr. James Levine, director of the Mayo Clinic-Arizona State University Obesity Solutions Initiative has recently gone on record saying, “Sitting is the new smoking”, and for many the pervasive sedentary lifestyle, both at work and at home, is significantly increasing the likelihood of disability affecting our lives.

These trends allied to the prevalence of other disabilities in society, suggest that now more than ever disability needs to be a concern for us all. Consider these statistics:

- There are 39 million disabled people in Europe [3].
- There are 11.6 million disabled people in Britain [4].
- Around 16% (5.7 million people) of the working-age population in Britain [4].
- One in six people aged between 16 and 64 in Europe has either a long standing health problem or a disability [5].
- Only 8% of disabled people in the UK use a wheelchair [3].

Lifts clearly have an important part to play in providing an accessible environment, a fact that was recognized more than fifteen years ago with the publication of the first standard for accessible lifts EN81-70. Adopted presciently and enthusiastically by many countries, the standard has delivered a very real improvement in the quantity of lifts designed for accessibility by all. However unchanged for fifteen years, the time for revision was well overdue, and the need for such a review never more relevant.

I was therefore delighted to be asked to represent the United Kingdom on the CEN TC10/WG7 committee to work on drafting the new standard. Our work commenced on 27th May 2014 with a committee comprising 12 regular members from Germany, Switzerland, Finland, Belgium, Austria, Spain & France. Members represented user groups, manufacturers and consultants.

2 THE NEW STANDARD

The first point to note about the new standard BS EN81-70 (2017) is that it is a full revision that replaces the old BS EN81-70 (2003). There is a two year adoption period during which time both standards will remain valid and installers may select which standard their equipment is designed to and record the same on the relevant Declaration of Conformity issued at the time the lift is placed into service for the first time. It should however be noted that where an installer elects to use the old BS EN81-70 (2003) standard with a new lift installed to BS EN81-20, some form of Notified Body agreement will be required.

The new standard has removed all content that is otherwise covered in other associated standards, e.g. requirements in relation to alarms (covered by BS EN81-28), or requirements in relation to door protection devices (covered by BS EN81-20).

2.1 Introduction

Like most standards there is some important information in the Introduction which informs the reader on scope and assumptions. Key points to note are:

- It is assumed that national building regulations specify in which buildings accessible lifts, according to the standard, should be installed.
- It is assumed that national building regulations will not conflict with the provisions of this standard.
- It is assumed that obstacle-free access is provided on all relevant floors and that visual and tactile guidance systems for finding lifts and their controls have been considered by building designers and adopted as appropriate.
- It is assumed that appropriate negotiations have taken place between the supplier and the owner to agree the intended usage of the lift and any implications such usage may have for the lift's specification.

It is also assumed that the reader of the standard is competent. Standards are typically drafted with great care and prompt much debate, some of it heated. The selection of auxiliary verbs for clauses is of particular importance and the reader's attention is drawn to the following when reading any standard:

- *Shall* – a requirement of the standard. Compliance with the standard cannot be claimed unless all such clauses (including normative annexes) are complied with.
- *Should* – a recommendation of the standard. Compliance with these clauses is not required in order to claim compliance with the standard.
- *May* – provides permission for options.

- *Can* –provides options for compliance with a requirement or adoption of a recommendation

Content within a *Normative* annex contains “shall” clauses and is therefore a requirement of the standard, content contained within an *Informative* annex contains “should” clauses and is therefore a recommendation of the standard.

Where the normative clauses of the standard have not been followed, approval from a Notified Body would be needed to demonstrate conformity to the EHSRs of the Lifts Regulations.

2.2 Contrast

Key to providing an accessible environment is the ability to visually distinguish one’s surroundings. The old Part 70 standard required many elements of the lift to be “suitably contrasted” from their surroundings but did not define what was suitable and what was not.

The new Part 70 standard addresses this issue with what has proved to be the most contentious content of the revision. Contrast is a complex and often subjective phenomenon, and there is so much debate ensued on methods of measurement, the need to provide a set of requirements that could be easily understood, designed to, and where required measured on site. The committee decided to adopt measurement of light reflectance value (LRV) to assess the level of luminance contrast. This is an established measurement criterion referenced in a number of other complementary standards on accessibility.

The table below defines the new contrast requirements:

Table 1 Minimum difference of light reflectance value (LRV)

Clause	Item	At landings		In the car	
		Minimum LRV point difference	Viewing angle	Minimum LRV point difference	Viewing angle
Table 4, item c)	Active part of push buttons to their surrounding	30	45° above horizontal	30	45° above horizontal
Table 4, item d)	Face plate to its surrounding	30	Perpendicular	30	Perpendicular
Table 4, item j)	Symbols on push buttons to active areas	30 (60 recommended)	45° above horizontal	30 (60 recommended)	45° above horizontal
5.4.3.3.1 c)	Lift identification to background	30 (60 recommended)	Perpendicular	-	-

LRV may be determined by a black and white photograph of a sample with an adjacent LRV scale and comparing the surfaces of the sample with the LRV scale. Alternatively, by placing a LRV scale against the surface of interest a reasonable match can be identified.

It was recognized that these new requirements could have significant implications for the design of current and future fixtures, and as such an incremental approach is intended. Certain elements have a minimum LRV point difference of 30 with 60 recommended. This is intentional and seeks to establish a new benchmark of 30 points whilst encouraging the market to move towards an enhanced level of 60 points.

The standard also contains some additional guidance on material selection to enhance luminance contrast through the use of diffuse reflective materials.

2.3 Car Types

The old Part 70 standard defined three types of car of varying size. The new standard broadens the range of car sizes to five, and provides some additional requirements in terms of the building types within which each type of car shall be used. The new requirements are as set out in the table below:

Table 2 Minimum car dimensions for cars with a single entrance or two entrances

Type of car	Minimum car dimensions [a]	Accessibility level	Building types, usage	Remarks
1	Car width: 1 000 mm Car depth: 1 300 mm (450 kg)	This car accommodates one wheelchair user without an accompanying person.	Shall only be used in existing buildings where building constraints do not permit the installation of a type 2 car.	Type 1 provides only limited accessibility for persons using a manual wheelchair as described in EN 12183:2014 or an electrically powered wheelchair of class A described in EN 12184:2014. This type also provides accessibility for persons using walking aids (e.g. a walking stick) and for persons with sensory and intellectual disabilities.
2	Car width: 1 100 mm Car depth: 1 400 mm (630 kg)	This car accommodates one wheelchair user and an accompanying person.	Shall be the minimum size for new buildings.	Type 2 provides accessibility for persons using a manual wheelchair as described in EN 12183:2014 or an electrically powered wheelchair of class A or B as described in EN 12184:2014. This type also provides accessibility for persons using walking aids (e.g. walking sticks, crutches or rollators). Passengers with wheelchairs or walking aids are unlikely to be able to turn around in this type of car and have to leave the car backwards.

3	Car width: 1100 mm Car depth: 2100 mm (1 000 kg)	This car accommodates one user with a wheelchair of class C and some other passengers. It also allows transport of stretchers.	Recommended size for cars in public areas (e.g. outdoor facilities, stations, etc.) and for cars where transport of wheelchairs of class C shall be provided	Type 3 provides accessibility for persons using a manual wheelchair as described in EN 12183:2014 or an electrically powered wheelchair of class A, B or C described in EN 2184:2014. It also provides accessibility for persons using a manual wheelchair with tractor unit (propulsion attachment). When cars of this type are configured with two opposite entrances this can provide straight through circulation from the main entrance to different floor levels.
4	Car width: 1 600 mm Car depth: 1 400 mm or Car width: 1 400 mm Car depth: 1 600 mm (1 000 kg)	This car accommodates one wheelchair user and a few other passengers. It also allows a wheelchair to be rotated within the car.	Shall be the minimum size for cars with doors on adjacent walls[b].	Type 4 provides accessibility for persons using a manual wheelchair as described in EN 12183:2014 or an electrically powered wheelchair of class A or B as described in EN 12184:2014. Type 4 provides sufficient space for most wheelchairs users and for passengers with walking aids.
5	Car width: 2 000 mm Car depth: 1 400 mm or Car width: 1 400 mm Car depth: 2 000 mm (1 275 kg)	This car accommodates one wheelchair user and several other passengers. It also allows a wheelchair to be rotated within the car.		Type 5 provides accessibility for persons using a manual wheelchair as described in EN 12183:2014 or an electrically powered wheelchair of class A, B or C as described in EN 12184:2014. Type 5 provides sufficient turning space for persons using wheelchairs of class A or B and for persons using walking aids (e.g. walking frames, rollators, etc.)

[a] The car width is defined as the horizontal distance between the inner surface of the structural walls of the car, measured parallel to the front entrance. The car depth is defined as the horizontal distance between the inner surfaces of the structural walls of the car, measured perpendicular to the width.

[b] The distances between doors and adjacent car walls as shown in Figure 1 should be as large as possible.

Key changes are:

- Type 1 cars have an increased minimum depth of 1300 mm (previously 1250 mm). This increase is in response to a review of current wheelchair dimensions.
- Type 1 cars shall only be used in existing buildings where it is not possible to install a Type 2 car.
- Type 2 cars shall be the minimum size for new buildings.
- The old Type 3 car is now referenced as a Type 5 car and has vice-versa dimensions allowed in terms of car width and depth.

- Type 3 is now a new car size with minimum dimensions of 1100 mm (w) x 2100 mm (d) and is recommended as a minimum size for cars in public areas such as railway stations, and/or where the transport of class C wheelchairs is required.
- Type 4 is now a new size for cars with adjacent door configuration. Type 4 cars shall have a minimum size of 1600 mm (w) x 1400 mm (d) or vice-versa.

As before clear internal dimensions are permitted to be reduced by finishes by up to 15 mm on each wall whilst still maintaining compliance with the required car type.

2.4 Doors

The new standard now requires Type 2 cars to have a clear door opening width of at least 900 mm. In the UK this is typical but now it becomes a requirement of the harmonized standard, and an enhancement over the requirements of The Building Regulations as defined by Approved Document M2 (2015).

The new standard also recommends that door dwell time is set to at least 6 s for persons with reduced mobility.

2.5 Handrails

The new standard provides more comprehensive requirements for handrails, in part to clarify the confusion created by the old standard and the recurrent "is the rear wall a side wall" question.

The new standard requires the following:

- A handrail shall be installed on the side wall where the car operating panel is located.
- The handrail shall be interrupted where the car operating panel is located in order to avoid obstruction of the control devices.
- The handrail may be installed on only one side of the car operating panel if the shorter side would not accommodate a handrail with an overall length of at least 400 mm.
- For car types 4 and 5, a second handrail shall be installed on the opposite side wall or on the rear wall.

The location of the handrail relative to the floor level of the lift car and the size of the handrail itself remain unchanged from the old standard. The new standard now also provides a drawing illustrating the dimensional constraints in cross section.

The ends of handrails still need to be closed but they only need to be turned towards the wall where there is a risk of collision with the otherwise projecting end.

For car types 1, 2 or 3, if the handrail would restrict the car entrance width, the handrail may be moved to the opposite side from that where the car operating panel is located.

2.6 Tip-Up Seat

Whilst not a common provision, the new standard enhances the load carrying capacity of any tip-up seat from 100 kg to 120 kg and loosens slightly the positional tolerance above the floor of the lift car from 500 mm $^{+/- 20\text{ mm}}$ to 500 mm $^{+/- 25\text{ mm}}$.

2.7 Control Devices

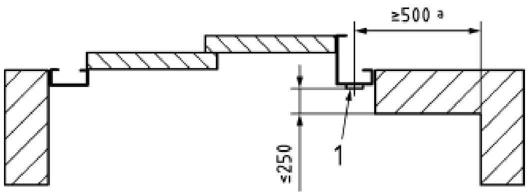
This part of the new standard required the most work and in respect of requirements for destination control (particularly with touchscreens) was most in need of revision. Consequentially and for clarity the new standard separates requirements for collective control systems (conventional control) from those for destination control systems.

2.8 Collective Control

The new standard retains the summary table of requirements for landing and car controls, albeit now offers two separate tables, one for design and one for arrangement.

Most requirements remain unchanged, however a few have been enhanced including, *inter alia*, the following:

- The height of relief required remains unchanged at 0.8 mm, though the standard now recommends an enhancement to 1.0 mm. (Again this is intended to start to move the industry towards more accepted design benchmarks in other areas of accessible design.)
- The minimum distance between the floor level and the centerline of any button has been reduced from 900 mm to 850 mm.
- The minimum lateral distance between the centerline of any control button to any corner of adjacent walls remains at 500 mm, but now has an enhanced recommended dimension on 700 mm. There is also now an additional diagram illustrating the principle applied with a recess and as shown below:



Key
1 landing button
a preferably 700

Figure 1 Arrangement of landing buttons

- The nomenclature for floors has been clarified with the new standard highlighting that the symbols associated with car buttons should be consistent with the building's floor nomenclature, and preferably (but not necessarily) -2, -1, 0 ,1 ,2.
- A car operating panel shall now be provided on both sides of the car when the car width exceeds 1600 mm.
- Two car operating panels shall be provided in the case of adjacent entry cars.
- Landing signals shall be visible with an angle of view as before of at least 140° in the horizontal plane but now also at least 70° in the vertical down plane.
- The provision of an induction loop (to EN 60118-4) is now a recommendation, subject to negotiations on likely car usage.

It should be noted that this section references keypads and accessibility buttons in recognition of the fact that such systems may be used in conjunction with conventional control, even though they are more typically seen as part of destination control systems.

2.9 Destination Control

With the prevalence of destination control, especially in the commercial sector, it was felt that separate sections were required in the new standard to deal with the particular issues such control presents for accessibility.

The new standard provides clearer and more specific requirements for the design of landing keypads and moves these requirements from the normative annex in the old standard into the main body text of the new standard. Keypads shall meet the requirements of the general design and arrangement tables with the following exceptions and additional requirements:

- not exceed 120 mm in overall width
- not exceed 160 mm in overall height
- the distance between the pushbuttons shall be between 5 mm and 15 mm (previously 10 mm and 15mm)
- have numbers on the active part of the button but the numbers shall not be in relief
- have the star and the minus symbol in relief
- have the single dot on the number 5 in relief
- Braille shall not be used

The requirements are also illustrated in a more detailed figure than that that appeared in the old standard. This figure is as shown below:

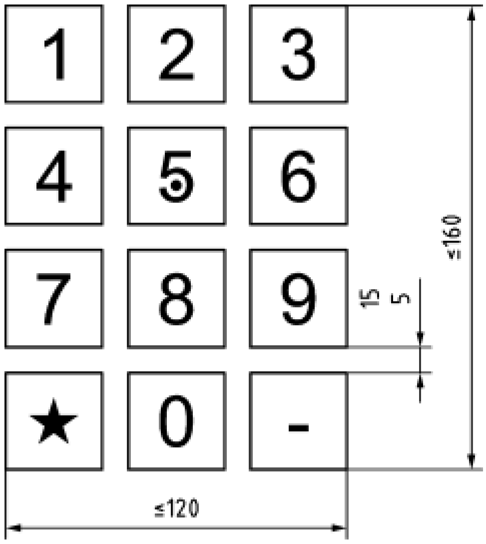


Figure 2 Illustration of keypad

The new standard now formalizes the requirement for an accessibility button which shall be provided adjacent to all keypads, preferably below the keypad.

The accessibility button shall initiate additional audible guidance to facilitate the use of the control device. Pushing the button shall allocate a car adjacent to the relevant control device or alternatively extend the door dwell time of the allocated car. It may also activate additional features such as extended time to place a call, assignment to a larger car, enhanced contrast, etc.

The selected floor and allocated lift shall (as before) be confirmed with a visible signal, though the need for an associated audible signal is now linked to activation of the accessibility button, i.e. audible signals are not required unless the accessibility button is activated.

Lift assignment characters on screen shall be at least 25 mm high and, if displayed in response to the use of the accessibility button, shall remain displayed for the duration of the associated audible signal.

Lift markings (e.g. A, B, C, D, etc.), may now be placed adjacent to the landing door as well as above, and between 1800 mm and 2500 mm above the FFL as before. The height of the markings shall be at least 40 mm as before however they now also need to meet the contrast requirements to their surrounding in terms of minimum LRV point difference.

Touch screens

The subject of touch screens was one of the most vociferously debated during the evolution of the new standard. Some views considered the technology as inherently inaccessible and therefore never suitable, other views maintained such technology has been in the market for some time and indeed in some circumstances can offer enhanced levels of accessibility.

A consensus view was eventually reached that the new standard had to recognize the prevalence of such technology in the market and respond with suitable guidance.

The new standard therefore contains a normative annex covering the use and design of touch screens. Touch screens shall provide the following:

- A display screen providing a luminance of at least 300 cd/m^2.
- Active areas and symbols shall be contrasted with their immediate surroundings.
- Background areas shall be solid and static.

The design of the buttons shall meet the requirements of the general design and arrangement tables with the following exceptions and additional requirements:

- Items c), d), e), g), h), i), j), k) and l) do not apply.
- The exit button shall be preferable green or have a green frame;
- The symbols shall be on the active area;
- The symbol height shall be between 15 mm and 40 mm;
- The distance between the active parts of buttons shall comply with Table 5 except c).

Lift assignment symbols shall be at least 25 mm high and displayed for the duration of the associated audible announcement, if activated.

An accessibility button shall be placed adjacent to the touch screen, preferably below, for activation the verbal announcements and floor selection. Upon activation of the accessibility button, the following sequence shall be followed:

A sequential announcement of available destinations (e.g. at the entrance level counting from the lowest to the highest floor or at an upper floor starting with the entrance floor then counting from the highest to the lowest floor.

The required destination shall be selected by a subsequent operation of the accessibility button or by operation of the relevant touch button

In a building with many floors, first a zone of destinations may be selected before the final destination.

3 ADDITIONAL COMMENTS

The new standard contains an expanded normative annex dealing with extra large control buttons designed to provide further enhanced accessibility. The content of the annex builds on the previous standard’s guidance, the key difference being that the new standard’s content is in a normative annex whereas the old standard’s advice was informative only.

Annex D of the new standard is an informative annex providing further guidance for enhanced accessibility, noting that this may be particularly important in public facilities such as train stations, hospitals, nursing homes, etc., where a higher proportion of users may be less abled. Amongst this annex’s recommendations are the following:

- The height of landing and car doors and the clear height of the car should be at least 2100 mm.

- Handrails should be installed on all car walls without doors.
- If braille is provided, then the characters should comply with ISO 17049 and have a minimum distance of 5 mm to their associated symbols.
- Glass landing doors should be marked to avoid confusion caused by transparent materials. Transparent elements in the walls of the car, well, and/or doors may reduce the risk of panic, and in the case of trapped passengers, assist in communication.

4 CONCLUSION

Whilst naturally a little biased, I strongly recommend the new standard to the reader.

The new standard is not perfect (few if any are) but does take a significant step forward in defining suitable levels of accessibility for current designs. Its content represents a reasonable and balanced set of requirements and is a very significant improvement that is applicable to a very large number of lifts.

The subject of contrast and LRV points difference remains one of ongoing debate and a formal review is likely next year to assess the market's reaction to the new standard and to identify what opportunities may exist to enhance further the contrast requirement.

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BIOGRAPHICAL DETAILS

Adam J Scott BEng (Hons) CEng FCIBSE MIMechE

Adam started his career in the lift industry 26 years ago with Otis in London, UK. After twelve years working in construction, service, modernization and new equipment sales, he moved into the world of consultancy with Sweco (formerly Grontmij and before that Roger Preston & Partners) and has subsequently worked on the design of vertical transportation systems for many landmark buildings around the world.

Adam is a Fellow of the Chartered Institution of Building Services Engineers (CIBSE), and a past Chairman of both the CIBSE Lifts Group and the CIBSE Guide D Executive Committee. He is the current codes and standards representative for the CIBSE Lifts Groups and sits on the British Standards Institution's MHE4 technical committee. He is also a member of the BCO vertical transportation technical review committee and currently the UK nominated expert for WG7, working on the revision of EN81-70.

An Analysis of Airflow Effects in Lift Systems

Nishant Singh[1], S. Kaczmarczyk[1], Thomas Ehrl[2]

[1]Faculty of Arts, Science and Technology, The University of Northampton, UK

[2]thyssenkrupp Elevator Innovation GmbH, Berner Feld 60, 78628 Rottweil, Germany

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Abstract. The current trends towards the design of lighter cars for high-speed lift systems and multiple car lift systems have encouraged the design of more aerodynamic efficient car geometries. Lighter lift cars are susceptible to aerodynamic drags and piston effects. The issue of piston phenomena affecting smoke control in traditional lift shaft configurations have been studied extensively. Considering the complexity of multiple car, multidirectional shafts and the susceptibility of lighter cars to aerodynamic drag and piston effects, it is important that relevant analysis is developed to determine the aerodynamic effects arising in those systems. With advances in the field of Computational Fluid Dynamics (CFD), it is now possible to compute 3D compressible large eddy simulation for a multi-car lift systems. A better understanding of piston effect in the context of lighter and faster multi-car systems is necessary to further calculate the impact of these forces on lighter structures. In this paper, a coupled Fluid-Structure Interaction (FSI) model is developed based on stiffness and damping of the system and boundary values from transient CFD study. This study will help understand the impact of excitations due to aerodynamic forces and understand the effect of aerodynamic drags and piston forces in the multi-car shaft systems.

1 INTRODUCTION

The operation of lift systems is affected by vibrations and associated vibro-acoustic noise. Aerodynamic loadings due to the airflow around the car result in excessive noise and flow-induced vibrations of the car structure [1]. This affects ride quality and results in a high level of dynamic stresses in elevator components.

2 AERODYNAMIC PHENOMENA

The aerodynamic phenomena affects the performance of lifts. At high speeds the air flows 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 broad band (100 – 500 Hz) acoustic energy transmission to the car interior in high-rise 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 has 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.

Lift piston effects have been studied in the context of smoke control [5 – 6] and lift shaft pressurization [7]. A better understanding of piston effect in the context of lighter and faster multi-car systems [8] is required.

CFD has been an effective tool for the flow simulation for last decades. Incompressible CFD solvers reduces the computational effort but that saving in computational time is achieved at the cost of losing acoustic information from the problem, as wave propagation speed is infinite in the incompressible solver. Such acoustic information is often critical to the Fluid-Structure interaction problems. For a compressible solver, acoustic simulations or turbulent flow simulations require highly resolved spatial and temporal resolution and therefore are computationally expensive. However, a better understanding of lift aerodynamics and its interaction with lift structures requires a high fidelity compressible simulation.

3 MODELLING METHODOLOGY

A lift installation can be considered as a multi-body system (MBS) with discrete and continuous (distributed-parameter) components [1]. In a Fluid-Structure interaction scenario, the flow of the problem is solved using the Navier-Stokes equations and the structural part of the problem is solved using Lagrangian system of equations.

The instantaneous compressible Navier-Stokes equations can be transformed into an Unsteady Reynolds Average Navier Stokes form (URANS) through time averaging to form a set of equations as summarised below, see [9] for a full description:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho}\hat{u}_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial \bar{\rho}\hat{u}_i}{\partial t} + \frac{\partial \bar{\rho}\hat{u}_i\hat{u}_j}{\partial x_j} = -\frac{\partial P}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} + \frac{\partial \bar{\sigma}_{ij}}{\partial x_j}, \tag{2}$$

$$\frac{\partial \bar{\rho}\hat{E}}{\partial t} + \frac{\partial \bar{\rho}\hat{u}_j\hat{h}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\bar{\sigma}_{ij}\hat{u}_i + \overline{\sigma_{ij}u_i'}\right) - \frac{\partial}{\partial x_j}\left(\bar{q}_j + c_p\overline{\rho u' T'} + \bar{\sigma}_{ij}\hat{u}_i\tau_{ij} + \overline{\rho u' k}\right) \tag{3}$$

where
$$P = (\gamma - 1)\{\bar{\rho}\hat{E} - \tfrac{1}{2}\rho(\hat{u}^2 + \hat{v}^2 + \hat{w}^2) - \bar{\rho}k\}, \tag{4}$$

$\widehat{\ }$ denotes density weighted Favre-averaged variable, $\bar{\ }$ denotes averaged variable, $\bar{\sigma}_{ij}$ is usually modelled by the Boussinesq assumption (provides S_{ij}) and

$$\hat{h} = \hat{E} + \frac{\bar{p}}{\bar{\rho}}$$

$$\bar{q}_j = -\frac{c_p \hat{\mu}}{Pr} \frac{\partial \hat{T}}{\partial x_j}.$$

In the Unsteady RANS approach it is assumed that the time averaging process occurs over a period of time sufficiently long to capture the turbulent fluctuations, whilst still short in comparison to large scale temporal changes in the flow field.

In order to derive the differential equations of motion for the structural part of such a system, Lagrange‘s Equations techniques can be applied [5]. The use of Lagrange equations facilitates the derivation of equations of motion in terms of generalized coordinates, without the need of free body diagrams. Considering the difficulty of mixed mode vibrations in the context of moving mesh systems, a one-way-coupled system is adopted in this work where structure is assumed to have a prescribed vibration. OpenFOAM [10] has been used as a fluid solver and MATLAB module is developed for the structural solver in a Lagrangian framework.

4 COMPUTER SIMULATION AND RESULTS

The fluid flow is coupled to the structure in one-way and the solution scheme is based on Lagrangian formulation for the structure and compressible CFD formulation for the fluid regions. The computer simulations are executed in open source OpenFOAM solver.

Table 1 Fundamental parameters of the system

Parameter	Value	Unit
Car	1000	kg
Frame	400	kg
Lift height	4	m
Hoist Length	30	m

The air properties are considered as density of 1.14 kg/m^3, specific heat ratio of 1.401 at 20 ^{0}C with gas constant (R) of 287 J/ (kg.K). A second order spatial and second order Crank Nicholson scheme is used for the CFD simulation in OpenFoam environment. A mesh of 5 million grid points with adequate near wall thickness is generated as shown in Figure 1(a). A velocity contour of the lift is shown in Figure 1(b). Apart from the RANS simulation, Detached Eddy Simulation (DES) with near wall K-ω SST turbulence model is also conducted on this geometry to obtain an accurate estimation of drag behind the lift body, as shown in Figure 1 (c). Simulation is conducted in parallel cluster on 64 cores at University computing facility.

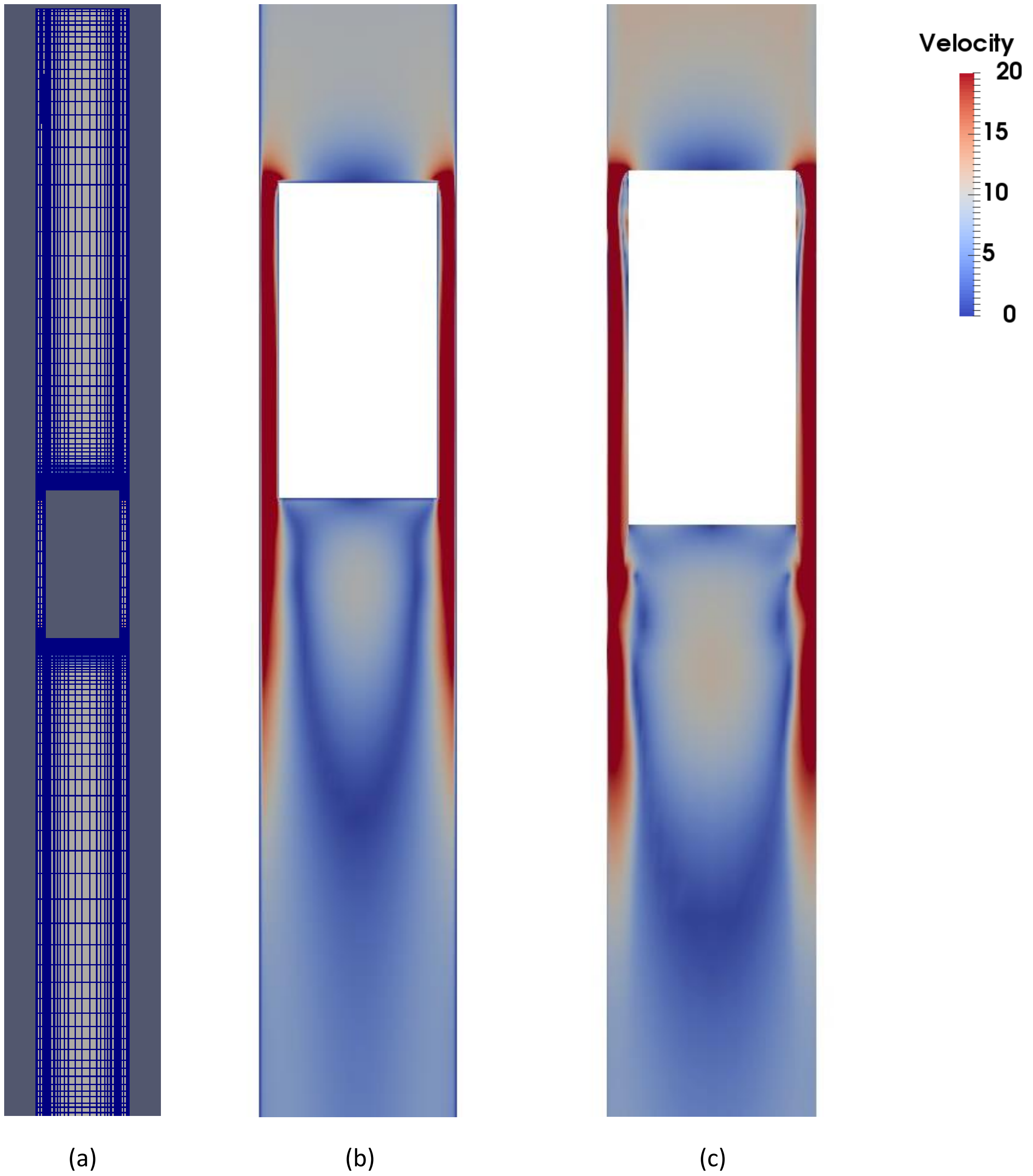

Figure 1. *(a) CFD mesh. (b) Velocity contour (RANS). (c) Velocity contour (DES with K-ω SST).*

A structural model is formulated for the investigation of fluid forces on the structure. The general equation of motion for the lift car can be written as follows:

$$m\ddot{y} + c\dot{y} + ky = F(t) \tag{5}$$

Where *m* is the structural mass, *c* is structural damping, *k* is spring constant and *F(t)* is fluid force. Skop and Griffin [10] expressed the time varying force F(t) as:

$$F(t) = \frac{1}{2}\rho U^2 D l C_Y$$

Which can be transformed in terms of the Strouhal number (*St*) and the frequency of vibration (f_s) as follows:

$$F(t) = \frac{C_Y \rho D^3 l f_s^2}{2\, St^2} \tag{6}$$

Where D and l are geometric parameters and C_Y is the fluid dynamics force coefficient which is a function of y and $\dot{y}$. It is important to consider the geometry of the lift installation shown in Figure 1 (a). A simplified setup of current problem has been considered as a rectangular box in the passage. In addition, the surrounded wall facilitates a nozzle structure in the lift installation, as shown in Figure 1(c). Hence, the fluid force can have two components in this case and the Equation (6) can be divided into two different Strouhal number regimes, as below:

$$F(t) = \frac{C_{Y1} \rho D^3 l f_{s1}^2}{2\, St_1^2} + \frac{C_{Y2} \rho d^2 D l f_{s2}^2}{2\, St_2^2} \tag{7}$$

Where d is the clearance between the lift car and the surrounding wall, St_2 is the associated Strouhal number and f_{s2} is the frequency of vibration of the associated geometry. The Strouhal numbers are a known function of flow velocity and their associated structural parameters (Reynolds number). A known correlation of $St = f(U, L, D)$ can provide an analytical expression for the vibration associated with the structure.

The velocity contour in Figure 1(c) provides clear indication of presence of larger wake modes from the lift body and other shorter nozzle modes from the lift-wall clearance. A high-fidelity CFD simulation of a typical lift geometry can provide us with correct estimation of the frequencies in the wake region, either emanating from the lift wake or the wall clearance. A closer consideration of the model provides us with some important information. The Reynolds numbers associated with the key geometrical features of the lift car puts the geometry in the critical or supercritical range of flow features. Some overshoot in Strouhal number have been observed in these critical zones. A better understanding of these overshoots can be better understood with the compressible CFD studies.

5 CONCLUSIONS AND FUTURE WORK

The very fast development of the construction of high-rise buildings raises an essential need for the design of high-speed lifts, which has led to increasing interest in the fluid-structure interaction in such systems. This research describes the application of compressible CFD in development of an analytical formulation for identification of various modes leading to the vibrations in lift systems. CFD can aid to the development of the model either by correct estimation of Strouhal number or by comparing the actual averaged fluid forces or frequency of vortex-induced vibration from CFD to the model fluid forces of the analytical model. The flow field, pressure distribution, velocity, drag forces and the flow patterns have been studied in detail. Furthermore, high fidelity Detached Eddy Simulation with near wall model have been carried out for better estimation of vortices structure and accurate formulation of the model. Refinement of various parameters in the analytical model are facilitated with various CFD flow simulations. The initial results show an acceptable level of Strouhal number estimation, consistent with the analytical estimation for a rectangular bluff body. An acceptable level of one-way coupling between the CFD and structural model is achieved.

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Understanding EN 81-77: 2013 & prEN 81-77: 2017 Lifts Subject to Seismic Conditions

Rory S. Smith

University of Northampton, Northampton UK
rory.smith@thyssenkrupp.com

Keywords: Lifts, Standards, Earthquakes

Abstract. Around the Pacific Rim, the potential for earthquakes to severely damage lifts has been recognized for decades. EN 81-77: 2013, enacted in November 2013 now brings seismic standards to the rest of the world. This standard addresses the seismic risks to lifts and establishes standards for mitigation. European Standard prEN 81-77: 2017 makes changes to the existing standard [10].

These standards are explained in practical terms, examples of seismic damage, particularly in California, are explored, and the reduction in damage that has occurred in subsequent earthquakes as a result of new codes enacted after each major earthquake are examined.

1 INTRODUCTION

EN 81-77: 2013 states the aims of the standard, describes the hazards to lifts caused by seismic accelerations, defines protective measures that can be taken to deal with the hazards, and quantify anticipated accelerations at a specific site [1].

Before reviewing EN 81-77: 2013, it is important to have an overview of how earthquakes are caused and where they can be expected to occur.

2 EARTHQUAKES

The outermost shell of the earth is made up of Tectonic plates [2]. These individual plates are in contact with each other and in constant motion relative to each other. There are two types of plates; continental and oceanic. The major landmasses are part of the continental plates while most of the ocean’s floor is made up of oceanic plates. Oceanic plates are thinner and denser than continental plates.

The motion between plates is not smooth. The plates are often bound together at a location known as an asperity and remain bound until there is sufficient stress to cause a sudden movement of the plates [3]. These sudden movements are known as earthquakes.

When an oceanic plate and a continental plate converge, the dense oceanic plate is driven under the less dense continental plate. This action is known as subduction [3]. Friction between the plates causes intense heating which melts the rock and the molten rock being less dense that the continental rock rises through the rock and causes volcanos to appear on land. Subduction is not smooth and so the movement causes earthquakes. The Pacific Northwest of the USA, home of the Mt. St. Helens volcano, is an example of this type of convergence.

When two oceanic plates converge, the underwater convergence also involves subduction of the denser of the two plates. Earthquakes are always a part of the subduction process. The friction between the two oceanic plates also melts the rock and creates volcanos that rise above the surface of the sea in the form of island arcs. The Japanese Islands are one such island arc [2].

When two continental plates converge, mountain ranges are formed. The convergence of the Asiatic plate and the India plate has formed the Himalayan Mountains and resulted earthquakes.

When two plates slide past each other they form a transform boundary. The two plates grind against each other creating earthquakes. The San Andreas Fault in California is an example of a transform boundary.

3 THE AIM OF EN 81-77: 2013

The Introduction of EN 81-77: 2013 states the following [1]:

Avoid loss of life and reduce the extent of injuries

Avoid people trapped in the lift

Avoid damage

Avoid environmental problems related to oil leakage

Reduce the number of lifts out of service

4 HAZARDS IDENTIFIED IN EN 81-77: 2013

The hazards to lifts identified in EN 81-77: 2013 that can be caused by seismic activity includes the following [1]:

1. Ropes, belts, chains, and traveling cables can get snagged by components in the hoistway.
2. Car frames can become separated from the rails. This can result in collisions with building elements and other lift components.
3. Counterweight frames leaving the rails. This has resulted in counterweights colliding with cabs, potentially at rated speed.
4. Counterweight filler weights leaving the frame. Falling filler weights can cause damage. A reduction in counterweight mass can result in a loss of traction.
5. Hydraulic pipe rupture. Unchecked, pipe rupture can cause a car to fall. Hydraulic fluids, depending on their type, can pollute.
6. Hydraulic tank rupture. Hydraulic fluids, in addition to having a potential to pollute can constitute a fire hazard.
7. Guide rail deflections that let the car or counterweight leave their guides. This creates a collision hazard.
8. Machinery anchorage. Poorly anchored machinery has been known to “dance” across the machine room floor during earthquakes. Such machinery will not be able to function after an earthquake.
9. Landing switches and final limit switches that need to be able to withstand the accelerations associated with an earthquake and be guarded against impact by ropes.
10. Loss of electrical power. An automatic rescue device can avoid entrapments.
11. Car doors can come open and that can permit passengers to become injured. Car door locks can prevent this condition.

5 DESIGN ACCELERATION

The accelerations that act on the lift as a result of an earthquake are directly related to the damage that the earthquake can produce. The greater the acceleration, the greater the effort required to mitigate the risk. For this reason, the standard requires that a calculation of the potential accelerations at the installation site to be calculated.

The EN 81-77: 2013 provides the following two formulas are used to calculate design acceleration [1]:

$$\alpha_d = S_a \left(\frac{\gamma_a}{q_a}\right) g \tag{1}$$

$$S_a = \alpha \cdot S \cdot \left\{ \frac{3 \cdot \left(1 + \frac{z}{H}\right)}{1 + \left(1 - \frac{T_a}{T_1}\right)^2} - .5 \right\} \tag{2}$$

Where:

α_d Represents the design acceleration in meters per second squared.

g Represents the gravitational acceleration 9.81m/s².

S_a Represents a non-dimensional seismic coefficient.

γ_a Represents an importance factor for a building. Minimum value is 1 but could be higher for buildings such as hospitals.

q_a represents the behavior factor of an element and has a value of 2.

α $\alpha = {}^{a_g}/_{g}$ Where a_g represents the ground acceleration expected for a particular location with Type A soil.

T_a represents the fundamental vibration period, expressed in seconds, of the non-structural element. T_a = 0 if the lift does not affect the fundamental vibration period of the building.

T_1 represents the fundamental vibration period, expressed in seconds of the building.

z represents the height, in meters, of the non-structural element above the application level of the seismic action.

H represents the building height in meters above the application level of the seismic action.

The values for local accelerations are in documents published by the individual countries. The values of S for the various ground types is shown in Table 1 below taken from EN 1998-1: 2004 [4]:

Table 1 Ground Types and S values

Ground Type	Description	S
A	Rock	1.0
B	Very dense sand, gravel, or clay	1.2
C	Dense sand, gravel, or clay	1.25
D	Loose to medium cohesionless soil or soft to firm cohesive soil	1.35
E	Surface alluvial layer of C or D, 5 to 20 meters thick over a much stiffer material.	1.4

The values of γ_α are shown in Table 2 taken from EN 1998-1: 2004 below [4]:

Table 2 Building types and importance values

Importance Class	Building Type	γ_a
I	Buildings of minor importance for public safety, (agricultural buildings, etc.)	0.8
II	Ordinary buildings, not belonging in other categories	1.0
III	Buildings whose seismic resistance is of importance in view of the consequences associated with a collapse, (schools, assembly halls, cultural institutions, etc.)	1.2
IV	Buildings whose integrity during earthquakes is of vital importance for civil protection, (hospitals, fire stations, power plants, etc.)	1.4

The design acceleration formulae can be simplified. In the formula below, q_α is a constant with a value of 2. Therefore the formula can be restated as follows:

$$\alpha_d = S_a \left(\frac{\gamma_a}{2}\right) g \qquad (3)$$

$$S_a = \alpha \cdot S \cdot \left\{ \frac{3 \cdot \left(1+\frac{z}{H}\right)}{1+\left(1-\frac{T_a}{T_1}\right)^2} - .5 \right\} \tag{4}$$

The shaded area, in many cases, has a value of 2.5, because z/H and T_a often have values of zero. Therefore, S_α is as follows:

$$S_a = \alpha \cdot S \cdot 2.5 \tag{5}$$

Combining the simplified formulae into one formula yields the following:

$$\alpha_d = \alpha \cdot S \cdot 2.5 \cdot \left(\frac{\gamma_a}{2}\right) g \tag{6}$$

It is now possible to understand how the various parameters affect the design acceleration as follows:

The value of α increases in proportion to the magnitude of accelerations at a particular site.

The value of S increases as the soil becomes less solid.

The value of γ_a increases with the importance of the building.

6 SEISMIC LIFT CATEGORIES

EN 81-77: 2013 (Table A.1) establishes Seismic Lift Categories based design acceleration. Table 3 defines those categories.

Table 3 Design accelerations and Seismic Lift Categories

Design acceleration (m/s²)	Seismic lift category	Comment
α_d < 1	0	The requirements of EN 81-20 are adequate. No further actions required
1 ≤ α_d < 2.5	1	Minor corrective actions required.
2.5 ≤ α_d < 4	2	Medium corrective actions required
α_d ≥ 4	3	Substantial corrective actions required

7 CORRECTIVE MEASURES FOR CATEGORIES 0, 1, 2, AND 3

The corrective measures for each category include the corrective measures for categories of a lower number. For example, Category 3 must address the corrective measures for Categories 0, 1, 2, and 3 while Category 2 must only comply with the requirements for 0, 1, and 2. Likewise Category 1 must only comply with Category 0 and 1 requirements.

The corrective measures must be based on the design accelerations for the particular Category. In most cases, design documents must be prepared.

7.1 Category 0

The lift must only comply with EN 81-20.

7.2 Category 1

The following preventive measures are required:

1. Prevention of snag points
2. Machinery spaces and hoistway located on the same side of expansion joint
3. Counterweight retaining devices
4. Protection of traction sheaves
5. Compensating chain guides
6. Precautions against environmental damage
7. Guide rail system
8. Machinery
9. Electrical installations in the hoistway
10. Information for use

7.3 Category 2

The following additional preventive measures are required for Category 2:

1. Car retaining devices
2. Car door locking devices
3. Special car behavior in case of power failure

7.4 Category 3

Category 3 requires the following measures in addition to those required for Category 1 and 2:

1. Seismic detection system
2. Seismic operation mode
3. Primary wave detection system (Optional)

8 THE CALIFORNIA EXPERIENCE

Three major earthquakes in California caused serious lift damage. The earthquakes are known as the 1971 San Fernando Earthquake, the 1989 Loma Prieta Earthquake, and the 1994 Northridge Earthquake. Each earthquake revealed areas that needed protection and caused caused California code changes to be adopted.

8.1 1971 San Fernando Earthquake

At the time this magnitude 6.6 earthquake struck on February 9, 1971, the lift code in place did not address seismic events. 674 counterweights came out of their rails [5].

As a result of the lift damages, the lift code was modified in 1975 and required modifications to virtually all existing lifts.

8.2 1989 Loma Prieta Earthquake

This magnitude 6.9 earthquake struck 70 km south of the San Francisco Bay area on October 17, 1989 [6]. The electrical grid serving the San Francisco Bay area failed near the earthquake's epicenter. As a result, most elevators were stopped due to lack of power before the seismic waves reached the lifts.

Only 98 counterweights came out of their guides. However, there were 6 car and counterweight collisions that occurred when power was restored. Although, these lifts had seismic switches installed, they were not battery backed up. When the power was returned, the cars were free to run with counterweights out of their guides.

Codes were changed requiring battery back-up or latching contacts on seismic switches.

8.3 1994 Northridge Earthquake

Although this earthquake that struck on January 17, 1994 only was a magnitude 6.7 quake, sensors recorded the highest ground accelerations ever observed in North America. 688 counterweights left their guides [7, 8].

As a result of the experience gained by analyzing the damage caused by this earthquake, seismic codes were established not just in California, but in all of the USA.

9 THE UPDATED STANDARD

European Standard prEN 81-77: 2017 makes changes to the existing standard. The changes are summarized as follows:

1. EN 81-20: 2014 and EN 81-50: 2014 are referenced in lieu of EN 81-1 and its revisions.
2. Additional references to EN 81-72, *Safety rules for the construction and installation of lifts – Particular application for passenger and goods passenger lifts – Part 72: Firefighter lifts.*[10]
3. Reference is made to EN 81-73, *Safety rules for the construction and installation of lifts – Particular application for passenger and goods passenger lifts – Part 73: Behavior of lifts in the event of fire* [11].
4. Section 5, Protective Measures has some modifications.
5. Section 6, Verification of safety requirements and or protective measures has changes in Subsections 6.1 and 6.2.
6. Annex C, Primary Wave detection has changes in trigger level and frequency response
7. Annex D, Proof of guide rails uses additional parameters in the calculations.

10 CONCLUSIONS

Earthquakes are a serious problem in seismically active areas. There are serious costs associated with addressing this problem. However, there are serious consequences if these issues are not addressed. EN 81-77: 2013 addresses this problem.

This standard at first seems complex, however, in its simplified form one can assess its impact on most projects.

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[11] European Standard EN 81-73, *Safety rules for the construction and installation of lifts – Particular application for passenger and goods passenger lifts – Part 73: Behavior of lifts in the event of fire.*

BIOGRAPHICAL DETAILS

Rory Smith is Visiting Professor in Lift Technology at the University of Northampton. He has over 48 years of lift industry experience during which he held positions in sales, research and development, manufacturing, installation, service, and modernization. His areas of special interest are Machine Learning, Traffic Analysis, dispatching algorithms, and ride quality. Numerous patents have been awarded for his work.

Exotic Flowers Blooming in the Dark
Women in the Lift Industry in Europe

Undine Stricker-Berghoff

ProEconomy, Distelkrog 73, D-23570 Lübeck-Travemünde, Germany
stricker-berghoff@proeconomy.de

Keywords: women, gender, female, Europe, lift industry, Lift Association, statistic, personnel, education, job, fitter, engineer, manager, career, diversity, minority, acceptance, advantage, children, family

Abstract. Five years of professional life in the lift business in Germany brought up the plan to look into the idea of women in the lift industry in Europe. A questionnaire (see enclosure) and a direct mailing in the lift industry brought some answers and interviews. Dr. Gina Barney assisted representing views from the UK lift industry.

After six weeks of intensive research in the summer of 2016, the results are disappointing: Nearly none of the European Lift Associations, "Big 4" or SMEs are aware of the topic and its implications. Though, certainly, the few women in the industry feel that the topic is important for themselves and their career. It is also vital for the future of the lift industry taking into account the dramatically rising demand for qualified personnel.

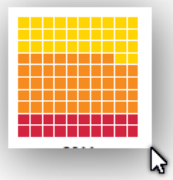
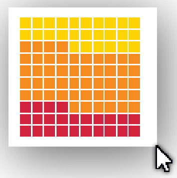
This paper will focus on four relevant topics:
- Associations as a mirror of the lift industry
- Support from the "stronger" sex
- Women speaking for themselves
- Are women looking into a brighter future soon?

The public presentation will help the next generation of women stepping "out of the shade" as well.

1 INTRODUCTION

Some statistics in table 1 give an impression of the female "force" in Europe, generally. More males are working than women, mostly in the higher ranking and better paid jobs.

Table 1 Statistics about working women and men in the EU-27 [1]

Type	*Females*	*Males*
Working persons 20-64 years	62 %	75 %
Qualification in % Yellow – high Orange – medium Red - low		
MINT studies	14 % (USA: Engineering and technical jobs ca. 16 %)	39 %
Architecture and building industry	Ca. 37 %	
Mechanics	Ca. 5 % (Germany)	
Doctors	Ca. 48 % Germany	
Doctor's assistants	Over 99 % (Germany)	
Nurses	Ca. 86 % (Germany)	
Management	Ca. 34 %	Ca. 67 %
Secretaries	Ca. 71 % (Germany)	
Part-time jobs	32 %	9 %
Due to family duties	46 %	
Number of working years	31,6	37,3
Gender pay gap	Minus 16 %	
EU Parliament	35 % (2009)	

2 ASSOCIATIONS AS A MIRROR OF THE LIFT INDUSTRY

The data in table 2 derives from the websites of the European Lift Associations in summer 2016, though many give no names at all. Nearly no site is in the English language and some are even in Russian or Greek characters. The active persons comprise mainly honorary board members and technical committee chairs. Some paid staff are listed, too, mainly general managers or secretariats. If this is a sign for the activities in the member companies of the Associations women are more or less a "rounding error". Though, if you look at the website of the French Association FA, strictly following a gender balance in its photos you might get another impression.

Through a direct mailing of the questionnaire to about 40 European Federation for Elevator Small and Medium-sized Enterprises (EFESME) and European Lift Association (ELA) member Associations the following information came in: Svein H. Kjærnet from HLF Heisleverandørenes landsforening (National Norwegian Lift Association) stated: "The Norwegian elevator industry is a man dominated business. It is about 1.3 % women among the educated installers." He contacted the HR manager Marit Aune from KONE saying, "We do not treat women differently in KONE Norway, both genders are to be treated the same."

Table 2 Statistics derived from the websites of the members of ELA European Lift Association and EFESME European Federation for Elevator Small and Medium-sized Enterprises, both based in Belgium

Country	*Association*	*Active Persons*	*Thereoff Females*
Germany	VDMA Fachverband Aufzüge und Fahrtreppen	9 honorary ? staff	0 women 1 woman
	VFA	8 honorary 5 staff	1 woman 4 women
	VMA	4 honorary	2 women
Italy	ANACAM	13 honorary	2 women ?
	AssoAscensori	13 honorary 3 staff	0 women 1 women
	Confartigianato Ascensoristi	4 honorary	1 woman
Poland	PALM	2 staff	1 woman
	SPBD	3 honorary ?	0 women
Portugal	ANIEER	9 honorary	0 women
Spain	FEPYMA	2 honorary 1 staff ?	0 woman 0 woman ?
Sweden	Swedish Ass. of Lifts & Escalators	8 honorary	1 woman
Switzerland	VSA	6 honorary 1 staff	0 women 1 woman
The Netherlands	VLR	2 staff	1 woman
Turkey	AYSAD	7 honorary	0 woman
In total		*101 persons*	*16 women = 16 %*

"We recommend elevator fitter as a very good job opportunity – also for females. We do exiting and different things every day!" Sunniva Utvik and Sofie Berntsen from KONE (see fig.1) are two out of only four female elevator fitters from a total of 800 in Norway. Their choice of profession was promoted by the Norwegian Elevator Union. They came into their service maintenance jobs after two years of school and two and a half years of internship in a company, followed by an examination. They do exactly the same work now as the ca. 200 male fitters in KONE Norway. Still, customers can be sceptical wondering whether the women are as capable as the men. The two women always have to prove themselves first. The same arises sometimes with new colleagues. Later on, everything is fine if they manage to gain their respect.

School girls are more interested in other topics for career choices. To attract more women, they have to see what they will be doing in a job. Also, their parents supported their choice of profession. They were proud and thought it a good idea for a safe future income. Sunniva Utvik has two younger children. They go to a full-day school. Her husband helps as well to look after them.

Fig. 1 From the workbench of Sunniva Utvik and Sofie Berntsen in Norway … (see also Fig. 2)

3 SUPPORT FROM THE "STRONGER" SEX

A direct mailing of the questionnaire to 205 male addressees led to three interviews:

"Get the best education you can!", my parents said, "Then you are able to do what you want … Don't be afraid to be on your own!" Dr Gina (formerly George) Barney (see fig. 2) is a consultant in vertical transportation and knows the best and worst of both gender worlds. Being 81 years old, she often was the first female in a job or position. Nowadays, a rising number of women appear on the political horizon like Hillary Clinton, the German Chancellor Angela Merkel and the British Prime Minister Theresa May looking for other solutions to national and world problems rather than war. She attributes this to the different communication and management styles of women and men. Women have in her opinion, for example, a broader variety of tools to control a meeting.

Fig. 2 (see also Fig. 1) … to ballroom dancing with Dr Gina Barney in the United Kingdom

The lift industry should not waste any talent by bringing in all people in all capacities whether full or part time. The work-life balance for women is still more difficult if they have children. The acceptance of male bosses and colleagues might help, as well as a contribution of a 50 % share of the fathers in child care. If the women take their timeout they can expect to come back into the same position that they left in the company on their return. They will sacrifice some seniority, but that's fair on the men, who soldiered on. It helps to find a suitable employer for this family period like a smaller company or a university, where you can bring your child to work or it matches school holidays. A household help is the minimum assistance required. These are things Gina discovered as a single parent.

If Gina Barney thinks hard she can come up with about 12 names of females in the lift world in the UK. Most of them are in the administration of companies, very few are outside in the field or in management. The younger generation does not bother about gender that much. The number of female students in engineering is rising. In management, she definitely sees no need for a quota. She would take simply the best, as she has done in her career. But to raise through the ranks women have to become more visible and she noticed they have to ask for pay raises.

"Don't be afraid of choosing technology as a job! There is now even a preference for women." Annick Martin, CEO of Schindler Benelux, (see fig. 3) studied industrial engineering. One of her professors came to her to enquire whether she was sure about her choice being one of two ladies from about 20-25 men. She started her career with EDF, the French electricity supplier, for 15 years, then moved on for four years to the waste collection operation in Suez Environmental, until three years ago when she joined Schindler.

Fig. 3 Annick Martin managing in Benelux Belgium - The Netherlands – Luxemburg

She learned that a lift is a complex technical product with a long lifespan. So far, she has had no problems being a female boss. Of course, there are always some remarks that "she moves in an unusual environment". She has her answers prepared and ready. It took her nearly one year to gain the know-how on the products and to win the confidence and respect of the organization. In the Benelux lift industry, women make up only about 12 % of the workforce.

Annick Martin is married. After her first child, she took a short break of 3 months but after the second, she took only 3 to 4 weeks. Her children then went to a crèche. When her children went to day school, she was not always available and sometimes felt guilty about that. The constant challenge is finding the right balance between work and family and then being a role model for your children.

In summer 2016, Brenda Borgman (see fig. 4) was employed since six months as the first female account manager with the Liftinstituut in Amsterdam/The Netherlands. In the meantime, she changed company.

She studied economics. She could be very convincing because she came into the job against 80 other applicants. In her spare time, she deals with her two children. In The Netherlands they have full-time school. In urgent cases her ex-husband helps with the children.

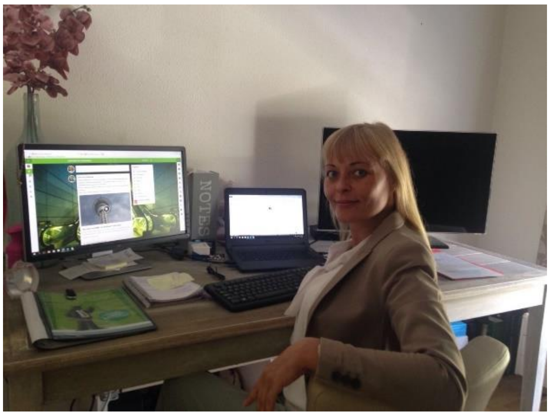


Fig. 4 Brenda Borgman from The Netherlands working at her computer

To the many male customers mostly in small and medium-sized enterprises (SME) she was very welcome: “Finally a woman!”. Sometimes they reacted “funny” or nervous on the first contact. In the “Big 4” (short version for the international companies Kone, Otis, Schindler and thyssenkrupp), women seemed to be mostly in office jobs. She met no female manager or technician there. She would have liked to see also more female CEOs paving the way for other females in their companies. “If we knew the reasons why there are so few we could act …“ she said.

4 SPEAKING FOR THEMSELVES

A direct mailing of the questionnaire to 22 women led to the following interview and some answers:

“Do not focus only on kids! Keep in touch with your job as much time as possible!” said Anja Blain (see fig. 5), since 1999 General Manager of Blain Hydraulics in Germany, who is running the company alone since the death of her husband. Professionally, she is an industrial business manager, studied languages and works closely with a good team of engineers. Her former job experience helps her a lot nowadays in her business when it comes to motivate staff or talk to customers all around the world. In the company, she has another 13 women, some are in the assembly lines but mostly they are in the administration. There is a good working relationship amongst the women in her business.

Fig. 5 Anja Blain leading her company in Germany

Being a woman working in the man's world is not difficult. On the contrary, she sometimes has a women's bonus. She even got a special discount from an Italian supplier on the interlift in Augsburg, Germany. She assumes it was due to her being female. The men tend also to overlook her lapses e.g. losing her thread in a public presentation on a trade fair in Mumbai, India. She just smiled and everybody smiled back, totally relaxed. So, it would be a pity if younger women would lose their womanliness only relying on their technical or management skills.

Anja Blain sees Germany at the political forefront of the women's movement. What helps are things like Kitas (Kindergarten for kids below the school age) and Elternzeit (paid time-off for both parents). She herself returned to her job the same day she was released from hospital after giving birth. She raised her two sons mostly with the help of a nanny since Kitas were not available 20 years ago. In the last years, the percentage of fathers driving children to school, involving themselves in the homework or going to sport events with the kids is steadily rising.

Marja-Liisa Siikonen Ph.D from KONE in Finland who is in charge of KONE People Flow Planning sent in some answers as well. She is already 32 years with KONE and since 2013 in her current role as director. In Finland, they recommend to have a certain percentage of women on the board of companies. She sees it as an advantage of women in the "steel" industry to bring in diversity and soft values. Therefore, she strongly advises not to look at the gender when filling up positions in the organization.

5 LOOKING INTO A BRIGHTER FUTURE SOON?

Matthias Horx, founder and owner of the ZukunftsInstitut dealing with megatrends in Germany, explained in his lecture on the 10th German Planner Day of Daikin, May 2014 in Germany, about the "Female Shift", and the influence of the changing role model of women in the working environment. Due to the skills shortage, this is extremely relevant in the cooling and air-conditioning industry which nowadays is still dominated by men – as is the lift industry in Europe.

As one of the first companies in the industry, Schindler makes an effort on diversity. The company has set up a diversity committee of eight women and six men reporting directly to the global head of

Corporate Human Resources to attract more women into technical and management jobs. This approach seems to be a good way to solve the problem of the shortage of skilled personnel in the sector. At the same time, it gives some hope to women that more companies are becoming aware of the importance of this topic for the lift business in Europe in the future.

Thanks to the American journal Elevator World who planned to publish the results of the study in autumn 2016, but, it was suspended due to lack of available space.

Thanks also to the women speaking their minds freely in the interviews. They are helping the next generation of women stepping "out of the shade" as well.

BIOGRAPHICAL DETAILS

The authoress was the Managing Director of VFA-Interlift e.V. in Hamburg, Germany.

She studied Mechanical Engineering at Ruhr-University in Bochum, Germany, and, immediately after graduation, worked as an energy consultant for ERPAG Lugano, Switzerland. Prior to joining VFA-Interlift, Stricker-Berghoff worked for VDI, the Association of German Engineers in Düsseldorf, Germany, as Secretary for Building Services and was in charge of the VDI-Guideline department. She also served one term as Director General for the Chamber of Commerce in Lübeck, Germany. Since 2005 she is working as a coach and consultant for management and marketing in her own engineering office ProEconomy in Lübeck-Travemünde, Germany, mainly for energy and building services companies.

Her "hobby" is women in engineering and management. So, she is a Member of the Board of VDI The Association of German Engineers – fib Women in Engineering, the VDI delegate in the DF National Council of German Women's Organizations and the VDI delegate in the Council of Women's Organizations of the German State Schleswig-Holstein.

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8 Apendix

Questionnaire
"Women in the European Elevator Business"

ProEconomy
coachen | planen | umsetzen
Undine Stricker-Berghoff
Dipl.-Ing. (TU) CEng MEI VDI
Distelkrog 73
23570 Lübeck-Travemünde
Tel.: 04502-770568
Fax: 04502-770569
mobil: 0172-2007146
info@proeconomy.de

I am writing an article for the U.S. magazine Elevator World in September 2016, hopefully with some fresh and unique data. Therefore, I would be grateful if you could personally answer a few questions **until Tuesday 16 August** by just typing in your answer and sending it back by mail to me. Please feel free to pass this questionnaire on to other women in the elevator business in Europe.

1. About you
   1.1. What profession did you train or study?
   1.2. How long have you been you working at all? In the elevator business? In your company? In your job?
   1.3. What type of company are you working in? e.g. producer of elevators/components, maintenance ...
   1.4. What is your job in the company? e.g. management/owner, project manager, sales person ...
   1.5. Do you want to share some personal experience on your work in the elevator business? What about a humorous or annoying story that happened to you?

2. Some statistics
   2.1. Do you have any figures on women in the elevator business in the EU, your home country and/or your own company?
   2.2. Do you have any figures about women in engineering and/or management in the elevator business in the EU, your home country and/or in your own company?

3. Political views
   3.1. What do you see generally as the advantages and disadvantages of women in the elevator business?
   3.2. What is done already to raise the percentage of women mainly in technical and management jobs in the EU, your home country and/or your own company?
   3.3. What should be done to raise the percentage of women mainly in technical and management jobs in the EU, your home country and/or your own company?

4. Contact data
   If you would like to be interviewed by phone please give me your contact data including name, company, country, phone number and mail address.

I guarantee that I will use all answers only personally and anonymously for this article or similar publications or lectures. I will not pass them on to anybody else at any time. Your name, photo or company name will only be mentioned after a phone interview which will be individually legitimated before publication, too.

Thank you for your kind support of the project by contributing any information you may have!

Undine Stricker-Berghoff

Fundamental Study on Rope Damage Reduction Using Intermediate Transfer Floor of High Rise Buildings

Hiroya TANAKA[1], Asami ISHII[2], Satoshi FUJITA[3],
Kazuhiro TANAKA[4], Yoichi OGAWA[5]

[1] Graduate School of Tokyo Denki Univ. Dept. of Mechanical Engineering 5 Senju-Asahi-cho, Adachi-ku, Tokyo, 120-8551, Japan, 16kmk13@ms.dendai.ac.jp
[2,3] Graduate School of Tokyo Denki Univ. Dept. of Mechanical Engineering 5 Senju-Asahi-cho, Adachi-ku, Tokyo, 120-8551, Japan
[4]Toshiba Elevator and Building Systems Corporation, 1,Toshiba-cho, Fuchu-shi, Tokyo/Japan, kazuhiro6.tanaka@glb.toshiba.co.jp
[5]Toshiba Elevator and Building Systems Corporation, 1,Toshiba-cho, Fuchu-shi, Tokyo/Japan, yoichi.ogawa@glb.toshiba.co.jp

Keywords: Lift Rope, Lift Travel, Intermediate Transfer Floor, Earthquake and Analysis.

Abstract. Lifts are essential for means of vertical transportation. In recent years, high rise buildings have become higher, leading to higher lifts and longer lift ropes. High-rise buildings have a longer natural period than conventional buildings. As lift ropes become longer, the natural period of the lift ropes become longer as well, and get closer to the natural period of the building. Consequently, the lift ropes are hooked to the equipment in hoistway when the lift ropes vibrate by an external force, such as a strong wind and earthquake. Secondary damage such as containment of passengers and lift service stop may occur. It has become a problem. For example, The 2011 off the Pacific coast of Tohoku Earthquake, 2215 cases such as catch and damage of lift ropes have been reported. However, operations of lifts after earthquakes are required. Therefore, this study constructs an analytical method capable comprehensive analysis. We aim to build a method to prevent catching by vibration reduction measures of the lift ropes. In this report, we examine the effectiveness of lifts using intermediate transfer floors for damage reduction of ropes. In the analysis, the maximum displacement of the main rope and compensation rope was examined when the lift travel is divided into two and four. The calculated results of the analysis confirmed that dividing the lift travel reduces the response of the main rope. On the other hand, the response of compensation rope was reduced by finely dividing the travel. It was confirmed that dividing the lift travel is effective for reducing the response of the rope.

1 INTRODUCTION

Earthquakes occur frequently in Japan, which causes various damage to lifts. Therefore, lifts require various seismic countermeasures, including reinforcement of seismic structure as part of their buildings. Another countermeasures is a vibration problem of the lift ropes. In recent years, numbers of high-rise buildings are increasing in urban areas with the development of building technology. Lifts installed in buildings use long objects such as main rope, compensating rope and cables. Due to the high-rise of buildings, the natural period of these long objects is prolonged. Since the natural period of the high-rise building is long, and as the long ropes and cables object becomes larger, the natural periods of the building and the long object approach and resonate due to disturbances such as long-period ground motions and wind. The rope collide with the hoistway by swaying. As a result, the lift ropes catch on the protrusions in the hoistway, causing damage to the rope and the confinement of passengers. In Japan, the evacuation staircase is said to be effective as an evacuation method when lifts stop. However, it is difficult to use the evacuation staircase in high-rise buildings. Moreover, there are many more people in high-rise buildings. If those people evacuate all at once, they are likely to cause confusion and congestion. In recent years, temporary evacuation areas on the middle floors of high-rise buildings are set up during disasters such as earthquakes and fires. In China, it is obliged to establish an "intermediate evacuation floor" that people can stay safely for a long time during disasters. At that time, evacuation methods using lifts are an attractive option. Therefore, lifts that can be operated at the time of disaster are required.

Therefore, in this research we aim to design lifts that can be operated even after earthquakes. In our previous research, it has been confirmed that the displacement of the rope is a small issue for lifts with low lift travel [1,2,3,4]. Also, I focused on the intermediate evacuation floor that is the evacuation method at the time of a disaster. In this report, we examine effectiveness of lifts using intermediate transfer floors for damage reduction of ropes.

2 ANALYTICAL MODEL

Construction of analytical method of traction type lifts is often used for high-rise buildings. Figure 1 shows the dividing model and analytical model. Model A shows a lift where only long travel is installed. Model B shows that the lift travel is divided into two, so as to divide the building height equally; the model has two lifts installed. Model C is a case that four lifts are installed, and the lifts are labeled as the first, second, third, and fourth from the top. In the analysis, the main rope is measured from the top end along the rope. In contrast, the compensation rope is measured along the rope from the bottom end.

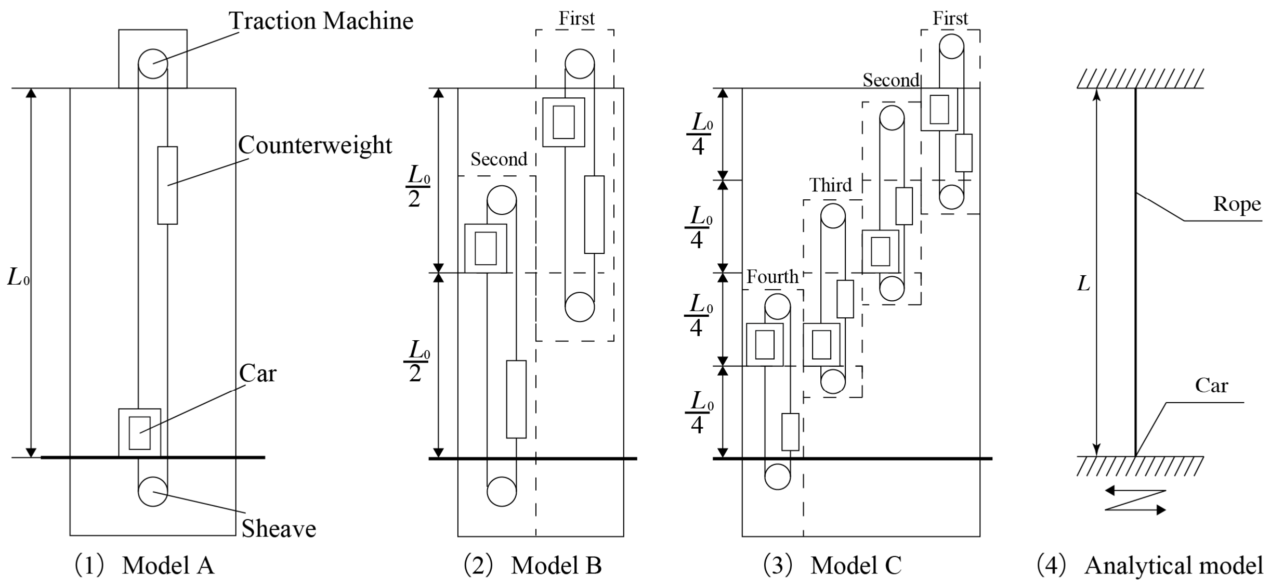

Figure 1. The dividing model and analytical model

2.1 Lift Ropes Model

The equation of motion of lift ropes as strings is as shown in Eq. (1).

$$\rho A\frac{\partial^2 u}{\partial t^2}+C\frac{\partial u}{\partial t}-\frac{\partial}{\partial z}\left(T(z)\frac{\partial u}{\partial z}\right)=0 \tag{1}$$

Where, ρA is a linear density of rope, C is a damping coefficient of rope, $T(z)$ is the tension considering the weight of the rope. u is the horizontal displacement of the rope, t is a time, z is position of elements except traction machine side. Eq. (1) is only valid when the lift is stationary. Eq. (1) is transformed to Eq. (2) by difference approximation [5,6].

$$\left(1+\frac{C\Delta t}{2\rho A}\right)u_{j+1}^{i}=2\left(1-\frac{T(z)\Delta t^{2}}{\rho A\Delta z^{2}}\right)u_{j}^{i}+\frac{\Delta t^{2}}{\Delta z^{2}}\left(\frac{T(z)}{\rho A}-g\frac{\Delta z}{2}\right)u_{j}^{i+1}+\frac{\Delta t^{2}}{\Delta z^{2}}\left(\frac{T(z)}{\rho A}+g\frac{\Delta z}{2}\right)u_{j}^{i-1}+\left(-1+\frac{C\Delta t}{\rho A}\right)u_{j-1}^{i} \tag{2}$$

Where, Δt is time step, Δz is length step, i is time coordinates, j is space coordinates, g is gravitation acceleration. Figure 2 shows a lattice point of the difference method.

2.2 Building Model

Figure 3 shows an analytical model of building. The structure in which a lift is set has been modeled as single-mass system. The equation of motion of structure is as shown in Eq. (3).

$$m\ddot{x}+c\dot{x}+kx=-m\ddot{z}_{H} \tag{3}$$

Where, m is a mass of structure, c is a damping coefficient of structure, k is a stuffiness of structure.
The natural period of structure is calculated using Eq. (4) [7].

$$T_{H}=0.025\times H \tag{4}$$

Where, T_H is a natural period of structure, H is a height of structure. Also, the vibration mode shape of the building is not straight but curved. Therefore, the shakes of the building are calculated using a correction coefficient for correcting the vibration mode. The correction equations used for the correction coefficients are shown in Eq. (5) and (6).

$$w=\alpha_{1}\times h+\alpha_{2}\times h^{2}+\alpha_{3}\times h^{3} \tag{5}$$

$$h=\frac{H_{position}}{H_{top}} \tag{6}$$

Where, w is vibration mode of building, $H_{position}$ is position of building, H_{top} is height of the top of the building, $\alpha_1=1.138$, $\alpha_2=0.5743$, $\alpha_3=-0.7083$. α were calculated by the Stodola method. The response value at the top of the building is calculated from Eq. (3). The response value of each building height is calculated by multiplying the response value obtained from Eq. (3) by the correction coefficient of each building height obtained from Eq. (5) and (6). The top and bottom of the rope vibrate synchronously with the building. Therefore, the response value obtained by the above method is input to the top and bottom of the rope.

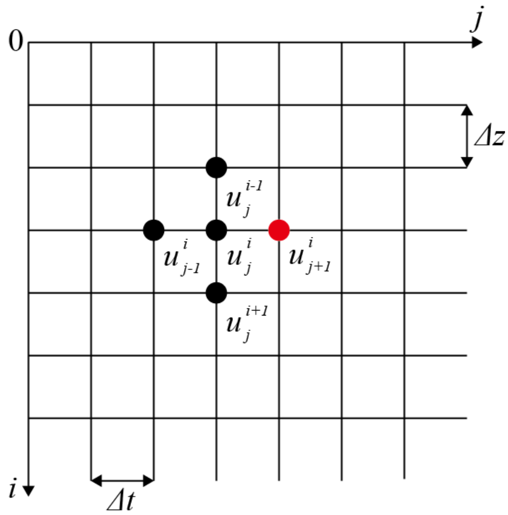

Figure 2. Lattice point

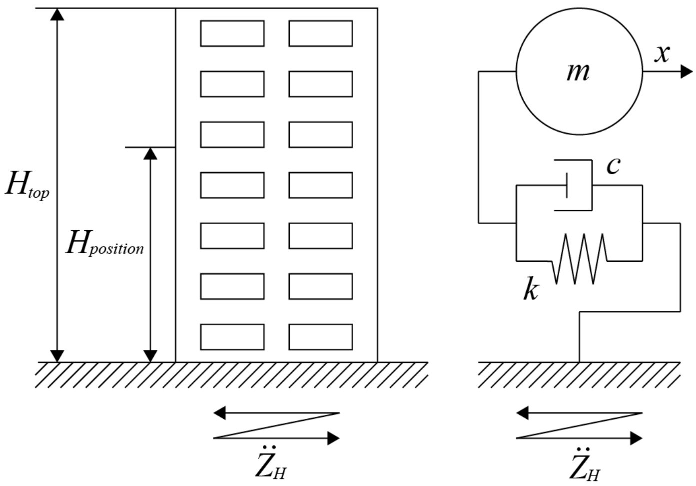

Figure 3. Structure model

3 ANALYTICAL CONDITION

3.1 Specifications of Structure and Lifts

We conduct seismic response analysis that was performed by using the derived equations in Section 2. Table 1 shows parameters of structure used for the analysis. Tables 2 to 4 show the parameters of each lift used for the analysis. Building height where the lift is installed is 240 [m]. The rope length used for the analysis was determined taking into consideration the height of car and sheave, hoisting machine and so on. The gap was determined by considering the actual lift dimensions.

Table 1. Specifications of building

Building height [m]	240
Natural period of buildings [s]	6
Damping ratio of buildings	0.02

Table 2. Specifications of model A

Roping		2:1
Car mass [kg]		2350
Counterweight mass [kg]		3450
Compensating sheave mass [kg]		554
Main rope	Number of ropes	6
	Linear density [kg/m]	0.494
	Length(Car side) [m]	3~238
	Length(Counterweight side) [m]	3~238
	Damping ratio	0.002
	Gap (cage side) [m]	0.8
	Gap (counterweight side) [m]	0.2
Compensating rope	Number of ropes	6
	Linear density [kg/m]	0.704
	Length(Car side) [m]	3~236
	Length(Counterweight side) [m]	3~235
	Damping ratio	0.02
	Gap (cage side) [m]	0.8
	Gap (counterweight side) [m]	0.4

Table 3. Specifications of model B

		First	Second
Roping		2:1	2:1
Car mass [kg]		2220	2220
Counterweight mass [kg]		3170	3180
Compensating sheave mass [kg]		167	167
Main rope	Number of ropes	5	5
	Linear density [kg/m]	0.494	0.494
	Length(Car side) [m]	3~118	3~124
	Length(Counterweight side) [m]	3~118	3~124
	Damping ratio	0.002	0.002
	Gap (cage side) [m]	0.8	0.8
	Gap (counterweight side) [m]	0.2	0.2
Compensating rope	Number of ropes	4	4
	Linear density [kg/m]	0.704	0.704
	Length(Car side) [m]	3~116	3~121
	Length(Counterweight side) [m]	3~115	3~121
	Damping ratio	0.02	0.02
	Gap (cage side) [m]	0.8	0.8
	Gap (counterweight side) [m]	0.4	0.4

Table 4. Specifications of model C

		First	Second	Third	Fourth
Roping		2:1	2:1	2:1	2:1
Car mass [kg]		2220	2220	2220	2220
Counterweight mass [kg]		3070	3080	3080	3080
Compensating sheave mass [kg]		167	167	167	167
Main rope	Number of ropes	4	4	4	4
	Linear density [kg/m]	0.494	0.494	0.494	0.494
	Length(Car side) [m]	3~58	3~63	3~63	3~63
	Length(Counterweight side) [m]	3~58	3~63	3~63	3~63
	Damping ratio	0.002	0.002	0.002	0.002
	Gap (cage side) [m]	0.8	0.8	0.8	0.8
	Gap (counterweight side) [m]	0.2	0.2	0.2	0.2
Compensating rope	Number of ropes	3	3	3	3
	Linear density [kg/m]	0.704	0.704	0.704	0.704
	Length(Car side) [m]	3~55	3~61	3~61	3~61
	Length(Counterweight side) [m]	3~55	3~61	3~61	3~61
	Damping ratio	0.02	0.02	0.02	0.02
	Gap (cage side) [m]	0.8	0.8	0.8	0.8
	Gap (counterweight side) [m]	0.4	0.4	0.4	0.4

3.2 Input Earthquake Wave and Specifications of Analysis

Figure 4 shows the input earthquake wave that was observed in 2011, when the earthquake at Shinjuku, (North-South Direction)[8] took place off the Pacific coast of Tohoku. Due to this earthquake, a large amount of lift damage was confirmed. Table 5 shows analysis time, time step and length step.

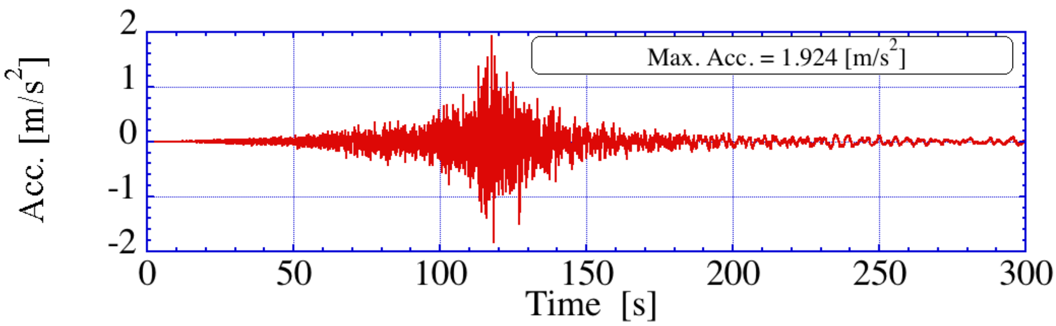

Figure 4. Input wave, The 2011 off the Pacific coast of Tohoku Earthquake at Shinjuku North-South Direction

Table 5. Specifications of Analysis

Analysis time [s]	600
Time step [s]	0.005
Length step [m]	1

4 RESULTS AND CONSIDERATIONS

Figures 5-10 show seismic response analysis results of the lift ropes. Figures 5-7 show the maximum displacement of each rope length of main rope. Figures 8-10 show the maximum displacement of each rope length of compensation rope.

From figure 5, the maximum displacement of the rope increases in proportion to the length of the rope. This is because the natural period becomes longer as the rope becomes longer, and it is close to the natural period of the building. Also, it can be confirmed that the displacement of the rope of the counterweight side is smaller than that of the car side. This is because the mass of the counterweight is larger than the mass of the car, and the natural period is short.

From figure 6, the maximum displacement on the car side and the counterweight side is smaller than model A's result. This is because dividing the lift travel has shortened the maximum rope length, and the natural period of the rope is no longer close to the natural period of the building. However, both the car side and the counterweight side can confirm that the maximum displacement of the rope is larger than the contact distance. And it can be confirmed that the displacement of the upper lift is larger than that of the lower lift. This is because the vibration amount of the rope depends on the amount of vibration applied to the top and bottom of the rope. It is considered that the displacement of the upper lift becomes larger because the amount of vibration of the upper lift is larger than that of the lower lift.

From figure 7, the maximum displacement on the car side and the counterweight side is smaller than the results of Model A and Model B. On the cage side, it can be confirmed that the maximum displacement of the rope is smaller than the contact distance. However, on the counterweight side, it can be confirmed that the maximum displacement of the rope reaches the contact distance. This is because the distance between the rope and the hoistway is smaller on the side of the counterweight.

From figure 8, the car side and the counterweight, the maximum displacement is obtained when the rope length is around 100 [m]. After that, the displacement is decreasing, and it can be confirmed that the displacement increases in the vicinity of 240 [m]. It is thought that this is because the compensating rope has lower tension than the main rope and its natural period is long. In the vicinity of 100 [m], it is considered that the first natural period of the rope is close to the natural period of the building. And in the vicinity of 240 [m], it is considered that the second natural period is close. Also, the length of the rope with the maximum displacement is changing. It is thought that this is because the number of ropes and rope length changed and the natural period changed.

From figure 9, the maximum displacement of the car side and the counterweight side is larger in the upper lift than the result of model A. This is because the vibration amount of the rope depends on the amount of vibration applied to the top and bottom of the rope. By dividing the lift, the amount of vibration input to the lower part of the compensating rope of the upper lift became larger than that of model A. Therefore, the displacement increased in the upper lift compared to the result of model A.

From figure 10, the maximum displacement on the car side and the counterweight side is smaller than the result of model A. This is because the rope length became shorter as the number of divisions increases, and the natural period of the rope and the natural period of the building no longer come close to each other.

From the above results, dividing the lift travel is effective for suppressing the displacement of the main rope. For the compensation rope, it is considered that displacement can be suppressed by increasing the number of divisions of the lift travel. Therefore, it is considered that dividing the lift travel leads to an improvement in the safety of the lift.

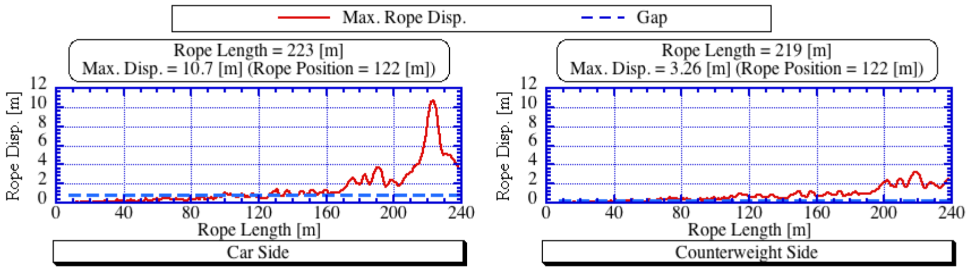

Figure 5. Numerical result of model A of main rope

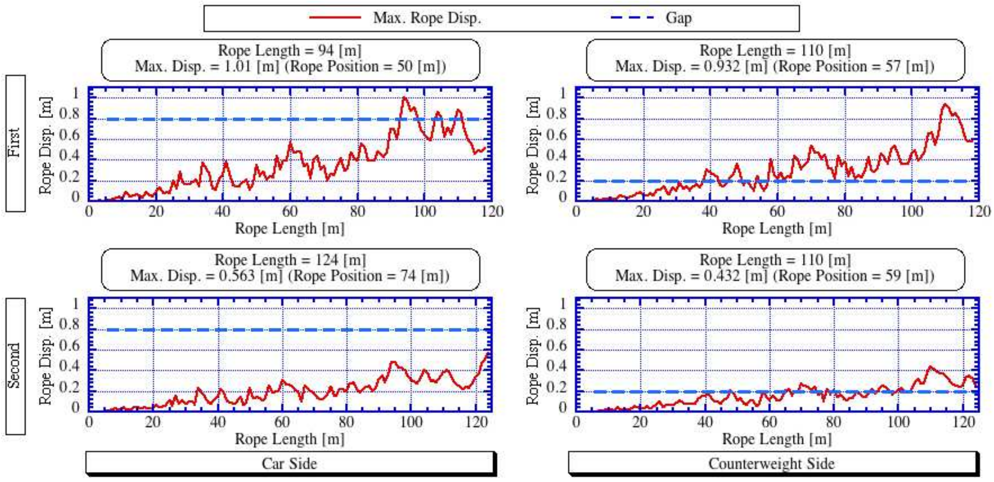

Figure 6. Numerical result of model B of main rope

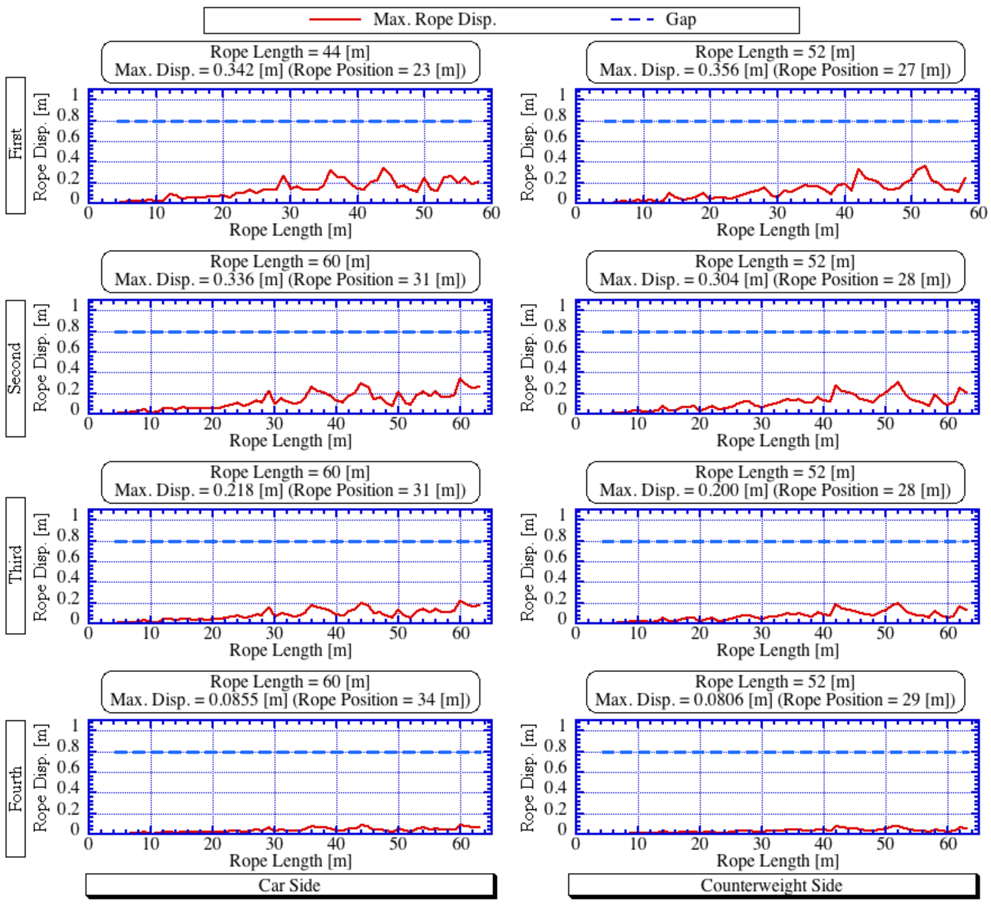

Figure 7. Numerical result of model C of main rope

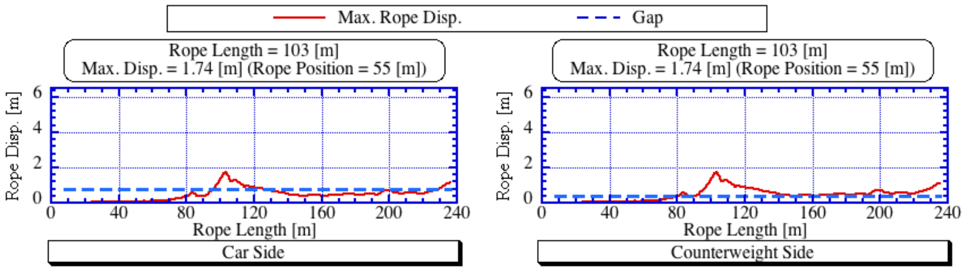

Figure 8. Numerical result of model A of compensation rope

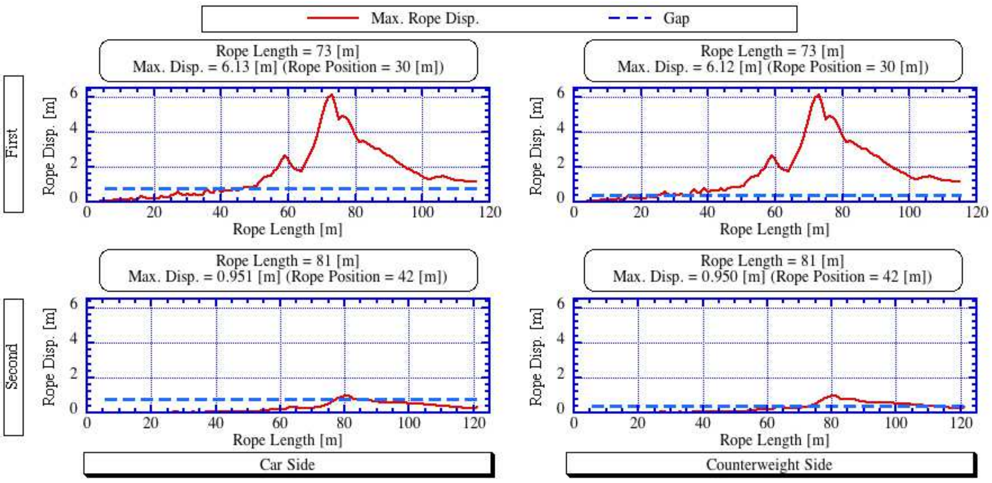

Figure 9. Numerical result of model B of compensation rope

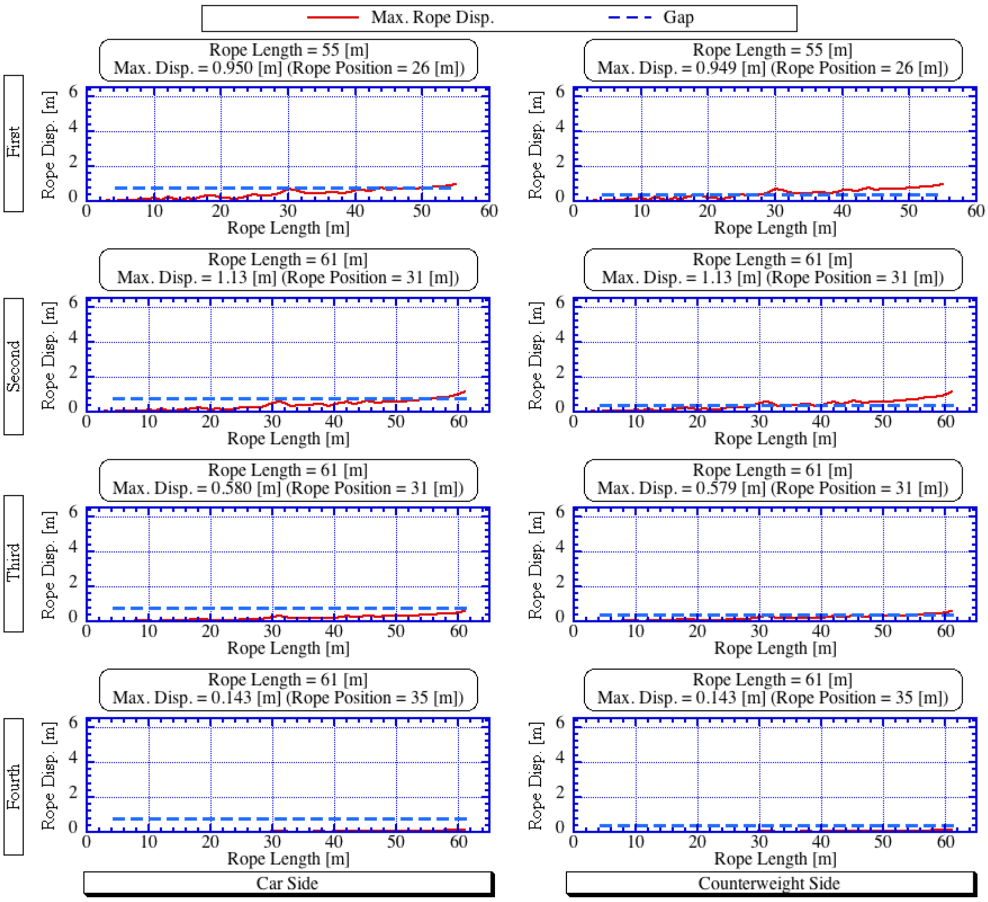

Figure 10. Numerical result of model C of compensation rope

5 CONCLUSIONS

In this report, we examined effectiveness of lifts using intermediate transfer floors for damage reduction of ropes. In the analysis, the maximum displacement of the main rope and compensation rope was examined when the lift travel is divided into two and four. As a result of the analysis, it was confirmed that displacement of the main rope could be suppressed by dividing the lift travel. And in the compensation rope, it was confirmed that displacement could be suppressed by increasing the number of divisions of the lift travel. Therefore, it is considered that dividing the lift travel can reduce damage of the lift rope. Analysis confirmed that this method is extremely useful for disaster prevention. Also, when dividing the lift travel, we confirmed that the displacement of the upper lift is larger than the lower lift. In the future, we will consider how to divide the upper lift shorter and the lower lift longer. Furthermore, We will consider the optimum division method and division number.

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BIOGRAPHICAL DETAILS

Hiroya Tanaka is master's course student in mechanical engineering of Tokyo Denki University. He researches vibration suppression of lift rope.

Miss Asami Ishii was received master’s degree in mechanical engineering from Tokyo Denki University, Tokyo Japan, 2006. She is now a doctoral course student of Tokyo Denki University. Her research interest includes seismic behavior of escalator and seismic behavior of lift ropes.

Prof. Satoshi Fujita, a JSME (Japan Society of Mechanical Engineers) Fellow, has ten years of management experience as a director, a dean of school of engineering and currently a vice-president of Tokyo Denki University. He has been engaged in engineering research and development of seismic isolation systems and vibration control systems for buildings or key industrial facilities for over 35 years at both University of Tokyo and Tokyo Denki University. In recent ten years, he has been a committee member of the Panel on Infrastructure Development of Japanese ministry of land, infrastructure and transport (MILIT), and a chair of the Special Committee on Analysis and Evaluation of Lifts, Escalators and Amusement Facilities Accidents and Failures held in MILIT. In addition, he has been a chair of the ISO TC178 Japanese committee.

Kazuhiro Tanaka, has been in Toshiba Elevator since 1995, is in charge of development for elevator system and representative of quality expert in development dept. He has developed many special elevators especially hi-rise one like applied in tall tower. He is also chairperson of expert committee of machine technology in Japan Elevator Association since 2016.

Yoichi Ogawa entered Toshiba elevator in 2013.He belongs to the Development Dept. and is engaged in the development of cage mainly.

Lift Energy Efficiency Standards and Motor Efficiency

Benjamin Watson

Otis Elevator Co.; 5 Farm Springs Road; Farmington, CT 06032; USA

Keywords: ISO25745-2, energy consumption

Abstract. The ISO25745-2 standard provides a systematic frame work for evaluating and ranking the energy consumption of various lift systems. The standard approximately models the drive system (motor and inverter) with a constant efficiency where the power lost is directly proportional to the shaft power out. The efficiency of the real system is, of course, dependent on the operating speed and the load in the car. This paper explores the effect of the constant efficiency assumption by comparing the calculated energy consumption of the ISO model to a more complete model that includes the dependence on speed and load. The magnitude of the deviation depends partially on the type of equipment used; permanent magnet motors can be reasonably approximated as constant efficiency, but efficiency of induction motors is highly dependent on the torque required for a given application. The paper also quantifies the customer value by relating the energy consumption calculations to operating cost.

1 INTRODUCTION

Energy efficiency and sustainability continue to become increasing important to government, industry, and the general public. The lift industry is no exception. In recent years, ISO has developed standards to evaluate and rank lift system energy consumption. The intent is to give our customers a simple and consistent way to evaluate energy consumption of the various product options. Precisely calculating any real lift system's energy consumption is, however, complex. For a standard to be useful, though, it is necessary to make many simplifying approximations. This paper investigates the effects of how the standards simplify motor losses.

2 BACKGROUND

The ISO25745-2 standard estimates the lift power consumption using a fairly simple method which is reviewed here. At a high level, energy consumption is separated into two components: non-running energy and running energy. The non-running energy component is based on measurements of the lift at idle and, if applicable, in reduced power standby modes.

The running energy component is also based on measurements. The energy consumption of the lift is measured for two round trip runs. The first run, called the reference cycle, is from the bottom landing to the top landing and then back to the bottom landing with an empty car. The second run, called the short cycle, is also with empty car and just long enough for the car to reach its full speed. Based on these two data points, the standard models the general running energy consumption with one fixed term for starting and stopping and a second term linearly proportional to the load in the car and the distance traveled. To estimate the running energy consumption for a given lift, the standard describes a way to use the model by applying estimates for average travel distance and average load in car. Implicit in this model is the assumption that the motor energy consumption is directly proportional to its output energy, or, in other words, that the motor efficiency is constant.

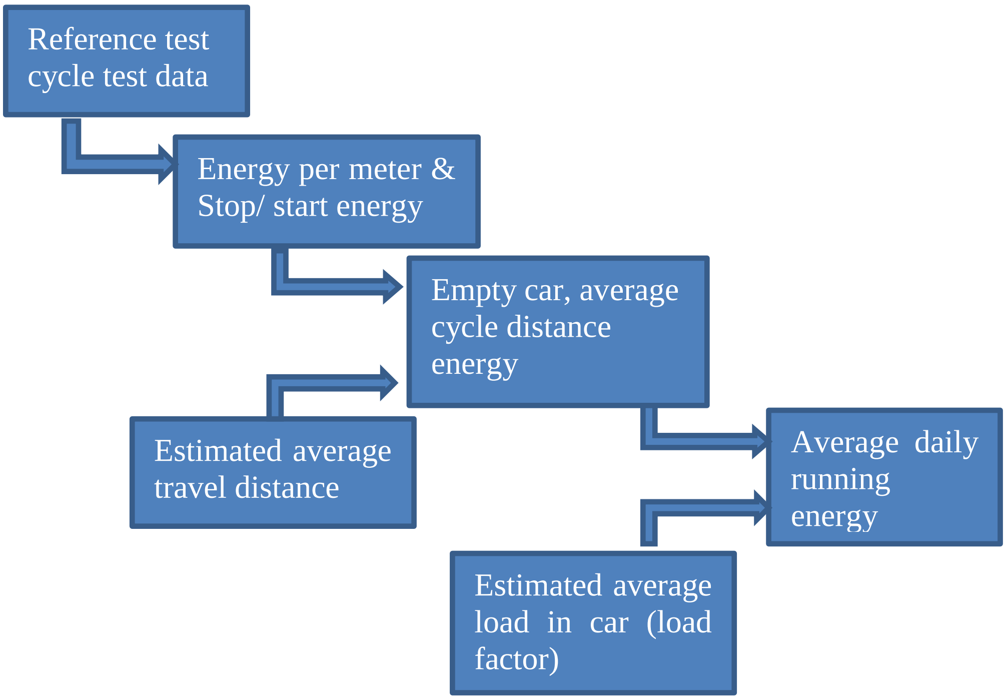

Figure 1 ISO25745-2 running energy consumption calculation flow diagram

ISO25745-2 is written in terms of energy consumption. For a given run, some portion of the energy used is useful work, and the remaining portion is losses from various sources. This paper distinguishes between general energy consumption and losses and focuses specifically on the energy losses.

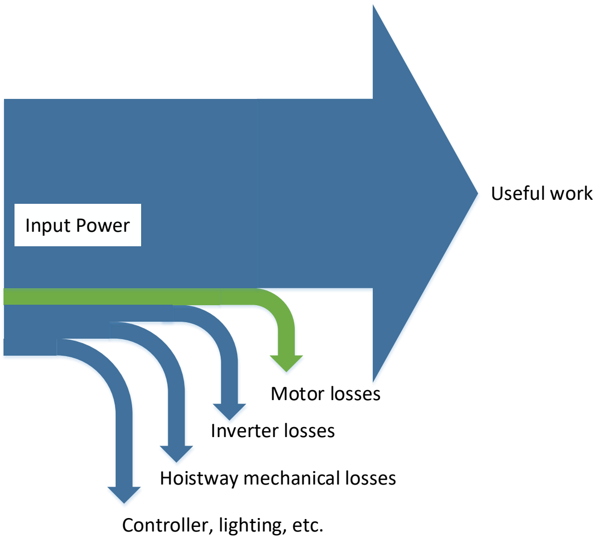

Figure 2 Energy flow diagram

To better understand the effects of the constant efficiency assumption implicit in the ISO method, two different methods to estimate motor energy losses are reviewed. The simplest method is to characterize motor losses in terms a motor's efficiency where efficiency, η, is simply

$$\eta \equiv \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out}+P_{loss}}. \quad (1)$$

In this case, the user simply calculates the required mechanical power out and uses the motor's nameplate efficiency to compute losses as

$$P_{loss} = P_{out} \cdot \left(\frac{1}{\eta} - 1\right). \quad (2)$$

This method is simple and does not require specialized knowledge or detailed information about the motor.

A motor's efficiency, however, is not a single, fixed value and depends on its operating point, or the torque and speed at which the motor is operating. For example, a motor may be 90% efficient when running at its rated torque, but only 70% efficient when running at 25% of its rated torque. A motor's losses can more accurately be expressed as the sum of copper losses and iron losses. Copper losses are the resistive losses caused as current passes through the motor winding and can be computed as

$$P_{cu} = 3\left(I_{ph}\right)^2 R_{ph}. \quad (3)$$

Where

$I_{ph} \equiv$ motor phase current, and

$R_{ph} \equiv$ motor phase resistance.

In the case of the induction motor, the current can be decomposed into two orthogonal components: torque current, I_t, and magnetizing current, I_m as

$$I_{ph} = \sqrt{{I_t}^2 + {I_m}^2}. \quad (4)$$

Further, the torque current can be approximated as

$$I_t = \frac{T}{k_T}. \quad (5)$$

Where

$T \equiv$ motor torque, and

$k_T \equiv$ motor torque constant (normally in Nm/A).

Therefore, copper losses are computed as

$$P_{cu} = 3\left(\left(\frac{T}{k_T}\right)^2 + {I_m}^2\right) R_{ph}. \quad (6)$$

Iron losses are a combination of eddy current and hysteresis losses that are caused by the changing magnetic field in the motor's armature laminations. Iron losses are approximately proportional to motor speed raised to the power of 1.5. (Note: the actual exponent may vary between 1.5 -2 based on the details of a given motor.) This is expressed as:

$$P_{fe} = \left(\frac{\omega}{\omega_{rated}}\right)^{3/2} P_{fe,rated}. \quad (7)$$

Where

$P_{fe,rated} \equiv$ iron losses at rated speed

$\omega_{rated} \equiv$ rated speed.

Total motor losses are simply approximated as the sum of copper losses and iron losses. This method requires more information about the motor than the efficiency method but returns a more accurate result. The table below compares the information required by the two methods.

Table 1 Loss model input parameters

	Efficiency Model	**Cu, Fe Loss Model**
Operating Point	P	T, ω
Motor Parameters	η	R_{ph}, k_T, I_m, $P_{fe,\,rated}$, ω_{rated}

3 ANALYSIS & METHODOLOGY

Given a set of basic lift parameters, usage conditions, and motor parameters, the average motor losses may be calculated. The analysis procedure is described here.

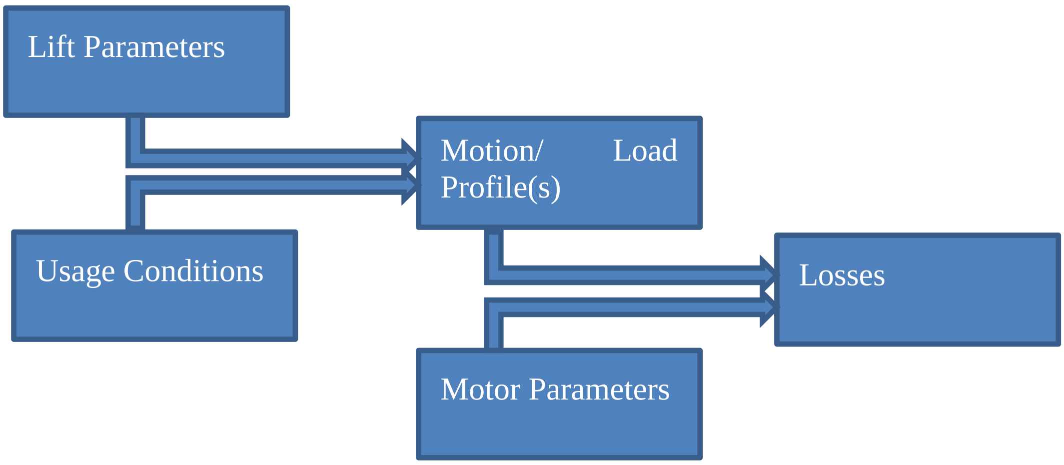

Figure 3 Loss model flow diagram

A sample low-rise lift system is considered. The basic lift parameters are shown below.

Table 2 Lift parameters of sample lift

Duty	630kg
Speed	1.0m/s
Rise	20m
Acceleration	0.8m/s²
Effective System Inertia	2kg-m²
Sheave Dia.	80mm
Starts per Hour	60

From these parameters, time histories are calculated for velocity, acceleration, motor torque, and motor power. The method for calculating these profiles well described in [2], [3].

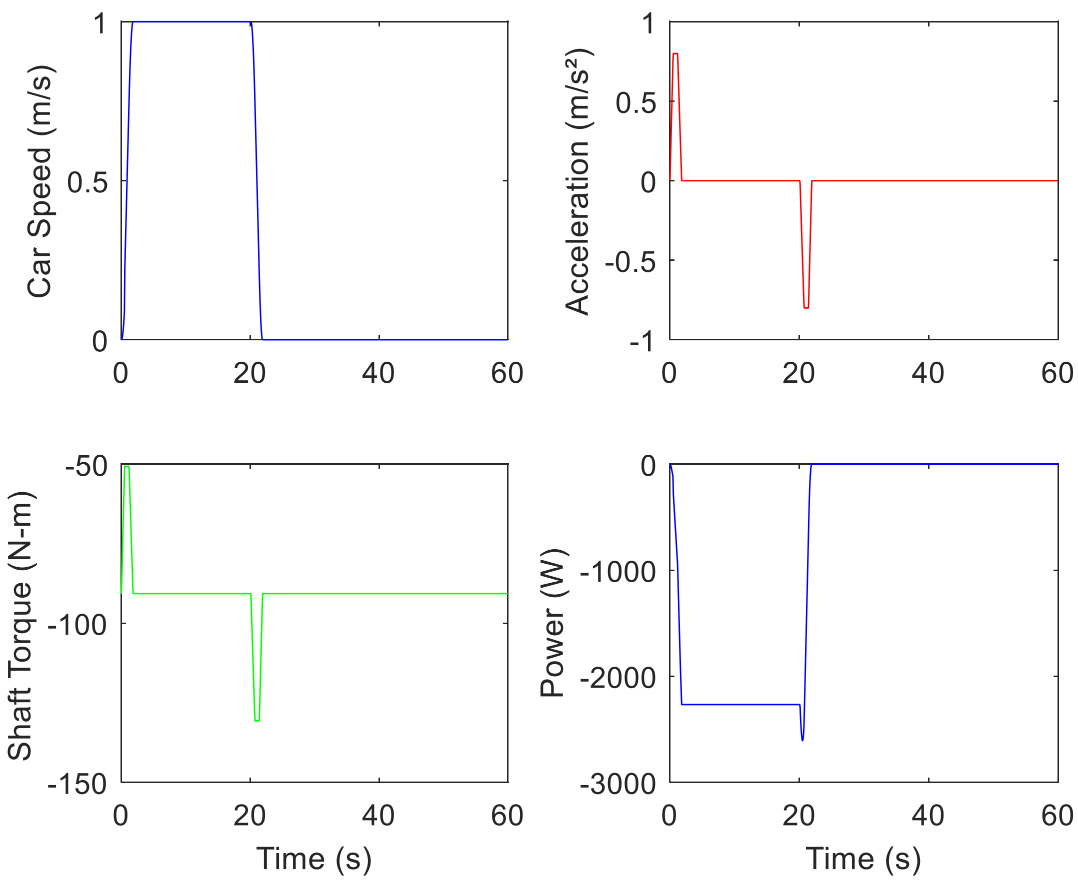

Figure 4 Sample lift run profile

Of course, the velocity and torque profiles depend on the specific lift usage parameters, including the load in the car and the travel distance. To approximate real lift usage, a range of travel distances and loading conditions are considered. Load and travel distance distributions are considered as shown below.

Table 3 Assumed load and run distance distributions

Load in car (% duty)	Percent of runs
0%	50%
25%	30%
50%	10%
75%	10%
100%	0%

Run distance	Percent of runs
3m	16%
6m	17%
10m	17%
13m	17%
16m	17%
20m	16%

Two example motors are considered and shown below. These examples are fictitious, but typical of real motors in this size range.

Table 4 Sample motor parameters

	PM motor	Induction motor
Rated torque	125N-m	125N-m
Rated speed	477rpm	477rpm
Rated current	15A	15A
Magnetizing current	--	8A
Phase Resistance	1.2ohm	1.2ohm
Iron losses @ rated speed	200W	200W
Rated efficiency	86.1%	83.4%

Motor loss can be computed as a function of time based on the efficiency and copper/ iron loss. The loss vs. time curves are computed using (2) for the efficiency method and as the sum of (6) and (7) for the copper/ iron loss method. Then, the average loss per run can be computed directly from each time history.

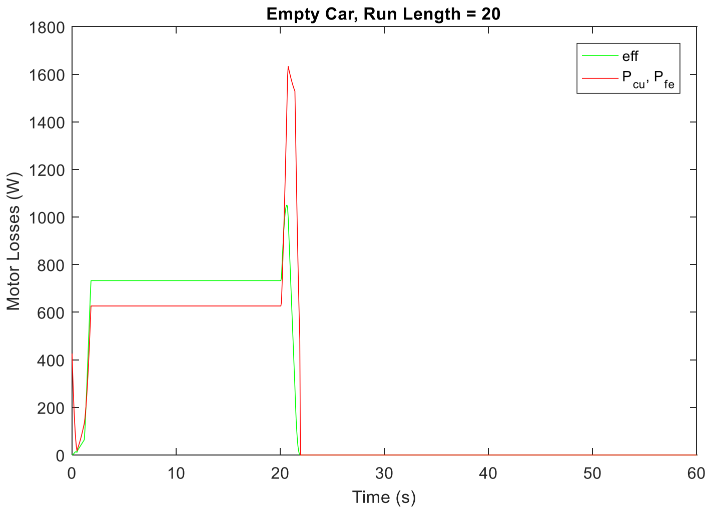

Figure 5 Motor loss over time for two models

The average loss per run is computed for each combination of run distance and load in car shown in Table 3, and the resultant average loss per run is computed as a weighted average as

$$P_{loss\_avg} = \sum_j n_s \cdot \left(\sum_i n_{l,i} \cdot P_{loss}(l_i, s_j)\right). \quad (8)$$

Where

P_{loss_avg} ≡ average loss per run considering all operating point,

P_{loss} ≡ average loss per run for a single operating point,

l ≡ per unit load in car,

n_l ≡ fraction of runs for a given load in car,

s ≡ travel distance, and

n_s ≡ fraction of runs for a given travel distance.

4 RESULTS

Based on the methods above, average losses are computed using both the efficiency model and the copper/ iron loss model. This is done for the PM motor and the induction motor.

4.1. PM Motor Comparison

As shown below, the efficiency method predicts roughly 6% lower losses than the copper/ iron loss method. For most purposes, this discrepancy is likely acceptable and the efficiency model may be used as a reasonable approximation.

Table 5 Loss model results for PM motor

	Average Motor Loss per Run [W-hr]

Efficiency Method	1.7
Copper + Iron Loss Method	1.8

4.2. IM Motor Comparison

For the induction motor, the efficiency method predicts 19% lower losses than the copper/ iron loss method. This is greater than the difference calculated in the PM motor case, and may be significant.

Consider a case where a customer is deciding between a lift system using a PM motor and a system using an induction motor. Using the efficiency method suggests the difference in energy consumption is small. Using the copper/ iron loss method, however, may lead him to a different conclusion.

Table 6 PM, induction loss model comparison

	Average Motor Loss per Run [W-hr]		Difference
	PM	**Induction**	
Efficiency Method	1.7	2.1	19%
Copper + Iron Loss Method	1.8	2.6	31%
Difference	6%	19%	

Notice that the induction motor efficiencies are slightly lower than the PM motor at rated torque. At low loads, they are substantially lower. The magnetizing current is constant, and at low loads the associated resistive losses become dominant. This means that when the lift is close to the balanced condition, the constant efficiency model will significantly under predict the losses.

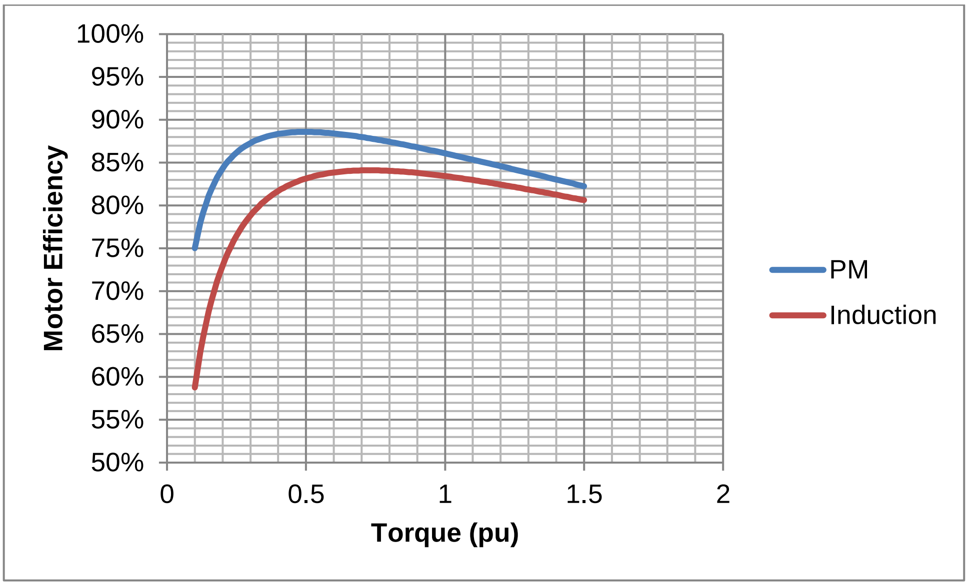

Figure 6 Induction and PM motor efficiencies by operating point

4.3. ROI of increased motor efficiency

It is well accepted that PM motors are more efficient than induction motors. For most customers, it is simply a matter of quantifying these savings against any additional costs. Below is a summary of the calculated savings with the constant efficiency assumption and the savings with the operating point model. In the example case considered, here, the two models result in significantly different conclusions; the efficiency method underestimates the potential savings by roughly 50% as compared to the copper + iron loss method.

Table 7 Five year energy cost savings from PM motor

Efficiency Method	$43.8
Copper + Iron Loss Method	$87.6

*Assuming 300 starts per day, 0.20 $/kW-hr

5 CONCLUSION

The ISO25745-2 standard creates a common language for lift manufacturers and customers about energy consumption and gives customers a simple way to compare products among manufacturers. The case considered in this paper, though fictitious, demonstrates that the standard does have some implicit limits. The standard is, for example, useful for contrasting a geared lift against a gearless lift. The standard may not, however, be as useful for detecting differences in two similar gearless lifts.

The primary goal of this paper is to simply make users of the standard aware of this limitation so that they may avoid misuse. The constant efficiency assumption implicit in the ISO standard will tend to underestimate the differences in energy consumption between PM and induction motors.

Other tools to evaluate energy consumption differences in lift motors are available, but their benefits must be weighed against the relative cost and complexity they introduce. Some options include:

- Creating an optional procedure in the ISO standard that includes at least one additional test case with a non-empty car;
- Creating a standard method for analytically determining power consumption and losses that includes a more complete motor model similar to that described in this paper;
- Characterizing motor (and drive system) power consumption separately from the rest of the lift system.

It is also suggested that further research study this effect beyond the fictitious low-rise application considered in this paper. Specifically, load distribution, traffic distribution, and motor size sensitivity should be investigated.

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